An Energy Future Transformed:

The Advanced Research Projects Agency-Energy (ARPA-E) – R&D Pathways to a Low-Carbon Future

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This report describes a new research and development (R&D) approach to addressing two major issues facing the United States today, improving energy security and combating climate change. Our nation now needs technologies that will drive a radical shift in the way the entire world powers its industries, homes, and transportation systems. The Advanced Research Projects Agency – Energy, if implemented correctly, offers the potential for delivering the needed transformational new energy technologies.

Addressing the Key Stakeholders

The report is designed to:

- Help the new administration position and empower ARPA-E within the Department of Energy (DOE) to best execute its mission to address the challenges of energy security and climate change;
- Help Congress understand how the agency should function and provide support through oversight, budgeting, and mission-level priority setting;
- Give the first ARPA-E Director concrete advice on how to structure the agency and optimize its performance as a creator of transformational new energy technologies.

United States Faces Two Energy-Related Challenges

In order to achieve energy security, the United States must have reliable access to the energy it needs at reasonable price. Today, the United States imports one third of its energy, with petroleum accounting for 83% of this imported energy. The reliance on imported energy adds to the net U.S. trade deficit and leaves the United States vulnerable to foreign pressures from and manipulation by countries that supply its fossil fuels.

In the area of climate change, the Nobel-prize winning Intergovernmental Panel on Climate Change (IPCC) concluded that human-induced (anthropogenic) greenhouse gas emissions have very likely contributed significantly to the global increase in average temperature, with fossil fuel combustion responsible for 75 percent of carbon dioxide emissions. There is general scientific concurrence that, even at current annual emissions, carbon dioxide will buildup in the atmosphere beyond safe levels, causing many negative environmental effects such as increased severe weather, extinction of species, increased disease prevalence, and sea level rise. As these annual emission levels are projected to rise with continued population growth, industrial development in many nations, and general increase in GDP globally, the time to act is now. Society needs to deploy available non-carbon and low-carbon technologies currently available, but this single wave of deployment will not be enough. As the underlying drivers of the problem continue for many decades into the future, society must plan for and implement many generations of new technologies to combat the problems.

Without new transformational technology options, society will have to make very difficult choices in the future, trading off economic growth, standard of living, energy security, and environmental impacts. Technological breakthroughs don't just happen; they are the result of hard work and long-range vision. The Advanced Research Projects Agency – Energy (ARPA-E) was created to accept and manage the risk required to do transformational R&D, to overcome the dual energy challenges the United States faces.

History of ARPA-E

In 2005, the National Academy of Sciences[1] recommended the creation of ARPA-E, patterned off of the existing successful transformational military R&D organization DARPA (Defense Advanced Research Projects Agency). In 2007, the U.S. Congress authorized the creation of ARPA-E in the America COMPETES Act. In 2009, the Obama Administration included $400 million to launch the agency as part of the American Recovery and Reinvestment Act of 2009.

How ARPA-E Fits in Energy R&D

Research and development (R&D) is one portion of the overall technology innovation system. R&D is in reality a complex system of interconnected and looping activities, but for the purposes of discussion, R&D can be broken down into phases that roughly correspond to the increasing maturity of technology. These phases of technology innovation are:

- Science/Discovery/Knowledge
- Technology Translation
- Technology Prototyping
- Commercial Viability Demonstration and Product Prototyping
- Manufacturing and Deployment (Market Acceptance)

Technology Maturation Phases

Discovery/ Science/ Knowledge	Technology Translation	Technical Prototype	Product Prototype & Commercial Viability Demonstration	Product Manufacturing & Deployment
Key Questions:				
What is it? How does it work?	Can the new device/effect/process become a technology? What are key technical barriers for applications and solutions? How much potential improvement over current technologies?	Technical Prototype Does the technology perform in the application and how well?	Demonstration Prototype Is the technology commercially viable?	How can product be optimized for customers' needs? How to manufacture inexpensively with good product performance? What continual improvement in manufacturing & product performance?

Figure 1: Technology Maturation Phases

1 *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, October, 2005, National Academies Press.

The first four phases above are R&D activities. Overlaid on this sequence of activities is whether the R&D is for the evolutionary, incremental improvement of technologies or for the creation and maturation of revolutionary, transformational technologies.

Before the creation of ARPA-E there was a gap in the organizational elements within the Department of Energy (DOE) needed to support the full range of energy-related R&D activities. The DOE Office of Science focuses on the science phase of R&D – discovery and knowledge generation. The DOE Applied Programs focus on the technology phases of R&D. However, there was no organizational element optimized around transformational R&D. Because evolutionary and revolutionary R&D are managed so differently, it is important that a transformational R&D organization have a structure, culture, staffing, and reward system different from the more traditional government R&D organization. Historically, transformational and evolutionary R&D do not coexist in the same R&D management organization well because the organization is optimized to do one or the other well.

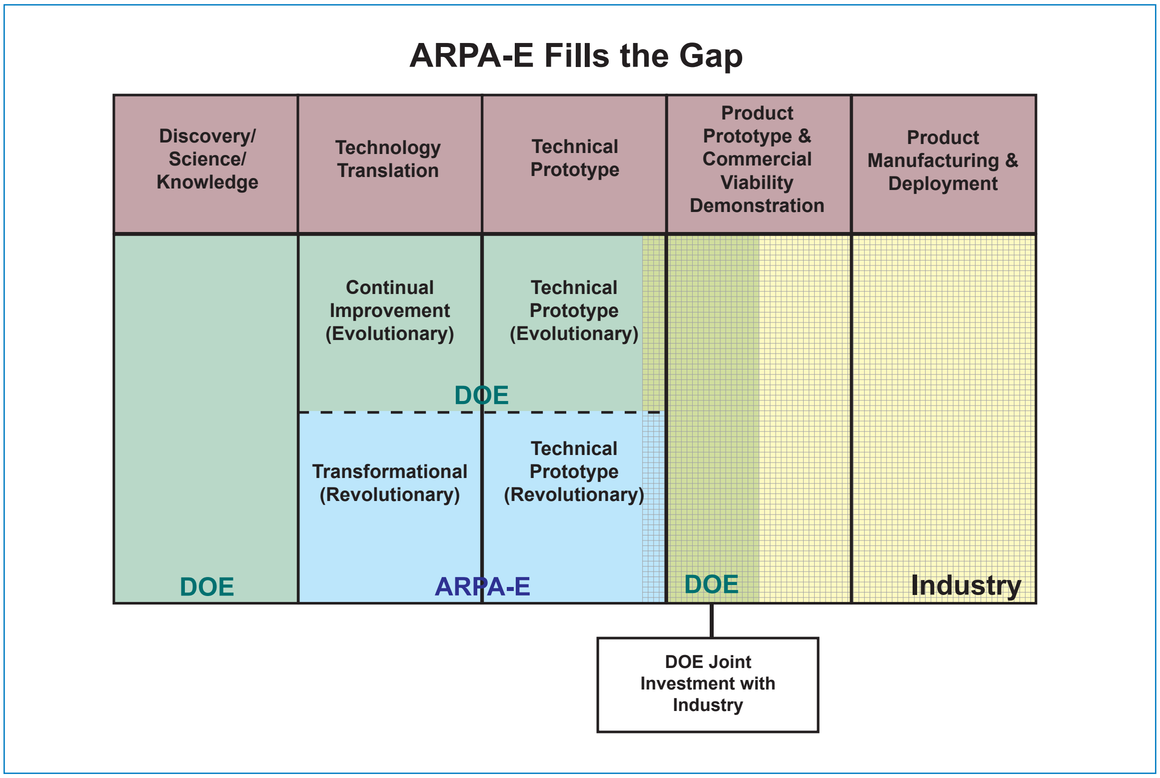

Figure 5: ARPA-E Fills the Gap

Transformational R&D

Transformational technologies are by definition technologies that disrupt the status quo. They are not merely better than current technologies, they are significantly better. Often, a technology is considered transformational when it so outperforms current approaches that it causes an industry to shift its technology base to the new technology.

Most technologies follow an S curve shape as the performance of the technology improves over time. At some point, the potential for increased performance gets less, and the difficulty in gaining the improvement becomes greater. This is the upper portion of the curve. As a technology starts to reach this point, industry looks for other technologies that will allow their product or application to continue to improve into the future. Alternative technologies that have not been matured will have a lot of uncertainty about their potential for improvement and about their suitability for use in real environments. This range of uncertain futures acts as a major barrier to industry absorbing and using the technology.

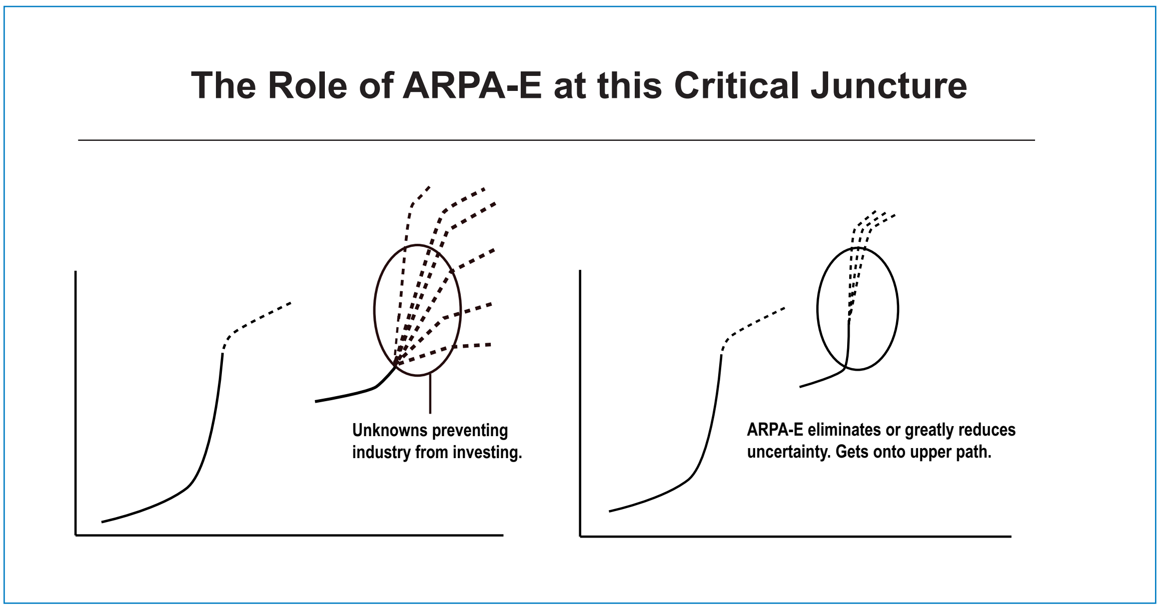

Figure 10: The Role of ARPA-E at this Critical Juncture

Transformational R&D is the process of performing enough R&D that the uncertainty is greatly reduced to the point that the remaining uncertainties are manageable by the next stage developer. After a successful late-stage ARPA-E transformational R&D program, industry should be able to take on the burden of completing the final R&D and incorporating the new breakthrough technology in products.

In evolutionary R&D, any improvement is likely to be absorbed. In transformational R&D, the improvements must reach a threshold where the combined performance aspects of the technology must reach a level of maturity at which industry believes the risks are now manageable to complete the R&D. This is a key reason why transformational R&D must be managed in programs, representing definable jumps in capability from the present state to beyond the threshold of acceptance. Unlike evolutionary R&D, a program that reaches 90% of its goals will be a failure. The outcome of the R&D program must reach the transition threshold.

Because transformational R&D programs must be thought of a tightly interconnected whole, rather than many aspects that can be independently managed, the multi-year budget must be established from the beginning and protected. Any external budget disruptions once a program is started will consume much of a Program Manager's time in the unnecessary replanning of all the interacting aspects of the program.

Because transformational R&D programs are so different from evolutionary R&D efforts, there must also be a different set of people to manage the R&D, processes to create and govern it, and organizational structure to support it.

Elements of a Transformational R&D Program

A strong ARPA-E transformational R&D program should follow a disciplined approach of:

1) identifying technologies with the potential for breakthrough performance,
2) evaluating the impact on the agency mission if the technology is successfully developed,
3) understanding the target for transition and the threshold for acceptance of the transformational technology,
4) identifying which technical barriers create the present uncertainty about the technology and prevent transition,
5) developing an R&D plan to overcome the key technical barriers,
6) developing an intellectual property strategy that will support the planned transition path,
7) developing and executing a competition and contracting strategy that matches the program,
8) actively managing the program of several R&D efforts to accomplish these goals, and
9) successfully transitioning to the next stage developer.

Each transformational R&D program is unique. It must account for the differences between technologies, but, more importantly, the differences in how different industries and sectors absorb new technologies. Some industries are quite risk averse and will not accept a new technology that is not shown to be very mature. Other industries are aggressive in accepting improvements and will reach down to technologies that are still in the laboratory. These differences require tailoring programs in three major ways: intellectual property, cost share, and maturity of any technical prototypes.

Different industries have different intellectual property strategies: trade secrets, blocking patents, or cross-licensed patent portfolios. If an ARPA program enforces an intellectual property strategy that is discordant with the target industry, then ARPA will have greatly reduced the likelihood the technology will transition. At the same time, there is a creative tension caused by ARPA's need to protect the taxpayer's investment. In each case, an experienced Program Manager who understands the nuances of the target industry must devise an intellectual property strategy that supports the likelihood the technology will transition and enter the market, but also serves national needs. One size definitely does not fit all in ARPA program intellectual property strategies.

In the area of cost-sharing, ARPA-E will need to be flexible, working with the performer to determine the appropriate level and the appropriate type of cost-sharing arrangements, which may include monetary contributions and/or other (in-kind) contributions. As rules of thumb, when the project risk is very high, the cost sharing should be lower. When the technology is closer to market or the future market is large and potentially very profitable, the cost share should be higher.

The characteristics of each transformational R&D program must be tailored to the unique aspects of that technology and the planned transition. To accomplish this extraordinarily complex task of creating an integrated R&D strategy and executing it, special people are needed as Program Managers.

Program Managers are Key to Success

The Program Manager is the central architect and manager of the program. People with the breadth of skills and experience required to be excellent Program Managers are rare.

Without the multi-dimensional knowledge and experience of seasoned entrepreneurial Program Managers, the risk of failure for transformational R&D becomes extremely high. Their expertise and vision shapes the understanding of how the future can be changed to meet national energy objectives through the development and transition of transformational new technologies and systems. Their technical expertise and knowledge of R&D identifies problems early and finds solutions. They understand how far the technology must be matured so that industry will accept the risk of using the new technology or bringing it to market. Their knowledge and experience lets them identify the right programmatic strategies tailored to the specific technology being developed. It also helps avoid creating a "poison pill" effect for a seemingly technically successful program that cannot transition for other reasons.

Three Level Structure Recommended for ARPA-E

Based on the successful staffing structure at DARPA, CA-CP recommends that ARPA-E use a similar three-level structure of Program Managers, Office Directors, and an agency Director/Deputy Director. The key aspect of an ARPA-style organization is to find good people for all the technical roles, empower them, and hold them accountable. They must be experts, capable of working in a flexible way, aware of and responding to all the different aspects of the complex job they are executing.

ARPA-style Program Managers should be hired as term appointments. This prevents the agency from getting locked into one set of technical expertise. When the Program Managers leave the agency at the end of their terms, the Director can shift into new technical areas as needed and also shift out of areas that are no longer promising. The term of appointment needs to be long enough for a Program Manager to develop a program idea, and then to initiate and execute the program.

Role of the Office Directors

Office Directors are responsible for developing a technical strategy, and recruiting and overseeing Program Managers to accomplish it. Since both Program Managers and programs are of limited duration, the Office Director must be continually seeking new replacements. The Office Director's role in interacting with the Program Managers is a complex mix of supportive coach and required governance.

Characteristics of an ideal first director

The Director must have deep technical knowledge in some area relevant to the ARPA-E mission, be savvy about technology transitioning, be aware of the various types of energy industries and how they use and adopt new technologies, and have experience with starting up an organization. Start-up requires experience with and knowledge of organizational structure, processes, reward systems, culture, recruiting, policies, and how government operations differ from industry (can be covered by getting an experienced Deputy Director). The Director must be an effective planner and communicator of the ARPA-E mission, strategy, and priorities to the Secretary of Energy and Congress. The Director can only be effective with the full faith and support of the Secretary of Energy.

Role of the Director

The Director's job is multifaceted and requires work both inside and outside the agency. If the ARPA-E Director has a deputy, the Director may decide to focus more on external relationships and delegate the internal work. The Director must develop a strategic vision for the agency, understand how best to accomplish the agency's missions, and align the internal structure and processes to best accomplish this work To succeed, the Director must understand not only national priorities in the areas of energy security, energy efficiency, and climate change, but must also have access to critical energy policy issues. This is why it is so important that the Director report directly to the Secretary of Energy, as provided by the law.

Because the Director decides which programs to initiate, he or she is the portfolio manager for the agency's investments. The Director must maintain a view of possible futures and invest accordingly. An ARPA-style organization is unusual in that it has both top-down and bottom-up aspects to it. The Director sets the agency strategy from the top-down, communicating the areas that would be most promising to fulfill the agency's mission. However, the agency should only fund R&D when a fully-formed program can be created by a Program Manager. In addition, there are usually a few programs that offer sufficient agency mission impact that even though they do not neatly fit the agency top-down strategy, they are still approved.

An ARPA-style agency when well run will never start a program in an area just to have a program there. Each program must meet the rigorous criteria of a well thought-out plan, dealing with all the complexities required in transformational R&D. The Director is the ultimate decider on whether the program plan and potential payoff is of the quality to merit investment.

The Director's leadership will establish the culture and expectations internal to ARPA-E. The technical staff must be brutally honest about the technologies and programs. Only by facing reality and being extremely open and honest about all aspects of the transformational work can the extremely high risks be managed. The Director must also demand excellence.

DARPA as a Model Organization

DARPA is the transformational R&D organization for the Department of Defense. In its 50 year history, DARPA has created many breakthrough capabilities: stealth technology, unmanned aircraft, GPS miniaturization, and the internet.

One of the criticisms of using the DARPA model for ARPA-E comes from the belief that DARPA always transitions to another government (usually military) R&D organization and that the eventual targeted customer is also within the government (the military). If this were the only DARPA model for transition, it would indeed not be applicable for most ARPA-E and energy-related R&D.

In fact, roughly half of DARPA's R&D investments transition through other pathways. In cases where DARPA is trying to leverage and motivate industrial investment, the DARPA Program Manager investigates the commercial market potential for the technology and identifies key technical risks for both military and commercial use. The program's technical goals are then set beyond the transition threshold for commercial investment and simultaneously informed by the long-term technical goals that support the agency mission – in DARPA's case, for the military. These programs transition into industry as the next-stage developer where industry will develop products primarily for the commercial market, but will also sell to military system integrators. Thus there is an already proven program strategy at DARPA for the government funding the development of transformational R&D and then transitioning it into industry. This is the paradigm that ARPA-E must follow.

Elements of Success

There are various potential organizational, staffing, and management errors that can lead to the failure of an ARPA-style agency. The following recommendations are ways to prevent the various kinds of failure:

- **Hire a strong Director**
- **Hire qualified Program Managers**
- **Execute transformational R&D in complete programs**
- **Keep contracting, general counsel, and political factors in bounds**

While contracting and general counsel are key support functions for a program, they must not be allowed to determine the program strategy elements. They assist the Program Managers in embodying the program strategy in competitive evaluations, contracting vehicles, and intellectual property clauses. They do not determine them, unless there is a specific legal impediment. The political process should dictate top level objectives, but politics must not dictate specific programs and projects. ARPA-E must be allowed to establish program objectives, schedules, and deliverables based on real opportunities rather than political desires.

Congressional earmarking is particularly damaging to an ARPA-style organization. The most valuable resource an ARPA agency owns is the Program Manager's time. Earmarked programs require vast amounts of a Program Manager's time in attempting to align the earmarked program's objectives with optimal value to the Government. The biggest damage is not caused by loss of money from the existing programs, but the diversion of Program Manager's time from high-priority programs.

- **Be willing to take appropriate risks**

  Internal processes and the reward system must support prudent risk-taking.

- **Limit bureaucratic drag**

- **Conduct a rigorous program generation and selection process**

- **Keep evolutionary and revolutionary R&D separate**

  Do not expect an ARPA-E to execute evolutionary R&D.

- **Maintain trust of R&D technical community**

  ARPA-E must maintain trust of the R&D technical community. ARPA-E does not perform its own R&D; it meets its R&D objectives through funding others. ARPA-E must be perceived to be open to new ideas, fair in its evaluation and decisions, expert in technical opinion and understanding of industry absorption of new technologies, and able to protect prized intellectual property. ARPA-E should be valued for more than funding. It should provide active technical advice, help identify problems early, identify solutions, and advise on the future.

- **Be flexible and agile**

  ARPA-E should own no fixed facilities. It should rotate technical staff to allow the agency to move into promising areas and out of ones with less potential. ARPA-E must be able to move rapidly forward on promising ideas.

Reasonable Expectations for the First Year

Congress should judge the first-year success of ARPA-E in several ways. First, the agency should have in place a Director and a beginning cadre of Program Managers.

Second, the Congress should expect that ARPA-E was able to run its first solicitation in such a way that the technical community responded with a batch of excellent proposals. The Congress may want to monitor whether ARPA-E is being given the resources (including contracting and legal staff) and the flexibility to negotiate and sign these first contracts rapidly and with the full flexibility that will probably be required for optimal projects.

ARPA-E must have established trust with the technical community. ARPA-E must develop a reputation for sound technical judgment, aggressive goals, challenging but feasible programs which have the potential for major mission impacts, protection of proposer's intellectual property, and respectful treatment of proposers and performers. ARPA-E should also be seen as flexible, nimble, visionary but practical, and demanding of the best, while accepting and managing risk. ARPA-E should not be expected to report technical accomplishments by the end of the first year, but it should be able to show an initial portfolio of projects and programs worthy of the mission it was given.

Summary

ARPA-E fills a needed gap in the complex of United States energy-related R&D organizations. If properly organized and staffed, ARPA-E has the potential to deliver breakthrough new technologies that, when further developed and marketed by industry, will transform the paired problems of energy security and climate change. ARPA-E is not the only answer, but it is an important part of the solution.

A Critical Need for Transformative Technology

This report describes a new R&D approach to addressing two issues facing the United States today, energy security and combating climate change, which have emerged as two of the greatest challenges of our time. It is now clear that the time has come for us to devote resources to creating the revolutionary energy technologies so badly needed. Steady improvement in technology is not enough. The United States needs breakthroughs.

New technologies come along every day, but technologies that revolutionize the way people live are few and far between. When significant technological breakthroughs do occur – like the development of the Internet – they often transform lives and societies in ways not even imagined by their creators. Our nation now needs technologies that will drive a radical shift in the way the entire world powers its industries, homes, and transportation systems. Technological breakthroughs don't just happen; they are the result of hard work and long-range vision. However, the process of developing new energy technologies today often lacks the capacity to make the resulting technologies truly transformative.

Proven Model – Newly Applied to Energy and Climate Change

This report examines how a new transformational energy-related R&D organization (ARPA-E), working in the mission areas of energy security and climate change, can be patterned on an existing successful transformational R&D organization, DARPA. In 1958, the United States created The Defense Advanced Research Projects Agency[2] (DARPA) for the purpose of pursuing this type of long-term transformational technology R&D. The agency created for its military stakeholders the revolutionary technologies that made possible, among other achievements, stealth and unmanned aircraft as well as Internet communication. DARPA identified the right technical opportunities, envisioned the radically better future they could make possible, accepted the risks to get there, and structured a well-managed path to that end.

Genesis of This Report

Clean Air-Cool Planet® (CA-CP) has always believed that technological development must be a major part of transforming energy use and addressing climate change. Responding to the National Academy of Sciences' report[3] recommending the creation of the Advanced Research Projects Agency - Energy (ARPA-E), CA-CP thought it was worth pursuing further how best to adapt the DARPA model, doing for energy and climate change what DARPA had done for our national defense needs. Thanks to a grant from the Doris Duke Charitable Foundation, CA-CP was able to embark on a study designed to explore and communicate options for the design and implementation of ARPA-E.

The first step in conducting the study was to bring on board Dr. Jane A. Alexander. She served as a

2 DARPA was created in 1958 as the Advanced Research Projects Agency (ARPA). Through the years, the name has been changed between ARPA and DARPA twice and is currently DARPA.

3 *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, October, 2005, National Academies Press.

high-level manager in both DARPA and HSARPA – the transformational R&D organizations for the Departments of Defense and Homeland Security. At DARPA, Dr. Alexander served in a variety of roles from Program Manager up to Deputy Director of the agency. As the first Deputy Director of the Homeland Security Advanced Projects Research Agency (HSARPA), she was responsible for organizing, staffing, and starting that agency. As Director of this study, Dr. Alexander brought a unique perspective, understanding both success models and failure modes for ARPA-style organizations. Drawing on her previous experience at DARPA and HSARPA, she helped formulate recommendations on how to best set up and operate ARPA-E. Dr. Alexander and the CA-CP team analyzed and studied the issues surrounding the missions of ARPA-E, as laid out in legislation. The CA-CP team conducted interviews with experts and stakeholders from a wide variety of backgrounds, including former DARPA and HSARPA employees, energy industry experts and other representatives from industry, academia, and national laboratories, as well as R&D policy, venture capital, and other R&D organizations. The conclusions of this report were presented by Dr. Alexander at several technology R&D conferences and forums to invite feedback.

As the study was originally designed, the report included several sections exploring in-depth the need for an ARPA-E. With the Administration's decision to initiate the agency, this material was de-emphasized in the main body of the report and much of it moved to the appendices.

Current Status of ARPA-E

In 2007, the U.S. Congress saw the benefits of the DARPA model and authorized the creation of ARPA-E. A properly designed and implemented ARPA-E would help develop the technologies needed to overcome the problems facing the nation and transition them rapidly to industry. So that ARPA-E could begin expeditiously to fulfill its mission, Congress – as part of the American Recovery and Reinvestment Act of 2009, signed by President Obama – included $400 million to launch the agency.

The ARPA-E Mission

This report explores in detail the mission of the new agency and the implications for how ARPA-E should be organized and function. When the U.S. Congress authorized ARPA-E to sponsor transformational energy research, the enabling legislation defined its role. ARPA-E's mission is to coordinate and manage applied R&D in order to deliver entirely new capabilities to the marketplace as quickly as possible – rather than making only incremental progress. The agency's mission comprises four main goals:

- Improve energy efficiency in all economic sectors
- Reduce energy-related greenhouse gas emissions
- Reduce dependency on foreign oil
- Maintain U.S. leadership in the development and deployment of energy technologies

Facilitating Fast Innovation

ARPA-E is not a performer of R&D and therefore doesn't comprise a new set of laboratories for the United States. Instead, the agency will accomplish its mission by funding existing R&D capacity at universities, companies, and national laboratories so that they can perform the work. The agency will identify fast-payoff and high-return energy technology opportunities and organize and manage efforts to bring targeted technologies to maturity quickly.

Addressing the Key Stakeholders

The report is designed to:

- Help the new administration position and empower ARPA-E within the Department of Energy (DOE) to best execute its mission to address the challenges of energy security and climate change.
- Help Congress understand how the agency should function and provide support through oversight, budgeting, and mission-level priority setting.
- Give the first ARPA-E Director concrete advice on how to structure the agency and optimize its performance as a creator of transformational new energy technologies.

Obama Administration's High-Level Policy on Energy and Climate Change

As it begins to implement its high-level policy, the Obama Administration is faced with many key decisions. In particular, the Administration must face the paired challenges of improving energy security and arresting climate change in a challenging economic environment. To offer guidance so that the Administration can make the best decisions, this report:

- Explores how an appropriately structured energy-related R&D strategy can make a significant contribution to addressing the nation's energy and climate challenges.
- Describes briefly the current system for U.S. energy-related R&D.
- Makes the case that creating new technologies is key to improving U.S. energy security, while addressing climate change *and* maintaining economic growth and quality of life.

Congress Plays a Key Role

While Congress has already pinpointed addressing climate change and energy security as mission priorities for ARPA-E, it will continue – through its appropriations and oversight committees – to be a key player in designing, implementing, and overseeing relevant elements of the agency. In addition to providing support through oversight, budgeting, and mission-level priority setting, Congress will need to monitor whether additional legislation is needed to adjust agency authorities.

It is important to the success of ARPA-E that Congress understands how an organization based on the ARPA model functions. As a result, this report explores structure, process, and budgeting in support of ARPA-related missions. Included are timelines and goals to measure the agency's progress and to hold it accountable, as well as other issues of interest to the Congress with respect to ARPA-E.

Operating an Effective Agency

The report also provides nuts and bolts guidance for ARPA-E's Director. A transformational R&D organization differs from the more common science-based R&D agencies and evolutionary technology-development agencies. While many lessons can be drawn from other transformational R&D agencies, these models must be adjusted to account for the specific nature of energy-related R&D.

The report also guides the Director on how to translate the agency's mission into the establishment and operation of a new federal agency aimed at transformational energy R&D. A portfolio management strategy is recommended to deal with uncertainties about the future, the breadth of the ARPA-E mission space, and the risks inherent in transformational R&D. The report includes detailed lessons learned about types of staff, organizational structure, reward systems, and management procedures and processes.

ARPA-E – The Future

ARPA-E is now an authorized and funded agency, albeit currently without a Director. Congress and the White House have already made many important decisions related to the creation of the agency. CA-CP hopes that this report will inform leaders on what the issues and options are to help ARPA-E succeed in its very important missions of curbing climate change and improving U.S. energy security.

The creation of the Advanced Research Projects Agency – Energy (ARPA-E) marked the culmination of several years of debate in the Congress over the merits of establishing an agency to break through the long-term and high-risk technological barriers to the development of new energy technologies to meet the energy security and climate challenges the United States faces.

In October 2005, the National Academies' report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* recommended establishing an ARPA-E organization. The U.S. Senate's version of the Energy Policy Act of 2005 (EPACT, PL 109-58) included language authorizing ARPA-E. In conference, though, legislators dropped the Senate's language and instead included a provision for the Department of Energy (DOE) to study whether to create such an agency. However, funding was not appropriated and the study was never conducted.

Discussion about the creation of the new agency continued. In 2006, the House Committee on Science and Technology held hearings on whether the Congress should establish ARPA-E.[4] Legislation for ARPA-E has since been part of many bills[5] and both the 109th and 110th Congress debated the merits of ARPA-E[6].

Congress Authorizes and Funds ARPA-E

Authorization language ultimately appeared in 2007 in the America COMPETES Act, sponsored by Rep. Bart Gordon, Chairman of the House Committee on Science and Technology. Senate Energy Committee Chair Jeff Bingaman sponsored companion legislation. The America COMPETES Act (Public Law 110-69[7]) – authorized by the House and Senate on August 2, 2007 and signed into law by President Bush on August 9, 2007 – established ARPA-E within DOE.

Congress authorized $300 million for ARPA-E in FY '08 and such sums as may be necessary for FY '09 and FY '10. However, President Bush did not request funding for ARPA-E in FY '09 and Congress made no appropriation. The 111th Congress appropriated $400 million for ARPA-E in the American Recovery and Reinvestment Act of 2009, which was signed by President Obama on February 17, 2009. In addition, Congress appropriated $15 million for ARPA-E in the Omnibus Appropriations Act 2009, although these funds were mistakenly placed in the DOE Office of Science appropriation.

4 House Committee on Science and Technology Full Committee Hearing. March 9, 2006. *Should Congress Establish "ARPA-E", The Advanced Research Projects Agency - Energy?* http://science.house.gov/publications/hearings_markups_details.aspx?NewsID=1056

5 America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act; PACE-Energy Act; Protecting America's Competitive Edge Through Energy Act (Source: www.govtrack.us)

6 U.S. Government Printing Office. www.gpoaccess.gov

7 The bill was introduced on May 10, 2007, reported by committee on May 22, 2007, passed in the House on May 21, 2007, passed in the Senate July 19, 2007, and both houses agreed to the conference report on August 2, 2007. See Appendix III for full text of the ARPA-E portion of the America COMPETES Act (Public Law 110-69).

Laying Out the Mission

The America COMPETES Act lays out the mission and goals of ARPA-E, noting that its goals include the enhancement of the economic and energy security of the United States by developing energy technologies to:

- reduce imports of energy from foreign sources;
- reduce energy-related emissions, including greenhouse gases;
- improve energy efficiency in all economic sectors; and
- ensure the United States maintains a technological lead in developing and deploying advanced energy technologies.

The law also specifies that ARPA-E will achieve its energy technology project goals by:

- identifying and promoting revolutionary advances in fundamental sciences;
- translating scientific discoveries and cutting-edge inventions into technological innovations; and
- accelerating transformational technological advances where industry is risk-averse because of technical and financial uncertainty.

The legislation also dictates that the Director of ARPA-E be appointed by the President, confirmed by the Senate, and report directly to the Secretary of the Department of Energy.

Through its choice of name for the new agency, Congress clearly intended ARPA-E to be a transformational R&D organization, similar to DARPA (the Defense Advanced Research Projects Agency). This style of transformational R&D is executed through creating multidimensional R&D programs based on technological opportunities that have the potential for major impact on mission areas. For ARPA-E to succeed, it must develop an in-depth understanding of its mission space and where there is potential leverage for increasing the energy security of the United States and curbing climate change.

Dual Challenges: Energy and Climate Change

In order to achieve energy security, the United States must have reliable access to the energy it needs at a reasonable price. Today, the United States imports one third of its energy, with petroleum accounting for 83% of this imported energy. The transportation sector uses approximately 69% of all petroleum consumed in the United States.[8] The reliance on imported energy adds to the net U.S. trade deficit and leaves the United States vulnerable to foreign pressures from and manipulation by countries that supply its fossil fuels.

ARPA-E can address the energy security challenge by finding and maturing the technologies that will displace the current approaches that consume so much petroleum. These technologies may range from

8 Energy Information Administration (EIA), *Annual Energy Review*, 2007.

domestically derived liquid fuels for aircraft and land vehicles to better technologies to enable hybrid electric and plug-in vehicles, to more efficient uses of petroleum by industry and in transportation. Among the challenges for ARPA-E will be the need to look at these areas in a different enough way that they can find truly transformational opportunities in areas that have already been so thoroughly investigated by the Department of Energy (DOE) and the Department of Transportation (DOT).

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has further solidified its body of research showing that human-induced (anthropogenic) greenhouse gas emissions have very likely contributed significantly to the global increase in average temperature since the mid-20th century. Anthropogenic greenhouse gas emissions stem primarily from burning fossil fuels, land use changes (for example, deforestation), and agriculture.[9] Carbon dioxide (CO_2) is the most significant greenhouse gas because it is one of the most prevalent and stays in the atmosphere for 100 years or longer. Projections show that the underlying drivers of climate change, such as population growth and per capita GDP growth, will not disappear after 2030 or even after 2050. Moreover, in order to reach the level of emission reductions that scientists believe is necessary to maintain climate stability, society needs to deploy available non-carbon and low-carbon technologies now, but this single wave of deployment will not be enough. As the underlying drivers of the problem continue for many decades into the future, society must plan for and implement many generations of new technologies to combat the problem.

ARPA-E was created to play a key role in solving the paired energy-related dilemmas facing the United States. The agency's challenge will be to develop technologies that transform each mission area (climate change and energy security) without harm to the other. In many cases, potential ARPA-E technologies promise simultaneous improvements in both areas. For more information on these two challenges, see Appendix II.

9 IPCC 2007: *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Summary for Policy Makers. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., p. 2.

Chapter 2: Appropriate Government Roles in R&D Funding

To examine the appropriate roles and methods for ARPA-E in developing transformational energy technology, it is important to first examine appropriate roles for the Federal Government in funding R&D. In the United States, it is generally agreed that government support for R&D is only appropriate where industrial or other private sector funding will not accomplish the needed scientific discovery, knowledge formation, and technology creation and maturation. Stemming from that approach, the four main purposes of government funding of R&D are to:

- **Promote science and discovery**

  Great benefits to the public flow from having a broad set of new ideas and a deep understanding of the discoveries that will form the foundation for future technologies and technological improvements. Private industry does not typically invest at this stage because the time to market is usually long and competitors may reap the benefits of these early-stage investments.

- **Expedite technology maturation**

  Before industry can invest in developing and manufacturing products, the key technical risks for new technologies must be overcome. This gap in translating science and discovery into moderate to low-risk technologies is usually referred to as the "Valley of Death" – it is too early for industrial or venture capital investment and Government support is often weak or non-existent. Industry doesn't typically invest at this stage because it's not clear whether technical risks can be overcome in a way that leads to a robust marketable technology.

- **Invest in technology and systems for government use**

  For technologies and systems needed for its own unique use, the Government must invest in the full R&D process because there is no commercial marketplace to make industrial R&D investment profitable. This is true because it is usually in the United States' interest to limit and control the propagation of this technology.

- **Develop technological options for future policies**

  The Government may decide to invest in R&D to create and mature technologies that are needed to understand and implement policy options in the future.

These and several other key functions associated with government R&D funding are explained further in Appendix I. The next chapter discusses how technologies move from discovery through technology maturation to the point where they become widely used products, and then examines how energy-related R&D was accomplished in the United States before the creation of ARPA-E. It is important to understand both the gaps in the past system of organizations and the appropriate government R&D roles discussed here to define the space within which ARPA-E should operate.

Chapter 3: Phases of Technology Innovation

This chapter examines the process by which technologies are developed – from initial discovery all the way to the point where the technology reaches and penetrates the marketplace. The chapter then shows how public and private investments in energy R&D relate to this technology maturation process. This includes an examination of the role for ARPA-E.

The Path to Technology Maturation

Technologies must pass through many stages of increasing maturity before they are widely used products and systems. R&D is a part of this overall innovation process. This section discusses the phases in a linear fashion – from least to highest maturity. However, in reality, technology maturation is a complex system with many looping interconnections. Any individual R&D program can combine more than one of the various steps in the process. In addition, when a program encounters a problem at a later stage of the process, the development effort may take a step back to an earlier stage to develop a solution. Its complexity notwithstanding, the technology maturation path can be usefully divided into the following five main phases:

- Discovery, scientific understanding, and deep knowledge
- Technology translation
- Technical prototyping
- Product prototyping and commercial viability demonstration
- Product manufacturing and deployment

Technology Maturation Phases

Discovery/ Science/ Knowledge	Technology Translation	Technical Prototype	Product Prototype & Commercial Viability Demonstration	Product Manufacturing & Deployment
Key Questions:				
What is it? How does it work?	Can the new device/effect/process become a technology? What are key technical barriers for applications and solutions? How much potential improvement over current technologies?	Technical Prototype Does the technology perform in the application and how well?	Demonstration Prototype Is the technology commercially viable?	How can product be optimized for customers' needs? How to manufacture inexpensively with good product performance? What continual improvement in manufacturing & product performance?

Figure 1: Technology Maturation Phases

Discovery, Scientific Understanding, and Knowledge

This phase includes the invention or discovery of a new effect, device, or process and creating the scientific understanding of what is actually happening – the physics, chemistry, biology, or other scientific underpinning. Usually labeled basic research, this phase sometimes extends into applied research. Scientific understanding is not only important for new discoveries; it may be enabling or critical for the improvement of existing technologies. Sometimes a technology will work fine without a deeper detailed knowledge of why it works the way it does, but future improvements may be stymied without this deeper understanding informing what can be improved and the limits to which improvements are possible.

This phase answers the following key questions:

- What exactly is this new effect, device, process?
- How does it do what it does?

Technology Translation

In this phase, technologists (as opposed to primarily scientists in the first phase) determine if a new invention or discovery – even an old technology used in a different way – can be used to create a new technology system or improve an existing one. This phase – called translational R&D – translates science into technology. In more conventional R&D terminology, this phase includes applied research and development.

The key issues for this phase concern the utility of the candidate technology. These candidate technologies range from hardware devices, scientific effects, computer algorithms and software, to manufacturing processes. The technologists must identify technical barriers to potential adoption and finds ways to overcome them.

In order to accomplish this phase, the generalized end application must be identified, although the specific product may not yet be defined. The reason for this is that a technology can be optimized in many different ways with many different sets of properties traded off against each other. Only with information on the application can the R&D manager decide how to direct the technology development to make it suitable for the real world environment in which the system must function. Examples of real world factors that may be considered, depending on the application, are vibrations and shocks the technology must survive or that it will generate, ultraviolet exposure from the sun, cost of raw materials, energy required to produce it, toxicity of materials and byproducts, temperatures it will be exposed to during use, other materials it must be compatible with for long term use, and degradation processes and lifetime issues. Higher performance must be traded off against higher costs and what the market will potentially accept. Phase I (discovery/science/knowledge) can be done without understanding the applications. This phase (technology translation) can not be accomplished without an eye to application.

The organization and management of this phase depends on whether the R&D is transformational – a disruptive breakthrough technology that will displace current ways of doing things – or evolutionary, where its aim is to make steady incremental improvements on existing technology systems. By its nature, transformational R&D is much higher risk and must be managed differently to overcome the technical and transition barriers inherent to this type of R&D. A strong, well-rounded R&D portfolio contains both evolutionary and transformational R&D. It is important to always be improving current technologies (evolutionary R&D), but without the investment in transformational R&D major leaps forward are not possible. The dichotomy between evolutionary and transformational R&D styles will be discussed further in the next chapter.

This phase answers the following key questions:

- Can this new invention or discovery ever be made practical? Are there unsuitable properties that can never be made compatible with real applications and therefore make further technology investments unwise?
- What properties must be improved for the technology to be used in a particular application? What technical and engineering solutions are there to make all these required properties simultaneously realized?

Technical Prototyping

In this phase of technology maturation, the technology is built into a system prototype. This technical prototype is done to determine how the technology (component or system) actually functions when placed in a realistic environment and how the technology components interact.

Technical prototypes are built to determine whether the new technology will work at all in a particular application and environment, and how well it works from a technical point of view. These prototypes are unlikely to be identical to a final product. They are built to evaluate whether the development has overcome key technical hurdles. As a result, a technical prototype may include lots of embedded instrumentation to facilitate testing. To minimize R&D costs, the technical prototype will purposefully omit some elements that an actual real system would include.

This phase answers the following key questions:

Does the technology work in the system application?

How well does the technology perform technically?

Product Prototyping and Commercial Viability Demonstration

This next phase is about designing, creating, and testing real technology products. The knowledge gained from earlier phases is used to design and create a product prototype, which, if found successful in testing, will become a real product. The prototype is often put through a commercial viability demonstration phase, especially in cases where the technology system is very expensive to purchase or the target customer industry is risk averse. A commercial viability demonstration must generate sufficient data to allay customer concerns, demonstrating reliability, for example, and detailing the cost to acquire, operate, and maintain the product.

At first glance, technology prototypes and commercial viability demonstrations may seem similar. Both are system demonstrations, but their purposes are very different and therefore the R&D projects need to be managed differently. Both require systems engineering expertise, but the degree of fidelity to the end application is much different. The technical prototype does not need to embody all aspects of the final system, only the ones being tested technically. By comparison, the commercial viability demonstration uses a version of the product that is close to its final form.

This phase answers the following question:

Is the technology commercially viable?

Product Manufacturing and Deployment

The final phase of technology innovation and maturation is beyond the scope of generally recognized R&D. At this stage of technology maturation, the application is known and the technology has been incorporated into an appropriate product. The goal here is to establish an efficient manufacturing process (which in itself may require new R&D), bring the product to market and gain market share over time. This phase is part of the innovation process because the product and its manufacturing process will continue to evolve as customers respond and the producing company improves its manufacturing capability and benefits from larger-scale production. If a technology does not reach this final stage by being included in a larger system or becoming the product itself, then all prior technology research and development efforts have not lead to their intended outcome.

This phase answers the following key questions:

- How can the product be further optimized to meet customer needs?
- How can the product be manufactured more cheaply and with better performance characteristics, especially reliability?
- What are the continual improvements needed or desired in manufacturing and product performance?

This section examines the roles of government and industry as they relate to the different phases of technology maturation. In the U.S. energy sector, industry is responsible for product manufacturing and deployment. Although its policies can and do affect these markets, the Government is not involved in the actual production and marketing of energy technology systems.

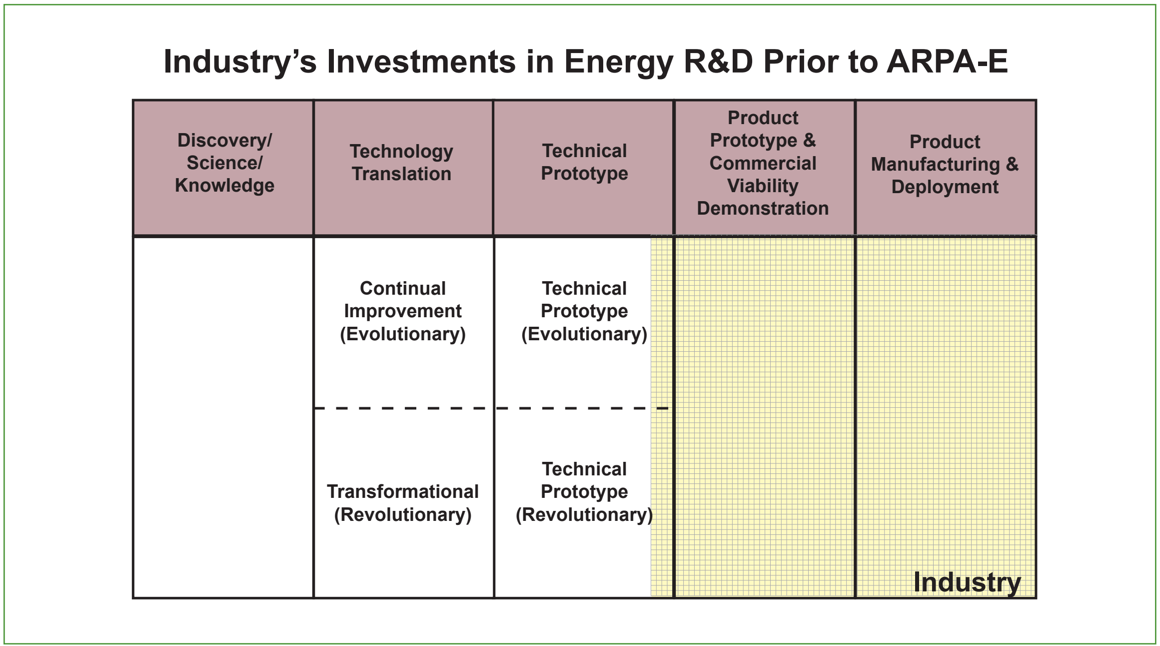

Figure 2: Industry's Investments in Energy R&D.

In the U.S. system of innovation, industry is expected to lead in product prototyping and commercial viability demonstration. Indeed, there are many types of energy technologies and systems for which industry completes all activities in this phase. Industry incorporates the new technology into products and tests them for customer acceptability, all without government funding or government R&D programs. Examples of energy-related technologies in this category are improved building insulation and lighting systems.

Funding from Venture Capitalists

One source of funds – other than companies' internal resources for this phase – is venture capital investment in start-up companies. Venture capitalists are not interested in technology for its own sake. They invest in companies where there is chance of a high financial return. Investments in start-up companies are risky; typically only one in ten investments will produce a major return. To increase the chance of success, venture capitalists look for companies whose technologies are mature enough to reach market products in the range of six months to three years. In discussions with venture capitalists during the preparation of this report, some expressed the concern that start-up companies frequently come to them with good energy technology product ideas, but that the technology is too immature for them to risk investment. One venture capitalist went so far as to say he wished that a DARPA-like entity existed for energy to mature potential breakthrough technologies.[10] Venture capital – not available in the earlier stages of technology maturation – is an important source of funds for the product prototype phase.

There is a portion of the energy sector that does have difficulty taking on all the financial risks of the product prototyping and commercial viability demonstration phase. New versions of large scale, capital-intensive systems, such as centralized power plants or alternative fuel production plants, have great trouble in penetrating the market without expensive and extensive demonstrations. Until the first real (or near-real) system has been built and demonstrated (operated for a time), industry is averse to purchasing the new systems. This is made even more difficult for power-producing companies regulated by public utility commissions, which are extremely averse to the cost risks implied in an unproven technology. To gain acceptance with customers for these types of large-scale systems, the system must be built and operated for a time before sales can be made. In cases like this, many companies – without government assistance in the commercial viability demonstration – could not afford to make the investment in such an expensive product prototype. As a result, the rate of innovation would slow dramatically.

Industry R&D Funding at Earlier Stages: Rewards and Risks

At even earlier stages of technology innovation, industry does make some investments. Start-up companies are typically at the technology prototype stage, trying to move into the product prototype phase. Large energy companies also make some investments at the discovery/ science/ knowledge phase and the technology translation phase. They may have their own industrial laboratories working on technology translation type R&D to give them continual improvement in their current uses of technology. Companies have banded together to fund the Electric Power Research Institute to perform translational R&D and prototyping. Industry may also choose to fund universities to do early stage work. One recent example of this is the decision by BP to fund a $500 million research program with the University of California Berkeley teamed with the University of Illinois, Urbana-Champaign and the Lawrence Berkeley National Laboratory, to explore bioscience for increasing energy production and lower environmental impact. However, one of the primary concerns of most companies about early stage investments is that it is difficult to garner all the benefits of those investments. The earlier the stage at which the investment is made, the greater the likelihood that the investor's competitors will also benefit from the investment.

Looking at the U.S. energy sector overall, industry puts the majority of their technology innovation efforts into the last two phases of technology maturation.

Government Organizations and Energy R&D

In examining government involvement in the creation and maturation of energy technology prior to the existence of ARPA-E, there are three major organizations to consider: DOE National Laboratories, DOE Office of Science, and the DOE Applied Programs.

First, the DOE has an extensive set of National Laboratories, the majority of which are Federally Funded Research and Development Centers (FFRDCs). These laboratories operate as an extension of

10 This conversation occurred in June 2008 before ARPA-E was funded.

the purposes of DOE, although the FFRDCs are not technically part of the Government (the facilities are owned by the Government, but operated by contractors). Because these laboratories are not a source of R&D funding – they are performers of R&D – they are not discussed further in this analysis of the organizations devoting their own resources towards R&D.

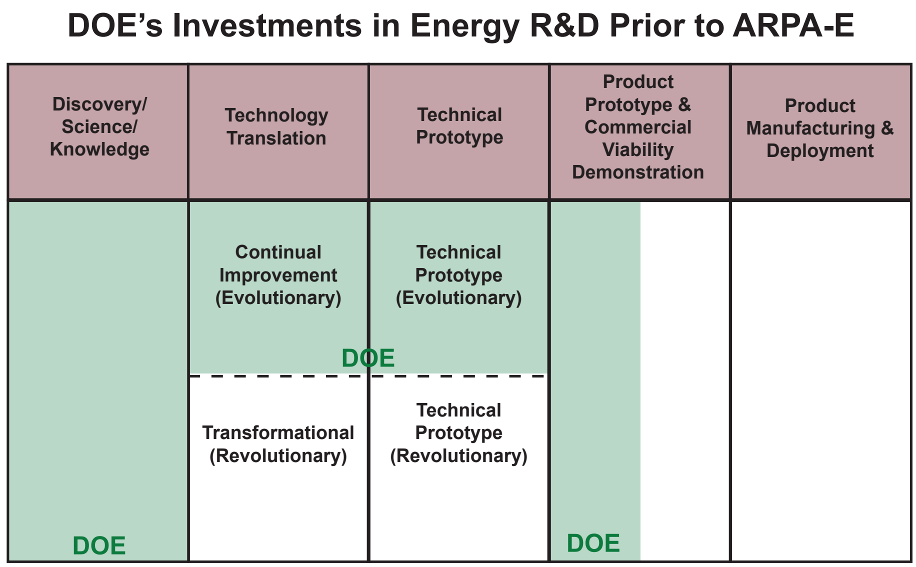

Figure 3: DOE's Investment in Energy prior to ARPA-E.

The DOE's Office of Science and its Applied Programs represent the two types of R&D funding organizations that existed within DOE prior to the creation of ARPA-E. As a key player in the energy-related R&D landscape, the DOE Office of Science runs a strong program based on discovery, the development of scientific understanding, and the generation of in-depth knowledge.[11] This DOE office focuses exclusively on the earliest stage of the technology maturation path.

The DOE also runs applied programs, such as the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Fossil Energy, and the Office of Nuclear Energy. As the names imply, these organizations are structured along fuel specific stovepipes. Their primary purpose is to ensure that technology innovation progresses, focusing on the technology translation, technical prototype, and commercial viability demonstration phases of technology maturation.

Although these organizations do sometimes fund transformational R&D projects, it is not their primary purpose. As a result, they are not organized optimally for doing transformational R&D. As will be discussed in the next chapter, transformational R&D is extremely risky and the best success rate requires specialized management techniques and structures. By contrast, the DOE Applied Programs organizations match the evolutionary – not transformational – type of R&D programs.

Another major thrust in the applied programs is the government support to energy-related commercial viability demonstrations. As discussed previously, there is a class of extremely expensive first-system energy prototypes for which the time from beginning such a demonstration project until the system

11 "The Office of Science manages fundamental research programs in basic energy sciences, biological and environmental sciences, and computational science." Source: http://www.er.doe.gov/about/index.htm

reaches market can be several years. In many cases, industry could not afford to risk that level of capital and without government support, innovations would not be possible. The DOE Applied Programs cost-share these efforts with industry.

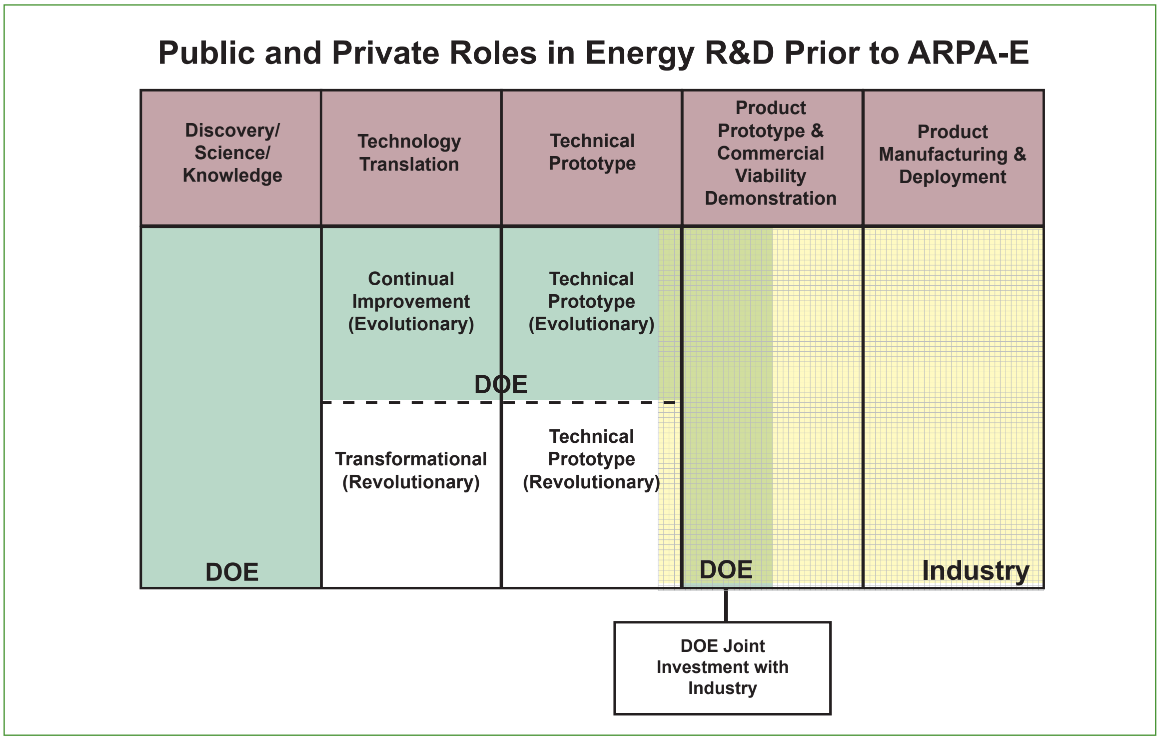

Figure 4: Public and Private Roles in Energy R&D prior to ARPA-E.

ARPA-E Fills the Gap

The diagram above shows the state of energy R&D funding sources mapped against the technology maturation phases before the creation of ARPA-E. There did not exist any organization within the Department of Energy or the broader U.S. energy sector with the express purpose of supporting transformational R&D. Congress created ARPA-E to fill this gap.

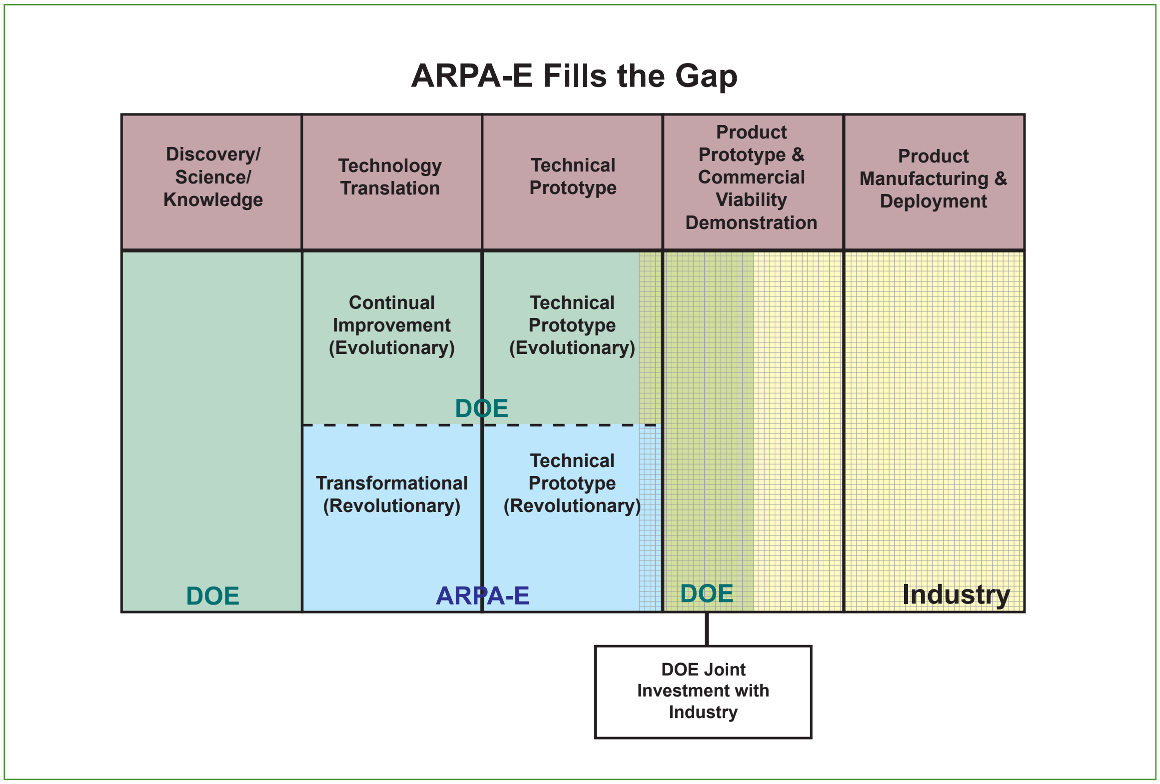

Figure 5: ARPA-E Fills the Gap

Although the legislation that created ARPA-E allows the organization to go back (to the left in Figure 5) into fundamental science and forward (to the right) into demonstration projects, the Congress also required that the agency avoid duplication of efforts. ARPA-E is given the mission of creating energy-related breakthrough technologies. It should therefore be organized around that unique mission, transformational R&D. In this way, ARPA-E can fill a vital role in the overall U.S. energy technology innovation system, moving the most promising breakthrough technologies through the maturity levels until the technology can be absorbed by industry. Since there are few mechanisms that can reach down into the technology translation and technical prototype phases for transformational technology, ARPA-E must carry the technology forward to the point that it can transition to industry.

It is appropriate to ask whether the funds for ARPA-E should come as a reallocation from existing DOE Offices or alternatively as additional topline funding to the Department of Energy. In the next section, the level of spending on energy R&D is examined.

Spending on Energy R&D Inadequate

The global energy industry – from extraction to refining, generation, and distribution and sales – is the largest industrial sector in the world. Annual revenue tops $2 trillion.[12] In addition, the International Energy

12 Nemet, Gregory F. and Daniel M. Kammen. U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35(1):746–755

Agency (IEA) estimates that $22 trillion will be invested in the energy-supply infrastructure by 2030.[13]

Despite its formidable stature in the economy, the energy sector spends relatively little on R&D, particularly in the United States. The U.S. energy industry invests far less of its revenues than other sectors in R&D. For example, from 1988 to 2003, the U.S. energy sector invested only 0.23% of its revenues in R&D, while high-tech industries invested between 5% and 15%. The average R&D investment for industries in the U.S. private sector was 2.6% of GDP.[14]

Both Government and Private Spending on U.S. Energy R&D Have Been Too Low

Several groups of scholars have analyzed the trends in public and private investments in energy-related research and development. In one of the most cited of these papers, Gregory Nemet and Daniel Kammen state "Investment in energy research and development in the U.S. is declining despite calls for an enhancement of the nation's capacity for innovation to address environmental, geopolitical, and macroeconomic concerns. We examine investments in research and development in the energy sector, and observe broad-based declines in funding since the mid-1990s. The large reductions in investment by the private sector should be a particular area of concern for policy makers."[15]

To help address this critical funding issue, the Obama Administration has already made a commitment to increasing the public investment in energy-related R&D. According to the White House website[16]: "Under President Obama, we will lead again, by developing an American clean energy industry, a 21st century economy that flourishes within our borders." The Obama Administration plans to support the next generation of energy technologies by investing $150 billion over the next ten years in energy research and development to transition to a clean energy economy.

Given the new priority that this Administration has placed on strengthening energy security and curbing climate change, there is no longer a need to make a difficult choice between underfunding transformational energy-related R&D or underfunding evolutionary energy R&D. Both are important to the nation and should be supported.

13 According to International Energy Agency's Reference Scenario using 2006 dollars. International Energy Agency (IEA), *World Energy Outlook*, 2007.

14 Nemet, G. & Kammen, op. cit.

15 Nemet, G. & Kammen, op. cit

16 http://www.whitehouse.gov/issues/energy_and_environment/

Chapter 5: Importance of Transformational R&D

Before the creation of ARPA-E there was no federal energy-related R&D organization whose primary function was supporting transformational R&D. This chapter explores why this gap is important and how such an organization must be structured and run to succeed in a high-risk area of operations.

Distinguishing Different Types of R&D

It is important to understand some terms used in talking about different types of R&D. Transformational R&D is about creating new ways of doing things. When successful, transformational R&D leads to the replacement of the technology base for current systems or totally displaces the current technology systems with the new. Transformational R&D is considered revolutionary because it overturns the use of current technologies by creating and maturing breakthrough technologies.

The other major type of R&D is described as incremental or evolutionary R&D. This type of R&D focuses on improving the current technological systems and the underlying technology base they depend upon. Incremental R&D is always trying to make progress in the performance characteristics of technologies.

The other term often mentioned in discussions of ARPA-style R&D is translational. This term is used to describe R&D whose purpose is to take a scientific discovery or laboratory prototype and develop the technology until it is mature enough to be considered for use in real systems. This type of R&D translates science and discovery into technology. It differs from science and discovery R&D, which is more focused on understanding a phenomenon or how a prototype works, not on optimizing it for real world use. It is possible to have both transformational translational R&D and incremental translational R&D. An ARPA-type organization is focused on transformational translational R&D. For the sake of brevity, the word translational will be omitted in the remainder of this chapter, although this is the type of R&D that is being discussed.

Transforming the Game

To understand why an overall system of R&D would include both transformational R&D and incremental R&D, there is a useful analogy in baseball, where two types of hitters do two different jobs: base hitters (trained to get on base) and “sluggers” or long-ball hitters, (trained to bring in home runs).

Incremental R&D is similar to base hitting: base hitters can get to first base and train to do that well. They are looking for consistency in getting on base. They ensure that the team is always making progress toward their goals. On the other hand, transformational R&D, which matures breakthrough technologies, is more like slugging. It’s not about making incremental progress or doing more of the same, only better. Nor is it about getting on base. It’s about fouling off the pitches you get until you get the pitch you want - the one that you can hit over the wall or for extra bases. It’s about making a large impact on the mission and finding a way to change the game. And it’s about hitting the long ball, regularly (though not always) over the fence. That is transformational R&D; it transforms the game.

Transformational R&D is called for when new challenges have to be overcome, so business as usual is not enough. The old ways of doing things have to continue in order for business to go on (deliver energy), and taking incremental steps to make existing products, systems, and technologies better is of course called for. But in order to overcome the major problem, to get onto new technology curves, transformational R&D is needed.

The nation and the world are facing two tremendous problems: climate change and massive consumption of petroleum. Simply continuing to evolve our current systems for energy production and consumption will not get us to the place where we need to be. There is a need for transformational R&D. In the U.S. energy industry, as in baseball, there is a role, indeed a necessity, for both approaches: incremental (evolutionary) R&D and transformational (revolutionary) R&D.

Base Hits and Long Balls

Given the urgency of the climate and energy security problems, why shouldn't all federal energy R&D be transformational? There are two answers to this. First, the results of transformational R&D that starts today will take many years to enter the market place and contribute to solving the problems. Therefore, it is important to continue the evolutionary progress of making current systems better. Second, a purely transformational R&D portfolio for the nation would have gaps – transformational R&D opportunities might not exist in every energy sector. Also transformational R&D is extremely risky. Even where opportunities exist, the technology may fail to meet its promise. The United States needs both evolutionary R&D and transformational R&D working side by side – just as a baseball team needs both its base and long-ball hitters. It doesn't make sense in the current situation to have only one; both are needed.

How Technology Transformation Works

This section of the report examines how a transformation in technology occurs and what the roles of evolutionary and transformational R&D are in that process.

Technology Performance Improvement Curve

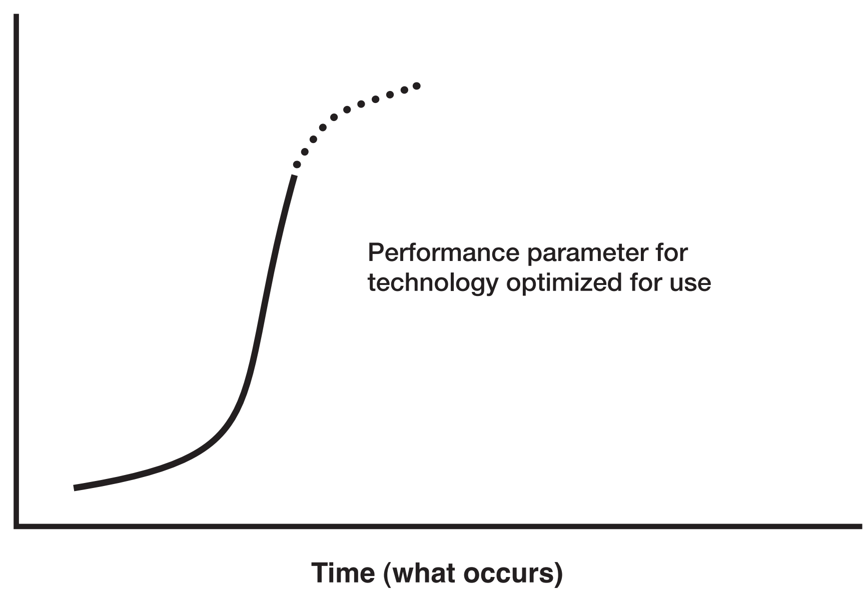

Figure 6: The Shape of Technology Development[17]

The lifecycle of most technologies (technology base, components, and systems) follow an S-shaped curve, where the x-axis is time and the y-axis represents technological performance. At first the rate of progress is slow, as technologists decide how this type of technology can best be used and various technology and application variants are explored. While the technologists sort out the options – and work to fully understand which performance parameters to improve for the most economically advantageous applications – the technology development path becomes more straightforward and rapid progress occurs.

As the performance improvements are wrung out of the system, the rate of improvement produced by a given investment in development and staff slows. Regardless of whether the duration of the "sweet spot" of technology improvements (illustrated by the point at which there is a rapid rise in the S curve) lasts for months or decades, the development of improvements eventually starts to plateau. In other words, the technology slows in its evolution as the incremental progress slows. Eventually the improvement stagnates or the technology is replaced by another that has strong potential for continued improvement. The replacing of the old technology is an example of transformation. (See figure 7) Before a new technology is mature enough to displace the existing one, transformational R&D has to take place.

17 This technology lifetime performance curve is reminiscent of the shape of technology adoption S curves, but is caused by different underlying factors. This curve's shape is a result of typical R&D investment decisions and the limited potential of any particular technology to improve. The steep part of the performance curve is partly related to the technology adoption S curves as larger markets make R&D investments in continuing improvements more attractive.

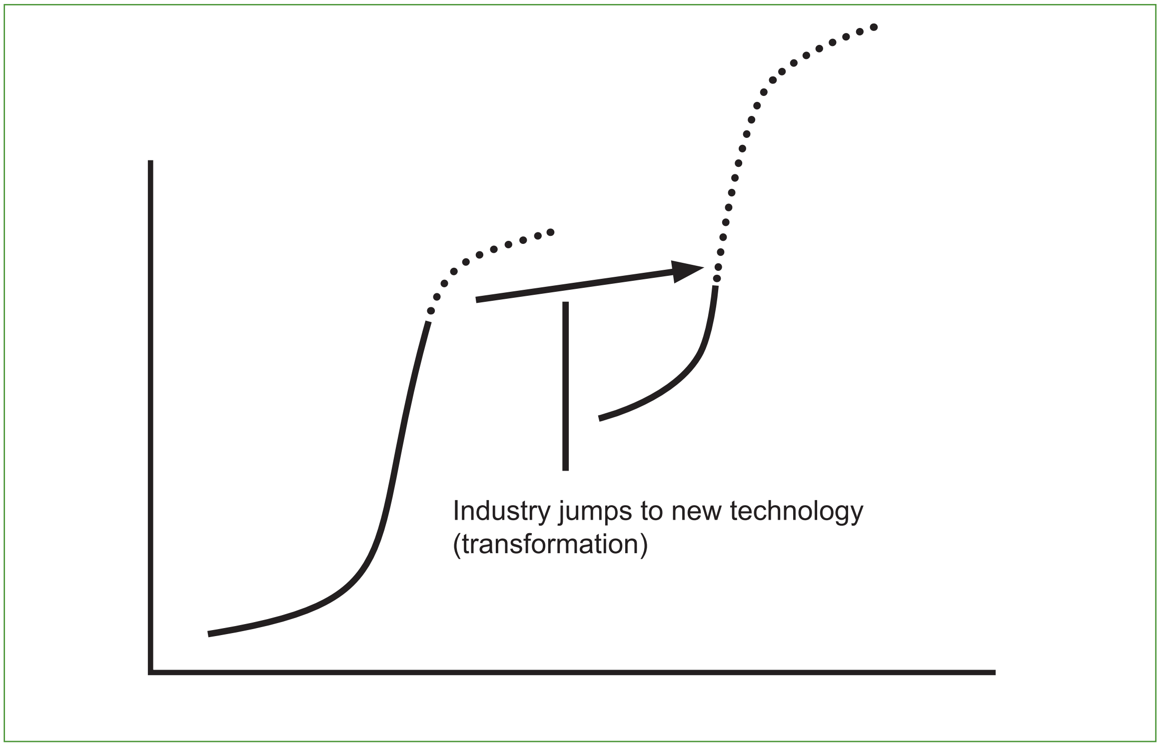

Figure 7: Transformational Jump in Technology

To better understand the technology performance S curve, let us examine the example of home recording of broadcasts. The video recorder was first invented for use at broadcast stations to tape live performances. The recorder was a large refrigerator-sized device. Technologists got the idea that such a device for home use would have a good market, but only if the size and complexity could be reduced. Various options were explored and the two main variants created by competing companies were VHS and Betamax. With the video recorders in use in homes, customers started demanding longer recording times per tape while keeping high quality. For both technical and market-related reasons, the VHS format eventually won out. There was a period during which VHS recording technology continually improved, offering more and more high quality recording time per VHS tape. But there is a limit to which such a technology (inexpensive magnetic tapes and magnetic readers) can be improved. The development path of the VHS technology was following the normal S curve of improvement.

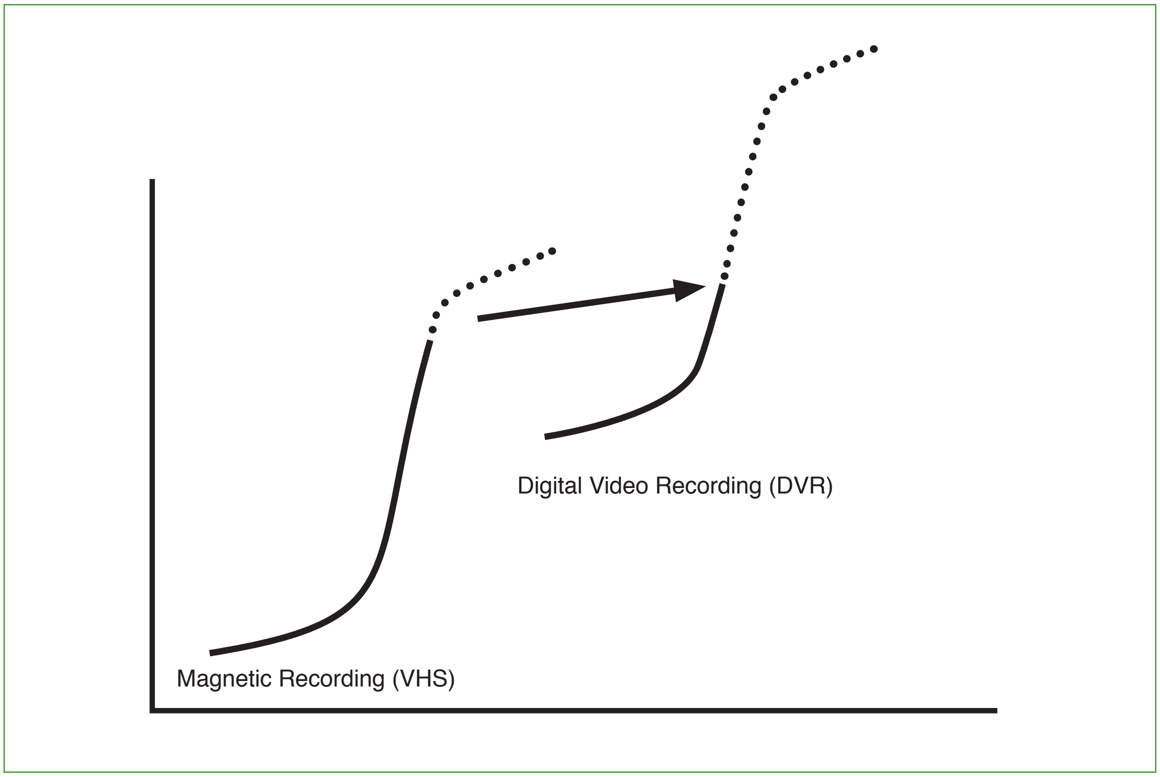

Figure 8: The Development of VHS and DVR Technologies

As the market developed, VHS magnetic recordings were used for home recording of broadcasts and to provide pre-recorded entertainment. Over time, there were two competing technologies developed – DVDs for pre-recorded entertainment and solid-state memory (for example, TIVO) for broadcast recording. The digital video recordings using laser playback technology were being developed with the promise of much higher densities of recording (many more hours of recordings in a smaller recording medium volume with a small recording and playback device), while offering higher quality. When the competing technology became robust enough for home use, the DVD player and DVR entered consumer electronic markets, displacing the older VHS technology over a period of time. For similar reasons, solid state memory displaced VHS for temporary recordings of broadcasts.

The DVD and solid state recording technologies are examples of transformational technologies displacing a technology for which its incremental improvement was slowing and stagnation was in sight.

In these cases just given, industry was able to sponsor and perform the transformational R&D and absorb (transition) the new capability. This is not always the case, especially when there is great technical uncertainty, the future markets are uncertain, and the time to progress through R&D to market is long. Government investment is important in cases where industry cannot fund the transformational R&D on its own *and* there is a national priority that demands new technologies to enable it. This is the case in the areas of curbing climate change and improving energy security, especially when the development of transformational capabilities is urgent.

Digging one layer deeper into understanding how incremental R&D and transformational R&D may interplay in the same arena, the following section breaks down the process further to examine exactly what happens and why.

When product development and R&D managers note that the rate of product improvement is slowing down because the technology can no longer be easily improved, they begin to look for other technology options to use in their future products. They are looking for a technology that has the potential for continued improvements into the future and that has all the necessary characteristics of their applications. They look for a technology that ideally has been shown to be robust in the environment where it will be used. For example, a technology may be required to withstand a range of operating temperatures and the shocks and vibrations of customers using the technology. Industrial R&D and product managers must decide how mature and proven the new technology has to be before they risk development funds and then again before they will incorporate the technology in their products.

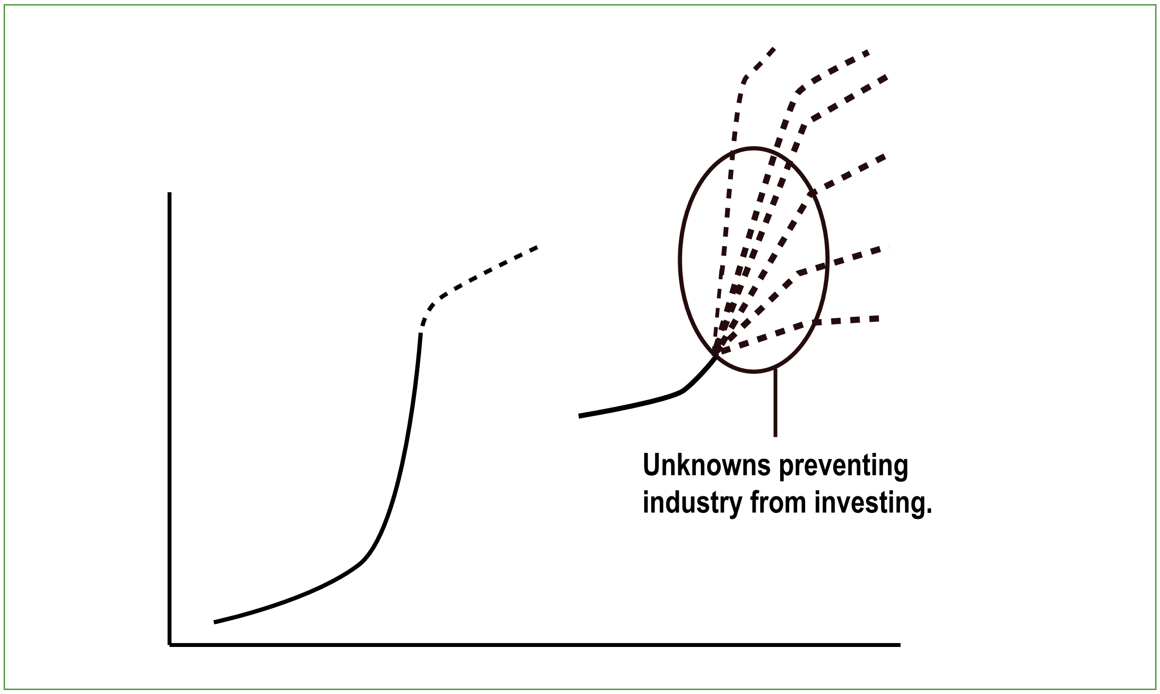

Figure 9: Slowing Rate of Improvements, New Possibilities

The solid curves in Figure 9 represent the historical development of two technologies and where they are now relative to each other in performance. The dashed lines are the predicted futures for each technology. On the left is the existing product technology which is predicted to slow in its improvement and on the right is a new technology that has a range of possible futures. The range of possible futures is wide because there are still major technical unknowns that create uncertainty about the new technology. Facing this level of uncertainty, few companies would risk jumping to the new technology. The risk is too great that investing a large amount of time and money will yield a technology that is simply not viable or that represents no great improvement.

However, among the possible futures, the potential improvements from one development may be truly stunning. This is exactly the situation where a transformational R&D manager plays a significant role. This manager:

- identifies the huge potential for transformational impact;
- then determines if there is a feasible R&D plan to reduce uncertainty and get the technology firmly on the path toward large future performance gains;
- develops the technology to the point that industry R&D managers and products managers will invest in the new technology.

The role of the transformational R&D Program Manager is to move the breakthrough technology beyond transformational R&D onto the mainstream path of normal development and application.

Mainstream R&D and product managers will not make the disruptive choice to move to a new technology base until it is clear that the new technology really will lead to continual improvement well beyond where current technologies will take their product performance. When a transformational R&D program is successful, it collapses the future uncertainty, leaving a future that is so much better than current technologies that industry is willing to tolerate the disruption it takes to jump to the new technology. This does not mean that all development risks have been eliminated at the end of the transformational R&D effort, but it does mean that all the key ones have been addressed and there is sufficient information on the manageability of the remaining risks for industry to choose to invest.

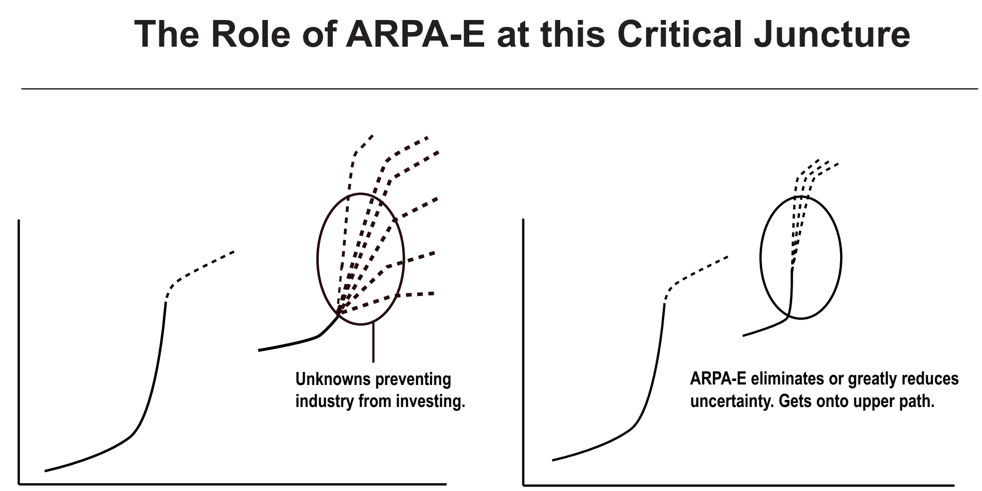

Figure 10: The Role of ARPA-E at this Critical Juncture

Transformational R&D Is Done in Concerted Pushes

There is a type of granularity to transformational R&D programs. It is not enough to take a potential transformational technology and improve it. If the uncertainty about the technology is not reduced beyond a particular threshold, then it does not transition into the product development stream and the effort was wasted. Incremental evolutionary improvement does not generally have this problem. Improvements on existing technologies can usually be incorporated easily. Transformational R&D is valuable only if the program leads to enough progress to convince next-level developers to take on the technology. This is the key reason transformational R&D is managed differently. The threshold for transition must be understood from the beginning of the transformational R&D effort and success is defined as crossing that threshold, not just making progress towards it.

Transformational R&D Programs

Transformational R&D (ARPA-style R&D) is managed in programs, which instills the discipline to define from the beginning what must be accomplished for transition to occur. The Program Manager lays out these key technical risks that must be overcome during the program. The technological maturity required for transition varies by industry and by the end product. For some applications, the technology must be shown operating in a prototype very close to the final product. In other cases, a laboratory demonstration in similar operating conditions is sufficient. But to be successful in all cases, the technology must be matured beyond the threshold for acceptance.

To be successful, the transformational R&D manager must:

- Identify immature technologies with the potential for major impact.
- Determine the key technical uncertainties that currently prevent industrial investment.
- Fully understand all the factors that will support or impede transition into the targeted industry.
- Define a feasible R&D program with end-state technical goals that will go from the current state beyond the transition threshold.
- Assess the costs of such development and compare it to the potential benefit of the transformational technology.

There are three things that must be present to justify transformational R&D:

1) a technical opportunity;
2) a large enough mission impact (for example, meeting a national need or creating a large, profitable market);
3) a program that connects the present to that possible future.

The goal setting for the program is extremely important. If the technical goals are not set properly from the beginning, then the risk of the already risky R&D becomes astronomical. Transition of transformational technologies is disruptive to industry and therefore difficult; but without understanding and meeting the threshold for transition, the transition is unlikely to succeed and the effort will be wasted.

Figure 11 shows examples of good and bad goal-setting. In case A, the transformational R&D program is built on an understanding of the transition threshold needed to attract investment in next-stage development. The program's end-state goals exceed this transition threshold. By contract, in case B, the end-state goals for the program are set too low. Although technological progress would occur in case B, it will not lead to anything real.

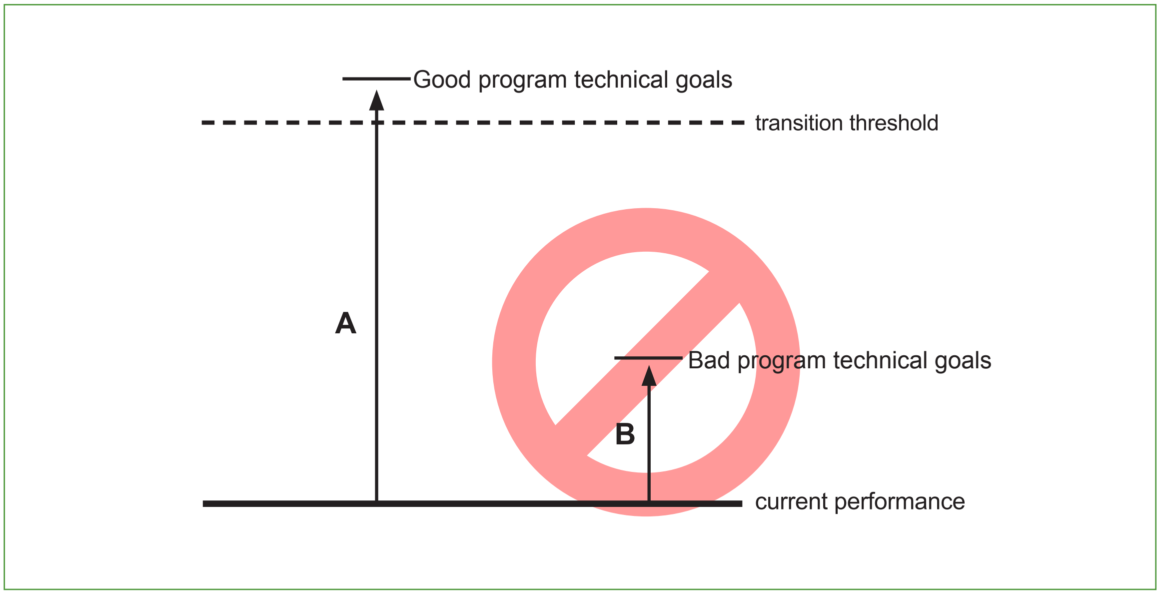

Figure 11: Importance of Good Goal-Setting

Not All Successful Transformational R&D Transitions to Industry

A final nuance must be noted for transformational R&D goal setting. The purpose of setting program technical goals is to identify the transition threshold from the beginning and manage the combination of performers to reach that end state. It is always about managing to transition. However, it is not always the case that the transition of the new technology is to industrial development. Rather, the transition is to the next-stage developer and some transformational R&D programs may transition by enabling other new transformational or evolutionary R&D programs. In all cases, well run transformational R&D programs have a defined goal set at or beyond the transition threshold.

Transformational R&D must not only be managed in defined programs, but it must also incorporate risk identification and management. If there were no risks in developing a high-return technology, then no transformational R&D would be required. Because transformational R&D programs are so different from incremental R&D programs, they are managed differently.

The Defense Advanced Research Projects Agency (DARPA) has a 50-year track record of developing transformational new capabilities for the military. The following section examines the DARPA models of transformational R&D management and the lessons that can apply to ARPA-E.

DARPA As a Model

DARPA Background

DARPA is charged with maintaining the technological superiority of the U.S. military and preventing technological surprise from harming our national security. DARPA also creates technological surprise for U.S. adversaries. Since its establishment as a Department of Defense (DOD) agency in 1958, following the Soviet Union's launching of Sputnik, DARPA's freedom to act quickly and decisively with high-quality people has paid handsome dividends in terms of revolutionary military capabilities.
Research is focused in a wide variety of scientific disciplines, and DARPA's contracted researchers build information systems, aircraft, robots, spacecraft, microcircuits, lasers, sensors, rifles, advanced networks, medical devices, and more. In its quest to fulfill its mission, DARPA's activities range from conducting basic, fundamental scientific laboratory investigations to building battlefield prototypes of military systems, and making the technology ready and available to the military services and defense contractors for use in military systems.
Source: www.darpa.mil

Transition strategies and pathways

One of the criticisms of using the DARPA model for ARPA-E comes from the belief that the only DARPA model for development and transition of transformational technologies is for the next stage developer after DARPA support ends to be another government (usually military) R&D organization and that the eventual targeted customer is also within the government (the military). If this were the only DARPA model for transition, it would indeed not be applicable for most ARPA-E and energy-related R&D, as the end customer is rarely government and the next stage developer is frequently industry. However, in reality, DARPA invests a large fraction of its R&D funds in programs that transition to industry and that are therefore appropriate as models for energy-related R&D.

"Systems Pull" and "Technology Push"

In general, DARPA R&D programs fall into either a "systems pull" category or a "technology push" category. In the systems pull category, the DARPA Program Manager has identified a potential new military capability that will greatly advance U.S. military superiority or solve a current vulnerability. This new military warfighting system is enabled by new technologies or combinations of technologies. The key objective of this type of program is to demonstrate a prototype that is realistic enough and has enough new capabilities that the senior military and civilian leaders of the DOD can decide that they want to transition the program into the normal requirements-based military R&D. It is not necessary for DARPA to build a full-scale, fully engineered prototype to meet the objective. DARPA saves money and time by focusing only on the key aspects – showing feasibility and new capability, not optimizing all factors that will need to be included in the final system. The Have Blue stealth aircraft development program is a good example of a systems pull transformational R&D program. This type of transformational R&D program (government developed technology transitioning to a next-stage government development sponsor for an eventual government customer) will not be relevant for most ARPA-E sponsored technologies, although there is an analog to it in transitioning complex systems to DOE Applied Programs for commercial viability demonstration projects, discussed later.

Roughly half of DARPA's R&D investments transition through other pathways. In a technology push program, the DARPA Program Manager identifies new technology that, when matured, has the potential to enable future transformational military capability. The focus is still on the military as the eventual customer, as required by the agency mission. However, the difference is that many of these breakthrough technologies, although offering major military advantage, are too expensive to develop and manufacture for only the military market. Sometimes the only way the military can access or afford a new technology is when it has commercial use. The other major advantage of a large commercial market is that the relatively small military investment in the early stages of the technology is then leveraged by much large investments from industry to mature and harden the technology. In cases where DARPA is trying to leverage and motivate industrial investment, the DARPA Program Manager then investigates the commercial market potential for the technology and identifies key technical risks for both military and commercial use. The program's technical goals are then set beyond the transition threshold for commercial investment and simultaneously informed by the long-term technical goals that support the agency mission – in DARPA's case, for the military. DARPA will frequently include a demonstration of the new technology for military purposes as part of the program, but not always.

Example of DARPA Innovation - Stealth Aircraft (Program Have Blue)

An entirely different way to fight the war

In the 1970s, people realized that the radar signature of airplanes could be reduced (enabling stealth), but there was concern that this would reduce the aircraft's aerodynamic properties. At the time, the U.S. Air Force's concept for fighter aircraft required the ability to outmaneuver an opponent. DARPA believed that it was possible to have stealth aircraft without large reductions of aerodynamic capabilities and that stealth technology would literally change the way war is fought, further reducing the need for maneuverability. DARPA did not attempt to build the actual final plane that the Air Force would purchase, but instead focused on designing and building a prototype aircraft that would demonstrate the principles of stealth technology and show its utility. This is a key element of how an ARPA-style organization works: developing the prototype and focusing the R&D program on key technology barriers that industry (or whatever the next stage developer is) fears to surmount, and demonstrating the performance benefit of the technology. An ARPA-style organization does not work out all the problems of, for example, manufacturability and maintainability. Nor does it address other aspects that are important in the final system, but which are in the purview of industry engineers and managers.

DARPA's investments in electronics, optoelectronics, and microeletromechanical (MEMs) devices are often this type of technology push program aimed at transitioning to the commercial market and leveraging it for military purposes. Often the investment is at an early stage of the technology, overcoming a major obstacle that prevents its use. DARPA identifies the technology as having transformational benefit for the military and major benefit for the commercial market. The long-term plan is that the DARPA program moves the technology beyond the transition threshold, industry then invests and develops the technology, and then, at a later stage, a military developer can pick up the now greatly matured technology and integrate it into a new military capability. DARPA investment at early stages, when several possible technologies might take off in the commercial marketplace but where most of the technologies may not be suitable or optimal for future military systems, ensures that the technology that is better for the national needs (military benefit) is nurtured.

Example: Development of Surface-Emitting Lasers

DARPA's investment in surface-emitting lasers is an example of this transition strategy. In the 1980s, most lasers on chips were made so that the laser light came out the edge of the chip. This was fine for many commercial applications, but DARPA envisioned a future in which many tiny laser beams could be used for chip interconnections within complex military systems. DARPA could see that the complexity of interconnection in military systems would become a bottleneck and the new laser chips could overcome this looming barrier. Realizing this vision for the future meant getting the laser light to come out the surface of the chip (surface-emitting lasers). There were designs and some demonstrations at the time for devices that would do this, but the devices required control of the chip fabrication at the near mono-layer (one layer of atoms) control. It required highly skilled researchers, typically at the Ph.D. level, to make the devices. Dr. Andrew Yang came to DARPA to run a program aimed at changing this situation, pushing the development of optoelectronic chip designs and manufacturing techniques to the point where they could be more than scientific laboratory curiosities. By funding academia and industry to explore a variety of ways to overcome the technical hurdles, DARPA turned surface-emitting lasers into a real technology, not just a subject for the technical literature.

After the initial successful program to develop and demonstrate a robust surface-emitting laser technology base, DARPA (through a series of Program Managers) moved on to programs aimed at developing and demonstrating specific component-level capabilities. Some capabilities were military-specific and some dual-use (good for the military and commercial application). Focusing then on the transition path for the initial program, the results of this program transitioned in many ways. The demonstration of the feasibility and flexibility of this new technology spurred lots of further investment, ranging from engineering programs sponsored by the National Science Foundation (NSF) to specific DARPA component programs and to industrial investments in exploring, developing, and using the technology. Thus the initial transformational technology program transitioned in many ways. The surface-emitting laser technology has great benefits to the military, enabling robust fly-by-light controls and is starting to enter complex computer systems. The biggest commercial application of the technology has turned out to be in the optical computer mouse.

The Model for ARPA-E Transitioning

This second type of transitioning that DARPA plans and executes is directly analogous to the approach ARPA-E will need to use. ARPA-E must find technological opportunities which have the potential for transformational impact on the agency mission areas (curbing climate change and improving energy security) and that, in most cases, will have strong commercial markets. The next-stage developer for most ARPA-E programs will be industry, which will absorb the technology and invest in the next-stage development.

For ARPA-E programs, the end customer for the technology is not primarily the Government. In the case of DARPA, even though the Government is the customer, it does not dominate the technology base and component-level market. Therefore, the DARPA method of program formation and execution for this type of transition pathway is likely to work well for ARPA-E. DARPA has a proven track record of developing breakthrough technologies in computers, networking, electronics, optoelectronics, and new materials that have successfully transitioned into the commercial market, while greatly benefiting the agency mission. ARPA-E should be able to do similar things for energy technology, enabling not only new energy capabilities but also ensuring support for those most likely to solve national problems. Commercial industry investment alone is not likely to foster these high-level national energy objectives as effectively.

ARPA-E Unique Transitions

There is one type of transition pathway that is fairly unique to the field of energy technologies. New technologies for large-scale, capital-intensive energy systems with a long life – such as centralized power plants – do not transition easily. In general, production unit number one must be built and operated successfully to provide commercial viability data before the technology systems will be widely purchased and operated. Part of the reason for this is that public utility commissions fear that unproven technologies carry financial risks that they find unacceptable. It is a "catch-22" situation where the new technology systems cannot find a market until after they have been in use. To alleviate this problem, DOE Applied Programs have carried out demonstration programs where the Federal Government shares with industry the cost of building and operating a prototype system. These prototypes are different from an ARPA-style prototype, which is only intended to show feasibility and the potential transformational impact. Commercial viability demonstrations must build and operate a real, fully-engineered system (known as a production prototype).

If ARPA-E chooses to develop technology systems that require this added step before transition into commercial industry, then the agency will need to work closely with DOE Applied Programs when the program begins. Planning for transition is always a key part of transformational R&D programs. In fact, there are some similarities between ARPA-E transitioning a new technology system to a DOE Applied Program and DARPA transitioning a new system to the next-stage military developer. However, ARPA-E must be aware that they are blazing a new trail as the agency applies this type of transition pathway to energy systems. ARPA-E must be especially careful to attend to the differences and actively design and observe the process.

Other Aspects of Strong Transformational R&D Programs

Among the other aspects that typify a strong transformational R&D program are the following:

- **The need for discipline and flexibility**

  ARPA-E's work is to hit the long balls with the knowledge that not every hit will make it over the fence. In its mission to help realize transformational game-changing technology, the agency must remain undeterred in the face of the occasional strike-outs that inevitably accompany success. The agency's efforts must be directed prudently. As it sponsors transformational R&D, ARPA-E must employ a rigorous process for program formation and execution. At the same time, ARPA-E's process and culture must be flexible enough to quickly explore the opportunity with the greatest potential and to exit those areas that prove to be less promising.

- **Complete programs**

  Evolutionary research – where an organization delivers small incremental improvement month after month – is research that is never finished. In contrast, ARPA-E Program Managers must be trained to look not just for an improvement in a technology (progress-oriented viewpoint), but at crossing the threshold to enable a whole new *transformational* technology (delivery-oriented viewpoint). ARPA-E needs to stay focused on its primary mission areas, finding breakthrough technology candidates that, with the benefit of an ARPA-E program, will transform the future for climate and energy security. The agency must not initiate full R&D programs without completing all necessary steps in the program development process, tailoring each program to the specific technology, industry, and foreseen technology transition pathway.

- **Budget discipline**

  ARPA-E must develop the budget discipline to go with the programmatic discipline. The agency must use a multi-year budget process internally, which allocates funds to the programs at the time they are initiated. As discussed previously, a transformational R&D program that does not complete its task (in other words, does not cross the transition threshold) is a waste of time, effort, and resources. The budget for each complete program must be set aside at the time the program is approved for initiation.

- **Multi-dimensional experts as Program Managers**

  The program is the core unit of transformational R&D work. The Program Manager is key to the creation and execution of such programs. As will be discussed further in the next chapter, the Program Manager must understand, foresee, and manage all aspects of the technology development and transition, not just the purely technical ones. ARPA-E must have an excellent staff of multi-dimensional technologists as Program Managers – experienced people with deep and broad technical expertise, who are also knowledgeable about transformational R&D, technology transition, industrial absorption of new technologies, and market penetration.

- **Risk essential for high return**

  Transformational R&D managers understand risk and know how to accurately assess and plan for it. Necessary risk is not to be avoided, but must be identified, mitigated, and managed. Any high-risk transformational R&D program must have the potential for a high return, proportional to the costs and risks of the R&D program. Taking appropriate risks must be rewarded by ARPA-E. This approach is not typical of government agencies.

- **Brutal honesty as a cultural value**

  Honesty – the willingness to face reality and communicate the truth - is an important aspect of an organization's culture. In incremental research, where part of the ethos is to *keep going*, the current government system for budgeting encourages under-budgeting and over-promising. Once the program begins, then budgets, goals, and expectations can be adjusted to match reality. However, in an organization like ARPA-E – where the evaluation of real costs, final goals, and projected schedules is part of risk assessment and the determination to initiate and continue programs – managers must exercise incisive analysis and a brutal honesty from the start. They have to constantly assess and manage risk because a project that runs short of funds or encounters major technical difficulties must be actively managed to keep it on the path to success. Transformational R&D programs are a tight knit whole, where small adjustments are continually made, but large funding swings and goal changes are particularly disruptive. Therefore, ARPA-E must expect and demand the truth from its staff about a program, as best known at that time. Because this ethos must be clear to all, this has huge implications for the nature of internal communications, rewards, and the working atmosphere.

Key Champions for Transformational R&D – Inside and Outside ARPA-E

There are two key types of champions for transformational R&D, both very important to the success of any particular program and to the success of the agency as a whole. They are the funding champions and the technology champions.

- **Funding champion**

  The type of transformational R&D that ARPA-E is chartered to sponsor can take years before the benefit is truly realized – reductions in greenhouse gases and imported petroleum as the result of widespread deployment of ARPA-E sponsored transformational technologies. In the early stages, the Director can and should be able to explain the projected benefits of his investment portfolio of programs. The Director can also report on progress on programs against their own self-defined metrics. What the Director cannot yet show in the early years is actual impact in the real world.

In a budget-oriented world – driven frequently by the question of what impact was delivered as the result of last year's investment – transformational R&D organizations are particularly vulnerable. Not only does it take time to see the results of transformational R&D, but funding changes are also more disruptive to transformational R&D programs. Many programmatic aspects are tightly interconnected and changes to a program schedule and budget can take much effort to re-plan and renegotiate.

Finally, transformational R&D comes with inherently high risk. So that a few programs can succeed spectacularly, the agency and its funding champions must tolerate many failures. Budget overseers often ask why the failures cannot be eliminated at the outset and investments made only in the winners. That is not possible in transformational R&D. As in the world of venture capital, many efforts must be undertaken so that some can succeed.

Therefore it is very important that agencies like ARPA-E have funding champions who understand the agency's mission and methods and will protect its budget so that programs can succeed. Especially during the start-up years for ARPA-E, when the track record will not yet be proven, the Secretary of Energy and the Congressional authorizing and appropriating committees must be the funding champions. They must understand and respect the multi-year funding aspects of the individual programs as well as support the top-line budget authority of the agency.

Internally at ARPA-E, the Director is the funding champion for the programs. Once a program is initiated, its budget must be protected from the vagaries of the process. If a program is failing, then it can and should be terminated. But if a program is proceeding as expected, then the budget must be supported and protected.

- **Technology champions**

  There are three types of technology champions important to transformational R&D organizations: visionary Program Managers, technology developers and R&D performers, and early users and adopters.

  – **Visionary Program Managers** are willing to bet their careers on creating and managing breakthrough technology programs, knowing that they may fail. They are very unique individuals who understand that nothing great is achieved without the risk of failure and that failing for the right reason – that a rigorous plan was followed to discover that their idea was not the solution – is not a failure.

  – **Technology researchers and developers** contribute their ideas and hard work to make the transformational vision a reality. ARPA-E needs to cultivate a working relationship with the technical community so that the agency gets the best and the brightest willing to work on its programs. DARPA has a saying about something being "DARPA-hard" and the R&D experts who work on DARPA programs are proud to say they are tackling those challenges and contributing to real transformations. ARPA-E will need to develop that sense of camaraderie and focus among its R&D performers.

  – **Early adopters and developers** work in the industries that are willing to accept some risk, make the disruptive leap to the new technology base or system paradigm, and incorporate the new technology into actual products. ARPA-E will need to develop strong relationships within the early-adopter community for energy technologies. There must always be that first next-stage developer that will take the risk of a new technology in order to realize the great rewards. Many companies prefer the strategy of starting to absorb a new technology after their competitors have already taken the first leap.

ARPA-E is intended to operate from the broader context of a comprehensive national energy strategy, not solely from a fuel-specific energy viewpoint. It is within, and from, that broader perspective that ARPA-E will be able to choose and mature technologies that offer truly transformational opportunities.

Transformational R&D must be organized and managed as the complex, dynamic interaction of many factors. Unlike science-based research – where the projects can be selected on the relatively straightforward basis of the best science and funded for multiple years at a time without significant government interaction – transformational R&D is about actively managing risk with a large number of variables that determine the fate of the technology being developed.

Need for Program-Oriented Management

One defining difference of an ARPA-type organization is that the agency neither selects nor defends programs based merely on their relevance to a top-level mission. The program outcome must make a significant leap forward; progress toward that top-level goal alone is not enough. Each new technology has a performance threshold at which it can be chosen for industrial development, aiming at productization. ARPA programs are designed to mature the technology beyond that or another transition threshold. So, for an ARPA organization, a significant leap forward is one that (1) crosses a transition threshold and (2) will eventually enable the creation of products that make a large contribution to one or more mission areas.

Because transformational R&D is best done in these well-defined programs, ARPA-E should be organized with a program-oriented management structure, beginning with a top-level strategy based on the agency's main mission areas of enhancing energy security and curbing climate change.

There will always be more program opportunities than funds available, so it's important that this top-level strategy gives the Director a basis to pick an optimized portfolio of programs, likely to meet national energy goals. The top-level strategy will also help determine when new programs need to be developed to fill gaps in mission areas.

Transformational R&D is inherently extremely risky. As in venture capital investment, the expectation should be that more than half of the programs will not fully meet their targets. Therefore, a portfolio approach should be used in selecting a variety of programs against the major agency missions.

DARPA has succeeded by combining a top-level strategy and portfolio approach with a rigorous method for developing and selecting programs to fit inside the strategy. One of the secrets of success at DARPA is that the agency will not fund a program only because there is a need for it. They will fund a program because there is both a mission need *and* a well-developed program strategy to meet that need. Therefore it is possible that for a time there are no suitable programs to fit an important aspect of the agency strategy. In these cases, there must be additional effort made to find technological opportunities for that gap and develop rigorous programs around these opportunities.

Top-Level Strategy

ARPA-E needs to thoroughly understand the issues and leverage points in the climate change and energy security problems. ARPA-E can only form an effective mission strategy by understanding how petroleum is used in the United States and what causes the largest energy-related greenhouse gas emissions. Much of this work has been done by others and ARPA-E needs to accumulate and internalize this analysis. It will form the basis of determining whether a program offers sufficient mission impact to justify the R&D investment. In addition, it will help identify promising areas for which Program Managers should be hired to explore and develop programs.

ARPA-E must operate from the broader context of an overall comprehensive national energy policy. The agency should select programs that support agency missions but simultaneously do not interfere with other policy concerns. At its core, an ARPA-style organization is about creating and shaping the future. That future should be aligned with the broader Administration view.

Another important element informing the ARPA-E Director's investment decisions will be an understanding of the road maps for current, continually evolving energy-related technologies. At the end of an ARPA-E program, the new breakthrough technology must be substantially better than the current technology or it must match the performance of current technology and have a greater potential to continually improve in the future. Without one of these conditions, the new technology has little hope of transitioning into industry. There are usually additional barriers to accepting transformational technologies because they are a major shift in the underlying technology base. If ARPA-E assesses that a potential program or existing project will create technologies with insufficient transformational advantage over the likely outcome of a competing evolutionary technology, then ARPA-E should abandon that program or project in favor of another with greater opportunity for revolutionary change. Although ARPA programs are ultimately about jumping off the road map, a program must be compared to the road map to understand its significance.

Although the majority of programs should fit into the top level strategy, an ARPA-style organization must also be willing to do a few programs that offer large mission impact even if the program is not well aligned with the main agency strategy.

Mission Flow-Down to Programs

While it is critical to understand where a program fits into the broader strategy, it is also essential that a Program Manager conducts a detailed analysis of a proposed program with a view to its quantitative effect on the agency's mission. It is not enough to say, for example, that a project will be "good for climate change." Program Managers must present a quantitative analysis of sufficient detail and credibility to permit comparison of the project's probable outcome with that of other R&D investment opportunities. Such analysis goes beyond how the program is relevant to a given mission goal; it says specifically how large the impact will be and why this represents a significant, transformational leap forward.

Another reason for ensuring that all program decisions flow down from the top-level national energy strategy and the agency mission is to address concerns that the government is picking winners and losers in commercial energy technology. By using a program or technology's contribution to the agency mission as the basis for selection – and being able to demonstrate that the result will have a transformational effect – ARPA-E can show the selection is not about the government favoring specific technologies, per se, or making technology decisions based on local political needs, but the choices are being made against a more rigorous, objectively-determined set of criteria.

Many Possible Future Worlds

When making decisions about which programs to initiate, the ARPA-E Director must consider how the world is likely to evolve with respect to the usage and price of energy, climate change, policy options, and other constraints. It is always the case in technology development to have to project the significance of the technology innovation in a variety of possible futures. However, the farther out that future is, the more difficult it is to project accurately. It can take a long time (between five and twenty years) for a technology to mature from the laboratory into products before becoming a significant part of the installed base, where the new transformational technology can make significant contributions to the ARPA-E mission. The relevant time horizon for applying the results of R&D are thus much farther out than a company's time frame for bringing newly developed products to market in, say, six months to two years. In the scope of 20 years or more, even small deviations in growth rates can lead to large changes in projected future populations and consumption rates.

For energy-related technologies there is additional uncertainty due to the inherent volatility of energy markets. There are many causes for this uncertainty. Among them are the price of fuels, actions by cartels (for example, OPEC), the size of tapped and untapped energy resources, regulatory changes, development of other technologies, and possible future policy changes affecting climate and energy. It is prudent then for the ARPA-E Director to make R&D investments against a range of possible future worlds.

Taking the Portfolio Approach

Taking a portfolio investment approach is meant to cover the full range of the agency's mission areas, to manage the uncertainty of how the world will change in the future, to mitigate the risk from any one program, and to cover the range of technology maturation activities within the ARPA-E role in translational transformational R&D.

Each program will have its own different characteristics, but taken together the programs fit into the following categories. (The numbers in parenthesis are recommendations for how much of the agency budget should be allocated to each category.)

- **Programs evaluating and creating potential payoffs for immature technologies (5% to 10%)**

  This part of the portfolio consists of programs with the objective of evaluating and exploring new discoveries and technologies which have the potential to hugely impact mission areas. The end point of this type of program is not to transition to industry, but instead is to determine what barriers exist to making the technology suitable for application. The program would also develop one or more technical options to overcome the identified barriers, or at least demonstrate that it is feasible. The intent is not so much to understand the discovery or phenomenon, as it is to understand how to harness it. Sometimes this also requires understanding the underlying phenomena. The difference between this type of program and a more science-oriented program is the end point. A science-oriented program's goal is understanding. An early-stage ARPA-style program wants to demonstrate a technological path to eventual application.

  In general, a technology area is a candidate for this type of program if the breakthrough or discovery has lots of apparent potential for mission areas but still raises basic questions about its suitability for real world applications. Examples of this type of phenomenon are represented by the discovery of high-temperature superconductors for energy applications and if there were a breakthrough in realizing quantum computing for computation and cryptology purposes.

These types of discoveries overcome one of the major obstacles to widespread deployment of the technology, but leave in question other key technical parameters. Programs in this category would explore the new opportunity and look into realizing the other technical operating characteristics so that the overall technology could be used. In cases like this, an ARPA-E program would seek to show – at the laboratory level – that the technology either did not have major showstoppers or showed a promising path to fully overcoming the barriers. The program would not, however, try to develop the technology to a high-maturity level where it could be immediately transitioned into use.

- **Overcoming key technical barriers to industry investment (80% to 85%)**

  The largest slice of the portfolio will comprise programs geared to meeting mission objectives in probable future worlds. These programs are designed and executed to overcome the key technical barriers that would prevent industry from investing in and absorbing the technology. The programs can also comprise a system-level combination of technologies or a system-level application of technology – rather than focusing on a single underlying technology or component.

  These programs may be based on the outcome of the programs above or more often come from outside the agency. Program Managers are experts who are aware of the technical tipping points for their mission areas. They know how to answer the question: If you could change one or two technical performance characteristics or system-level performance, what would you change to revolutionize your world? Program Managers are continuously scanning the literature, attending conferences, and scouting out possible new technologies and systems that could make these pivotal changes. When they find the technological opportunities, they evaluate them against mission impact in probable future worlds. If the impact is large enough, then the Program Manager continues with the full program development process given later in this chapter.

  The endpoint of these types of programs is to convince the next-stage developer, usually industry, that the technology is ready for their investment. For industry, this means that the technology is now mature enough that the remaining risks are understood and manageable and the potential market is sufficiently large to justify the investment.

- **Enabling a Different Future (5% to 10%)**

  The programs in this part of the portfolio develop options that may not be commercially viable under the current thinking of the most probable future worlds. The objective is instead to develop options with a desired social good in mind. Programs in this area might look at technologies that could support future policy options that could benefit the nation, but these policies are currently not feasible because of likely strong politically or economically unacceptable consequences. Examples of this type of R&D (if relevant technology options could be identified) are programs that develop technologies enabling government regulations such as imposing vehicular fuel efficiency standards at ten times the current levels, or requiring certain industrial sectors to consume one tenth of the power they currently use. With current technologies, these industries could rightfully argue that they do not have the technologies to meet such government mandates. If the Government desires to enact future policies that would place hardships on industry and the economy – given current technologies and their projected improvements – then ARPA-E could be called upon to develop breakthrough options to eliminate the onus. These options would not necessarily have to be economically competitive before the regulations or policies were imposed and thus would not fit under the category above.

Another type of program that fits under this category might be consequence mitigation programs for climate change, like direct air capture of carbon dioxide. The predominant greenhouse gas is carbon dioxide and much of the anthropogenic sources are related to energy production and consumption. ARPA-E could be called upon to develop these types of technologies. These technologies would only be used if the United States or some other government decided to pay for their production and operation or if the technology becomes economically viable in some version of a cap-and-trade system for carbon emissions and absorptions. On its own, the air capture of carbon dioxide has limited economic benefit.

In deciding to initiate programs under this category, the Director of ARPA-E must be very aware of and privy to high-level thinking by the Administration on policies they would like to impose but feel they cannot because of the negative consequences.

Importance of Program-Orientation

An ARPA organization funds and manages R&D in chunks, called programs. Unlike other R&D organizations, which have an objective of continual improvement, an ARPA-style organization is designed to make a big push forward in one particular area and then move on to a push forward in another. Thus the ARPA organization's work is organized into programs of limited duration, although the agency may or may not stay in a general area for a series of programs. The best known example is DARPA's creation and support of the Internet and networking technologies. Although DARPA has supported this area since the 1960s, it has done so through a series of specific programs, each of limited duration with specific technical goals

The purpose of an individual program is to accomplish a body of work that moves the technology forward to a critical point beyond which industry or traditional government programs can invest in further development or making products. The purpose of the program may also be to create realistic options that enable policy makers to implement policy strategies which, before the creation of the new technology, would have been detrimental to either the economy or society. These new policies will often create and drive a market for the new technology.

Pairing Up Opportunity with Mission Impact

Each program pairs up a breakthrough technological opportunity with potential major impact on a mission. A program should not be initiated without both – opportunity and impact. However, a program is much more than an R&D push within certain technical parameters. A program is about enabling the transition of the new technology into the real world where it can have a transformative impact. To do this, the technology must be developed and prototyped in a way that makes this possible and probable.

The analogy to this complexity in an ARPA-style program is looking at whether a possible new consumer product will succeed. Just because the product is a desirable improvement in one area (for example: better taste, lighter weight, or longer battery life), there are many other ways the product can fail. The product improvement may fail, for example, if the packaging is not attractive, the product is not placed in enough retail outlets, or the improvement is not added to the right products where it will make the biggest difference. Similarly, an R&D program focused solely on improving within technical parameters is not enough. The performance must be improved beyond a threshold of acceptance and must be done in conjunction with preserving and demonstrating other characteristics. The technology must be developed in a way so that it can be profitably manufactured in the future. In other words, a breakthrough meant to improve performance must avoid "poisoning" the technology for transition. Rather, it should be optimized for transition.

Technology Transition Is a Key Program Component

Technology transition is often talked about in terms of licensing already created technologies and marketing them to potential users. An ARPA-style program must consider technology transition from the beginning of the program. When an ARPA organization talks about technology transition, they are speaking in broader terms about the full technology development and deployment life cycle and whether there are barriers ahead that will prevent the technology from reaching its full potential for impact on an ARPA mission area.

Factors that optimize the likelihood of transition are critical to determining how the program is organized and executed. The metric for success for ARPA-E in the future will not be whether it makes technological improvements, but rather does it make real-world technological improvements that have a major impact on curbing climate change and improving energy security. Only if the technologies and systems move beyond ARPA-E will the agency succeed. Therefore, a key component in developing programs and deciding which programs to initiate is whether the program has a credible plan for transition.

The technology transition pathway is different for different industries and sectors within an industry. Some industries are quite risk averse and will not accept a new technology that is not shown to be very mature. Other industries are aggressive in accepting improvements and will reach down to technologies that are still in the laboratory. These differences require tailoring programs in three major ways: intellectual property, cost share, and maturity of any technical prototypes.

Different industries have different intellectual property strategies. They may keep intellectual property as trade secrets. They may use patents to block competitors for a time while they recover their development costs and get a return on their investment. They may patent so that they can trade for other patents necessary to manufacture and sell their products. If an ARPA program enforces an intellectual property strategy that is discordant with the target industry, then ARPA will have greatly reduced the likelihood the technology will transition. At the same time, there is a creative tension caused by ARPA's need to protect the taxpayer's investment. In each case, an experienced Program Manager who understands the nuances of the target industry must devise an intellectual property strategy that supports the likelihood the technology will transition and enter the market, but also serves national needs. One size definitely does not fit all in ARPA program intellectual property strategies.

Cost sharing the development with industry – when there are projected large profitable markets – is in the interest of the taxpayer. However, the amount of cost share must be tailored to the specifics of the program. For extremely risky efforts, which most ARPA programs are, the cost share expected from R&D performers should be lower. For large markets that are accessible in the near future, the cost share should be higher. If markets are large, but market penetration will be slow and profits far off in the future, then the cost share should be relatively lower. For small businesses that may have a great idea but limited capital, the cost share may be accepted as an in-kind contribution or a future royalty. For the development of technologies to enable future policy options but where no market will exist without the new policy, industry will be exceedingly hesitant to offer cost-share. Again, ARPA-E must evaluate all these factors in deciding the appropriate level and form of cost-share.

Reaching But Not Exceeding Industry Acceptance Threshold

Finally, the end point of the program's "demonstration" of a technology should be tailored to reach but not exceed the point at which the specific targeted industry will absorb it. It is not an appropriate goal for the Government to continue to invest beyond the point at which industry should and can invest without government assistance. For many technologies, building a prototype that works in a realistic environment is sufficient. One major exception to this in the energy sector is the development of new centralized, high-capital power plants. Transition of these system types into the market requires the acceptance from both the industry that produces these systems and the industry that buys and operates them. This process also requires the acceptance of public utility commissions, which are notoriously risk-averse to uncertain costs. These types of technologies typically require the construction and operation of the initial plant so that the commercial viability is understood.

This type of demonstration project is not well managed by an ARPA-style organization. Commercial viability demonstrations are large engineering projects that must pay attention to all the real-world details of the final real system. An ARPA-style organization is more optimized for rapidly developing a technical prototype that shows the feasibility of a technology or system, but does not have all the final details worked out. Thus for technologies that require full-scale commercial viability demonstrations to transition into use, ARPA-E will need to work with one of the DOE Applied Programs to transition the technology from an ARPA technology-development and technical-prototype demonstration program into a more traditional commercial-viability demonstration program in an Applied Program.

Each ARPA Program Is Unique

Although a common rigorous process is followed in creating an ARPA program, each ARPA program is a unique combination of strategies optimized around the technological opportunity, the potential mission impact, and the targeted transition path. As discussed above, all aspects of the program derive from these and are optimized to support the best outcome. This extends to unique strategies for technology development, transition strategy, intellectual property, and cost-sharing. It also extends to the number and types of performers and the breadth of technical ideas evaluated and developed. Thus, some programs may comprise:

- A single performer with a unique transformational idea.
- A single consortium/collaboration of several different performers (for example: all from industry, or a combination of industry/academia/national laboratories).
- Multiple teams with competing approaches to reach a very significant but extremely risky outcome.

Some programs are best structured to compete different efforts against each other with competitive down-selection (competitive selection of fewer contractors for the next phase) between phases. Other programs are more suited to a cooperative environment among performers.

Once the key program strategies are determined, the competition and contracting strategy can be developed to support these decisions.

All of this tailoring of program strategy elements is time-consuming and requires great experience and expertise. The accumulated wisdom of many years of DARPA programs developing and transitioning transformational technologies into industry shows this is the best way to go. If program design and execution does not attend to these other factors, a program can meet its technical goals but still fail to have any impact. The success of a transformational R&D program is not all technical; it is the sum of getting all these factors right. Transformational R&D involves risk – technical and transitional. The proven method for managing all the risks inherent in transformational R&D is to develop and execute an optimized program plan. It is not a simple process of putting a call out for ideas and picking those that rank highest. Good transformational R&D programs are managed in a complex multi-dimensional space balancing many factors affecting whether a technology can succeed technically and succeed in a way that it will transform the future to meet energy and climate goals.

The Program Lifecycle – A Flexible But Rigorous Process

The life cycle of an ARPA-style transformational R&D program has the following phases:

- Creation of a program plan;
- Director's decision to initiate;
- Competition for performers;
- Contracting and execution;
- Transition to next-stage developer.

Program Creation

The first phase is preparing a full program plan. The Program Manager is responsible for finding technological opportunities that promise the potential for transformational impact in one or more agency mission area. Program Managers are continually on the look-out for opportunities and employ a variety of methods for finding them: for example, technical literature, informal technical networks, recommendations from colleagues at other agencies, and contacts from the public. Program Managers will focus their attention on specific technical areas if the Director has made it clear where there are specific gaps in the agency strategy that require additional programs. Program Managers are very entrepreneurial people and will readily respond to the Director's guidance that a program in a particular area has a greater likelihood of funding.

After finding a good technological opportunity, the Program Manager then makes a quantitative determination of how much of an impact the identified technology could make on the agency mission. If this looks promising, the Program Manager moves on to developing all the aspects of a full program. He examines how current technology accomplishes the same job and what the drawbacks of current technology are. He looks at what the technical barriers are that prevent industry from adopting the new technology and looks for options to overcome these technical barriers. The Program Manager looks at the target industry for transitioning the technology to, examining the potential market, the investment that the industry will need to make after ARPA finishes their program, and other aspects of how that industry operates and uses technologies. The Program Manager then develops all the elements of a full program strategy: technical, technical prototype maturity at completion, intellectual property, cost-sharing, transition strategy, competition strategy, and contracting strategy.

Sometimes a program is developed starting from understanding problems with the current technology that limit its effectiveness or create problems for agency mission areas. In these cases, the Program

Manager carefully examines the technical issues and then seeks possible solutions. Once options are found, then program creation proceeds as described above.

This program creation phase often takes up to a year to complete, although it can sometimes be completed within a matter of days or weeks. More typically, because of the complexity of the process, this phase takes from 3 – 9 months, especially when the Program Manager is also managing an existing program.

Director's Decision to Initiate

When the program plan is fully developed, the Program Manager presents the program to the ARPA Director. The Director compares the described program impact against the agency mission and strategy. The program must promise enough impact to justify the funds to be expended. The Director also compares this program opportunity against others vying for limited resources within the agency. As described earlier in this chapter the Director is a portfolio manager of programs and is thus determining how and whether this new program fits in the overall agency portfolio. Just as a Program Manager manages the risks within his program by picking multiple performers and approaches, the ARPA Director manages the agency risk by picking an optimal portfolio of programs.

The ARPA Director is also evaluating whether the program has a robust program strategy. If not, then Director may ask the Program Manager to do more homework and come back with a better defined program strategy.

In many ways, the ARPA Director's decision is similar to a venture capital firm's decision to invest, with the important difference that the Director is looking for future mission impact rather than monetary return on investment. The Director looks at the totality of the program package presented and determines whether it is a robust program addressing all aspects of a successful program plan, if the risk management strategy is reasonable and the likely outcome is going to transform the future in a way to meet agency goals. (See sidebar on the Heilmeier Catechism)

Once the Director makes a decision to initiate the program (always within the Congressionally appropriated authority for the agency), the multi-year budget for the program is registered in the agency budget system so that the funds are available not just in the initiation year, but to support the life of the program. The Program Manager is now empowered and held accountable to execute the program.

Competition for Performers

Sometimes a program is based on a unique idea that is the proprietary property of a single performer. In these cases, the program is not competed, but instead executed in a sole-source manner. However, it is exceedingly rare that there are no other possible ideas to accomplish the program goals. In this case, the Program Manager announces the program objectives to the world and seeks R&D performers through a solicitation for proposals.

There is a curious dichotomy in ARPA-style programs. A good program cannot be initiated without having identified one or more good technological opportunities to reach the program's goals. However, once the program is approved for initiation, the Program Manager usually bases the solicitation on the technical goals of the program, not on the specific technologies already identified. This is because there may be even more transformational technologies out there that the Program Manager has not yet discovered and that can meet the same objectives in better ways. For example, if a Program Manager puts out a solicitation for LED-based lights with efficiencies above a certain levels, with lifetimes greater than a certain number of months, and with particular light qualities, then the proposers will only submit LED-based light R&D programs. If there is a totally different lighting technology that can meet the same performance specifications, it will not be submitted.

Leaving Open Possibilities for Better Choices

Because an ARPA program is usually described publicly at kickoff only in terms of its technical program goals rather than its identified underlying technical options, many people believe ARPA programs are only based on desired outcomes and not on careful evaluation of real opportunities.

In reality, the Program Manager uses the already-identified technical opportunities and their specific technical barriers to inform the objectives and constraints described in the solicitation. At the same time, the Program Manager is careful to leave the door open for even better choices. Thus it is possible that even though ideas A, B, and C were presented to the Director at the program initiation briefing, a different set of potentially better ideas – D, E, and F – might be selected during the competition. The Program Manager is held accountable for the program's outcome and mission impact, usually not for the specific technology mix.

For ARPA-E to be successful, it must get the best R&D ideas to meet its agency mission. To do this, it must develop a trusted relationship with the technical community. The R&D performers must come to believe that the agency is open to new ideas and new performers, that it will evaluate proposed R&D projects in a fair and competent manner, and that their intellectual property will be protected while being evaluated. All competitions must be run in accordance with these principles.

Finally, the Program Manager must design and execute the competition and selection phase in a way that it gives the optimal combination of projects to meet the program objectives. This cannot be done by simply ranking ordering the scientific quality of the proposals from 1 to N. The quality of the proposals must be judged and the poor technical ideas and plans eliminated. But then the Program Manager must move on to selecting the optimal combination of the remaining excellent proposals most likely to reach the program goals.

As in any other government agency, the competition process must be run in accordance with the laws, but an ARPA-style agency is more likely to need the full flexibility given by the law in designing and executing each competition to satisfy the program's unique requirements. Under good governance, the competition will also be overseen by a separate Selection Authority who will determine that a fair process was run and make the final decisions to confirm the Program Manager's recommended projects for funding.

Contracting and Execution

Once the competition phase is completed, a program moves on to the contracting and execution phase. The contracting strategy is integral to the overall program strategy, as the contracts must capture the correct sharing of risk between the Government and the R&D performer, have the correct balance of flexibility and rigor to manage risky R&D, target the right maturity of the technology at the end of the contract, and have the correct intellectual property strategy. The Program Manager must work closely with the Contracting Officer and the General Counsel to embody the correct elements of the program strategy in the individual contracts.

This type of contracting is quite challenging because each effort is in some ways ground-breaking, requiring tailoring of each aspect of the contracted effort to match the unique program of which it is part. For this reason, ARPA organizations utilize a variety of contracting vehicles: contracts, other transactions, cooperative agreements, and sometimes grants. Once the Program Manager lays out what must be in the contract, the Contracting Officer is able to determine which contracting vehicle best supports the contracting strategy. Just as it takes a very experienced person to be a good Program Manager, it takes a very experienced Contracting Officer to understand all the nuances of the various contracting vehicles and how best to craft them to protect the Government and maximally satisfy program objectives. Once the contracting vehicle has been signed and the work begins, the Program Manager's job is not over. The Program Manager is an active manager of the program – managing risks and preparing for transition.

Program Manager's Role in a Successful Project

The Program Manager will be held accountable for the overall success or failure of the program. Therefore, the Program Manager must continually interact with the R&D performers to understand how well they are progressing and whether they have encountered unforeseen difficulties. The Program Manager has many options for helping the performers overcome barriers – from getting them access to specialized equipment to providing additional funds for a specific additional task to finding a new performer to join the program to overcome the new barrier.

The Program Manager will also be continually planning and smoothing the way for transition. The Program Manager may hold informational meetings with the target industry or refine technical requirements for end of program technical prototypes to build industry confidence. Program Managers are continually seeking ways to ensure that a technically successful project will also transition successfully.

Director's Oversight of Programs

A final aspect of the program execution is the oversight of the program by the ARPA Director, who should review each program at least annually. There are several reasons for these annual reviews. First, the Director is the portfolio manager of all programs and must understand the risk and success profile of the existing programs before deciding on new programs. The Director must also be ready to explain the significance and progress of each program to the Congressional oversight committees. Without this knowledge, the Director risks having a program cut when the Congressional committee does not understand its significance.

The annual review also allows the Program Manager to create a new baseline for the program. By reporting on the specifics of the program, the Program Manager is able to get the Director's approval for the adjustments the Program Manager has made as a result of day-to-day management. The Director determines whether the cumulative adjustments are still within the high-level program authority given to the Program Manager when the program was approved. If not, the Director re-evaluates the adjusted program (goals, impact, strategy) and either terminates the program or authorizes the modified program. Finally, because the Program Manager is spending taxpayer funds, it is good governance to have a second person overseeing the details of program execution. If the agency is large enough to have Office Directors, they can perform this last function. Finally, for problem programs or those hitting significant milestones, additional reviews by the Director may be advisable.

Transition to Next-Stage Developer

The transition to next-stage developer is not a single point in time, but rather an ongoing process throughout the life of the program. That said, all ARPA-style programs are of limited duration. They end successfully when the technical barriers have been overcome and the technology transitions to the next-stage developer. For most ARPA-E programs, this will mean that one or more companies will pick the technology or system up for further development, making it into products and eventually marketing it widely. In some cases, the transition will be to a DOE Applied Program for a commercial viability demonstration. In other cases, the technology will transition into more conventional technology development programs.

In some cases, the program may have failed technically. It is important in these cases to document what the specific technical failure was and its cause. If in the future, a new discovery or technology makes it possible to overcome that point of failure, then ARPA-E should consider starting a new program which now has a better chance for success.

The Heilmeier "Catechism" - What is a good program?

The following is a modified version of the Heilmeier catechism, named for the eighth Director of DARPA, Dr. George H. Heilmeier. DARPA uses very similar questions to determine internally whether a program should be funded. The "catechism" is designed to promote the process of obtaining needed information on market acceptance and mission impact, which are important factors in deciding whether to initiate a program. The questions also require the Program Manager to have fully investigated key aspects of the technology and its development path and formed a robust program that is most likely to not only lead to technical success, but also to transition well too.

Program Start-Up and Management Questions

Program technical goals:	If successful, what specifically will the program accomplish technically?
Mission impact:	What impact would this success have on the agency mission when the technology becomes widely used? What is the current technology to accomplish this task and how much better will the new technology be?
Technical approach:	What are the key technical challenges and what are the ideas to overcome these barriers?
Transition:	What is the transition strategy? What are the key issues for transition? Under what future world scenario will the market absorb this technology or system?
Program metrics:	What are the metrics, milestones, and schedule for this program?
Budget:	What is the budget profile by year?

Chapter 7: Mainline Functions, Staffing, and Organization

The mainline function of ARPA-E is to develop and execute programs to mature technologies with transformational potential for curbing energy-related climate change and improving energy security. The keywords in this functional statement are technologies and programs. ARPA-E is patterned on the DARPA model, adjusted for ARPA-E's mission areas, technologies, and industries that will absorb its R&D successes. This chapter examines how DARPA is structured and the key roles of the mainline staff in creating and executing these technology programs. Recommendations are made on how to adjust this structure to match ARPA-E's unique qualities.

DARPA has three levels of staff involved in the mainline function: Program Managers, Office Directors, and a Director/Deputy Director. Although the specific responsibilities and authority levels have changed over time, the following section describes the predominant manner in which they have been allocated during the agency's successful history.

Program Manager

The Program Manager is the central architect and manager of the program. The Program Manager's role is to investigate new technical opportunities for single efforts or programs, develop new programs and seek a decision from the Director to initiate new programs, compete and execute the program, and transition the technology to next-stage developers.

During the program development phase, the Program Manager is responsible for all aspects of program development, from identifying technical opportunities to getting an analysis of mission impact. The Program Manager must work down from the technical opportunity and mission impact to defining the specific technical program goals and all elements of the program strategy.

During the competition and contracting phase of the program, the Program Manager (PM) leads a three-person team that includes a contracting officer (CO) and a general counsel (GC). The Program Manager determines the content of the solicitation and the program strategy, including the intellectual property strategy. The Program Manager is also responsible for determining the appropriate allocation of risk between the Government and the contractor, including cost sharing. The Program Manager takes lead on this because the Program Manager is the expert on what the magnitude of the risks involved in the R&D is and whether or not the potential contractors are in a position to cost-share the work with the Government – and to what extent it is appropriate or feasible for contractors to accept the high risks of that particular program. The Program Manager then works with the contracting officer and the general counsel to devise solicitation and contracting strategies that embody the Program Manager's program strategy. The contracting officer and general counsel should be competition advocates and ensure that solicitation and contracting are done in a legal manner, while supporting the program strategy. Both the creation of the solicitation and the negotiation of the contract require tight interaction among the Government team (PM, CO, and GC). The strategy for each program – and the contracts it negotiates – is unique. This necessitates the contracting officer closely interacting with the Program Manager during negotiations. It is not possible "to throw it over the transom" and ask the contracting officer to negotiate without the guidance and collaboration of the Program Manager. Having the contracting staff co-located with the program management staff is optimal because of the need for this tight interaction.

During the execution, the Program Manager must interact closely with the contractors. ARPA-style R&D is highly risky and the specific technical approach evolves as more information is gained during execution of the contracts. The Program Manager must be aware of any difficulties being encountered and must be a proactive agent in helping resolve the issues. Execution of an ARPA-type program is not about selecting a set of performers and checking on them yearly. The Program Manager must be a proactive manager, in frequent contact with the performers.

Program Managers Require a Rare Skill Set

People with the breadth of skills and experience required to be excellent Program Managers are rare. They must be:

- Knowledgeable about technology, about R&D processes, how the technology is used in the field, and how industry absorbs technologies and brings them to market;
- Visionaries for how technology can transform the world and understand what it takes and have the skills to mature technology far enough for that to happen;
- Excellent communicators of this vision and able to recruit and manage the best technologists to make the program succeed, and to garner and sustain the funding support for the program;
- Excellent managers of funds and people.

In general, the optimal candidates for Program Managers have from 10 to 20 years' work experience as technologists. The typical bench scientists may have the technical depth to be a Program Manager, but not the well-rounded qualities to sufficiently understand the technology development path and identify and overcome specific obstacles to transition to product development. Even having experience as an R&D manager for evolutionary development efforts may not be enough preparation for an excellent transformational R&D Program Manager because an ARPA-style PM must not only manage the R&D, but must also be able to identify new opportunities and evaluate their potential mission impact. The best Program Managers are highly sought-after technologists. Typically, they take a pay cut to come and work for the Government.

Characteristics of Program Managers

ARPA-E should look for the following characteristics when searching for Program Managers. The ideal Program Manager is someone who not only has in-depth technical expertise in fields of direct relevance to the program area, but who is also comfortable in seeking and evaluating technical information outside that specific expertise. The ideal Program Manager will also be:

- Transition-savvy;
- Either knowledgeable about operating conditions for program's technologies – or capable of learning rapidly;
- Knowledgeable that technology success is not just technical;
- Capable of defining and communicating the significance of the program for the agency's missions;
- Entrepreneurial, accepting and managing risk;

- Ethical and fair, and with high standards;
- Able to exercise sound technical judgment;
- Able to show minimal conflicts of interest that would interfere with programmatic work;
- Interactive with contractors to remain aware of successes and problems;
- An active problem solver;
- Delivery-oriented; and
- Able to develop strategies for both program and technology transition – identifying all barriers and selecting the most significant as well as creating a program structure and strategy around the key technical barriers currently limiting industrial investment.

Number of Program Managers Needed

An ARPA-style Program Manager typically runs programs and projects with an annual budget of between $15 million and $25 million. Programs can also be much larger or smaller. However, the number of Program Managers required to staff the agency does not scale evenly as the top-line budget for the agency grows. This is because the Program Managers must interact with large numbers of people who contact the agency to discuss possible new R&D program ideas.

As the number of Program Managers increases, the workload is distributed among more people. When the agency is small, interaction with staff will be a significant portion of the Program Manager's workload. So, for an ARPA-E with an annual budget of $200 million, there will need to be from 10 to 13 Program Managers who handle the workload of creating and managing programs, while also interacting with the technical community on new ideas. If ARPA-E grows to the point where is has a $500 million annual budget, the number of Program Managers required will be in the range of 22 to 27. At an annual budget of $1 billion, the agency will need approximately 40 to 48 Program Managers. The ultimate annual budget for ARPA-E, and thus the total number of Program Managers, will be determined over the next few years as the agency is able to demonstrate what benefits it can deliver at different levels of funding. Congress and the Administration will then have the information to determine how the agency should mature.

Recruiting Program Managers

There are a variety of places where potential Program Managers are currently employed. They may currently work in industry, not-for-profit laboratories, universities, other federal agencies, or other governmental agencies. Depending on where they come from, there are different mechanisms to bring them into service for the Government. Since the Program Manager's job is inherently governmental (making funding decisions), they either must be government employees of one type or another or they must be brought into the Government under provisions of the Intergovernmental Personnel Act (IPAs – see box on next page for more information).

The three most common mechanisms for ARPA-E to bring in Program Managers are likely to be: term employee, detailee, and IPA. The ARPA-E section of the America COMPETES Act gives the Director of ARPA-E the ability to establish mechanisms to recruit and employ Program Managers as term employees, outside the normal civil service. In establishing how to use this broadly flexible hiring authority, the Director should examine some of the other flexible hiring authorities at other agencies, including the 1101 hiring authority as implemented at DARPA and HSARPA, and the hiring of high-quality experts (HQEs) at DARPA. Although it would be theoretically possible to allow an individual to take a leave of absence from industry and come to work for the Government under these special hiring authorities, DARPA and HSARPA both determined that the actual conflicts and the perceived mistrust of competing companies would not make this a suitable option. The salary caps were set by these other pieces of legislation, but are not specified for the ARPA-E authority. However, the Director should consider several factors in setting a policy on the maximum Program Manager salary under the special authority, such as:

- Whether the salary cap should exceed the salary of the Secretary of Energy or the Vice President of the United States.
- Whether the maximum salary for a Program Manager should exceed twice that of a detailed Program Manager.

ARPA-E will need an experienced human resources manager to assist in setting Program Manager salaries below the cap and determining bonus caps. Unlike the normal civil service, many factors are considered by the other flexible authorities in setting salaries, such as competing industry salaries, salary and bonus history of the individual, stock options not yet vested at the time of government employment, the difference in cost of living between the location of the current home versus a home in the Washington area, and the need to divest of conflicting ownerships at a time before it is economically optimal to do so. There is no simple formula for doing this evaluation; it must be done by an experienced human resources person in collaboration with the senior hiring manager. The other flexible authorities include the potential for a significant bonus, up to $25,000 annually. The ARPA-E Director will need to decide how best to consider and manage the bonuses (for example: annual, specific performance, and retention) under the special hiring authority.

If the person is currently at another federal agency, then their home agency may be willing to detail them to ARPA-E for a term. ARPA-E would reimburse the home agency for salary and benefits. Some agencies would look favorably on such a detail as a way of broadening the employee's experience.

Rotation of Program Managers

ARPA-style Program Managers should be hired as term appointments. This prevents the agency from getting locked into one set of technical expertise. When the Program Managers leave the agency at the end of their terms, the Director can shift into new technical areas as needed and also shift out of areas that are no longer promising. The term of appointment needs to be long enough for a Program Manager to develop a program idea, and then to initiate and execute the program. The essence of an ARPA organization is to empower Program Managers and to simultaneously hold them accountable. If the same person does not do all program phases, it is too easy to drop the accountability. Of course, there will never be an exact match for the terms of both the program and the Program Manager because many Program Managers will start additional new programs after the first one. In addition, the agency will want to retain a small percentage of its most productive and capable Program Managers to help maintain the culture and the skills required for ARPA-style R&D management. This goal can be accomplished by retaining roughly 10% to 20% of Program Managers beyond their first employment period. If the program is in a critical phase, the agency must also have the flexibility to extend the Program Manager's term to match the program's requirements.

Using IPAs from DOE National Laboratories

The Department of Energy frequently uses IPAs from the DOE National Laboratories. Although there are many excellent technical people at the DOE National Laboratories, ARPA-E must be judicious in using them as IPA Program Managers. The culture of an ARPA-type organization must be delivery-oriented, not progress-oriented. Because the goal of the National Laboratories is generally to maintain expertise and make continual progress, they are more progress-oriented. ARPA-E must carefully guard its delivery-oriented culture and not allow it to become too heavy with individuals from a more progress-oriented background. To maintain a healthy internal culture, ARPA-E should limit the number of IPA Program Managers from the National Laboratories to no more than 10% to 15% of its total number of Program Managers at any one time. Another consideration is that Program Managers who are IPAs cannot make any decisions regarding their employer. Because the National Laboratories are one important source of technology ideas for ARPA-E, there must be Program Managers and Office Directors at ARPA-E who do not have conflicts of interest with the National Laboratories so that they can evaluate and manage these ideas without conflict of interest.

Intergovernmental Personnel Act (IPA)

The Intergovernmental Personnel Act makes it possible to loan personnel (IPAs) to the Government. These individuals are loaned by other government entities (state and local) or by not-for-profit entities. They remain employees of their home agency or entity, but are loaned to the Federal Government for a time. The federal agency reimburses their home-base employer for salary and benefits. ARPA-E will need a policy on whether to cap the amount of salary reimbursed. During the term of the IPA, the person can perform inherently governmental functions and must abide by the same rules and procedures as other government employees. However, if the person were to work on any project involving the loaning employer, this would create a conflict of interest. As a result, loaned employees may have no significant involvement in a specific matter affecting their home organization. Using IPAs is often a way to bring university professors into the Government for a term of service. Before bringing a person on board as a Program Manager using the IPA authority, the Director or Office Director must carefully examine whether the person's home affiliation would negatively affect the ability to perform the job. For example, the Program Manager may not evaluate proposals from or manage a contract with the home institution.

Filling the Role of the Contracting Officer's Representative

DARPA expects its Program Managers to be dynamic, active managers of the multiple dimensions of high-risk revolutionary R&D programs. Given the many high-level aspects of this type of program management, the DARPA Program Managers do not have the time to devote to the detailed tasks of being the Contracting Officer's Representative (COR) on each of their various contracts. CORs are responsible for many time-consuming detailed aspects of a contract, such as tracking deliverables, ensuring reports are complete and received in a timely manner, and approving invoices. DARPA typically does not allow its Program Managers to be the CORs, except in extraordinary circumstances. DARPA typically finds technical Program Managers – from other government agencies – who are willing to perform these detailed technical COR functions. This is one of the primary reasons for DARPA using other DOD agencies for its contracting, because it not only supplements DARPA's internal contracting capabilities, but it also broadens the technical program management capabilities of the agency. By using other Government agencies' personnel as CORs, it frees the DARPA Program Managers to focus on the higher level aspects of the programs.

The COR Function at ARPA-E

ARPA-E will not have many options for getting other government agencies to provide contracting and COR services for it. The COR job is inherently governmental and cannot be contracted outside the Government. At DARPA, using other agencies' personnel works because the COR's home agency is usually the target for transition of the technology within the military. Or that home agency also supports the same military mission that DARPA is trying to revolutionize in the program. ARPA-E's transition target will typically be industry. In addition, ARPA-E will rarely have enough commonality of purpose with other government agencies for them to agree to allow their personnel to support ARPA-E. In cases where the commonality does exist, ARPA-E should take advantage of it. In cases where the commonality doesn't exist, ARPA-E will need to provide for the COR function internal to the agency.

Need for an ARPA-E Assistant Program Manager

Given this very significant difference with DARPA in filling the COR function, ARPA-E should consider creating the role of Assistant Program Manager (APM). The APM must be a technically competent individual, but does not require the breadth of experience and knowledge required of a PM. The APM must work with the PM to ensure the contractors perform in a way to further the program's goals; however, the APM does not and should not need to be the architect of the program. Depending on the complexity of the contracts involved in the program, a single APM will likely be able to support between one and three Program Managers. If ARPA-E chooses individuals with a broad technical background for the position, then the APM will be able to support a range of programs, even as the agency evolves its program mixes to match opportunities and priorities. APMs will also need to be trained in all the bureaucratic details of being a COR and maintain their proficiency through annual training. For these reasons, APMs could be permanent civil servant positions, rather than the term appointments more appropriate for Program Managers.

Offices as Organizations with the Agency

Offices are groupings within the agency organized to give focus and impetus to specific mission areas or technical thrusts. As these focus areas shift with time, the agency will likely reorganize the Offices to reflect these changes. For many years, DARPA reorganized Offices every 18 to 24 months. A reorganization was triggered by one of the following events:

- A new priority given from the Secretary that would best be executed with a set of interacting programs.
- The continually evolving mix of new programs changed to the point that the agency would benefit from the programs being reorganized into different synergistic groupings.
- When the missions of the Offices overlapped enough that proposers were confused about which Office to contact. The distinctions between the Offices blurred as new programs were funded in whichever Office had proposed them.

Offices at ARPA-E in Start-Up Mode

Offices do not need to be formed at the beginning of ARPA-E, but can evolve with time. When HSARPA was first started and had a small staff, all PMs reported directly to the HSARPA Deputy Director. This worked well until the agency had grown large enough to divide into Offices. Once there are 10 or more Program Managers with more hires planned for the future, ARPA-E should consider establishing Offices. By that point in the evolution of the agency, it should be clear where the most urgent needs and promising ideas are clustering. In addition, the Director will understand how ARPA-E can contribute most effectively to the national energy strategy. The Offices should be created to emphasize the clusters that seem to have the greatest potential for more breakthrough work and in areas where synergies across programs are most important. Until ARPA-E forms the offices, the Director and Deputy Director of the agency will need to fulfill the functions of the Office Director.

A Comment On The Size Of The Office Operations

Over the years, DARPA has found that the optimum office size is between 12 and 15 Program Managers. An Office with fewer than 10 Program Managers will neither generate enough new programs nor have sufficient Program Managers to handle the influx of ideas from the outside. In an Office with more than 15 Program Managers, the Office Director is stretched too thin. In that case, the Office Director cannot spend sufficient time overseeing program execution while having to simultaneously look for new Program Managers and coaching existing ones in developing new programs. If an Office has more than 20 Program Managers, the Office Director tends to fail significantly in some aspect of the job. Another rule of thumb is that the largest Office in the agency should be no more than twice the size of the smallest. If the disparity is larger than this, it is time to reorganize the agency, either because one strategic area has shrunk in significance and does not merit the status of an Office, or one area has grown so much that it needs recognition and better organization.

Role of the Office Director

The Office Director is responsible for developing a technical strategy, and recruiting and managing Program Managers to execute it. Since both Program Managers and programs are of limited duration, the Office Director must continually seek new replacements. The Office Director's role in interacting with the Program Managers is a complex mix of supportive coaching and required governance.

Developing an Office Technical Strategy

The Office Director is a technical expert with broad experience in the areas relevant to the Office. One of the primary jobs of the Office Director is to develop a strategy within the central organizing focus of the Office, having looked broadly at the limitations of current technologies and those in the pipeline to satisfy the agency's missions. Having identified specific areas where technical breakthroughs would transform capabilities, the Office Director develops a strategy of program areas and thrusts. After conferring with the agency's Director on this strategy, the Office Director then recruits Program Managers with skills to match the office strategy, especially in technical areas where new programs are needed. Although the Office Director will use normal government job postings, this is rarely sufficient to find enough highly qualified individuals to staff the Office.

The Office Director must continually use significant time looking for the right Program Managers, especially given that the existing Program Managers continue to rotate out as their terms are completed. When an excellent candidate is identified, the Office Director helps that individual understand the job of a Program Manager and ascertains how the candidate would like to move the technology base forward. If the candidate has program ideas that will contribute to the Office strategy or will significantly move the agency mission forward in general, the Office Director recommends the hiring of that candidate to the agency Director. The agency Director interviews the candidate as a final check that the person has the experience and characteristics needed to be a Program Manager and the types of programs that the candidate is likely to develop have a reasonable likelihood of being funded.

Supporting the Program Managers

The Office Director works with the Program Managers, providing helpful advice on how to develop a well-rounded program initiation proposal to the Director. Within appropriated authorities, the Office Directors have some funding latitude (approximately 5% of the Office budget) to fund small efforts to explore the feasibility of a breakthrough technology or to evaluate the possible impact of a potential program. These seedling efforts are in some sense a business development fund for the Office, allowing the Program Managers to delve deeply enough into new technologies to determine whether a program can grow out of them. In these roles, the Office Director is both the coach and advocate for the Program Managers and their programmatic ideas.

Providing Governance

Another aspect of the Office Director's job is to provide governance. Because the funding comes from the public, the job requires high standards of behavior and execution. Good governance requires that the agency be open to good ideas wherever they come from; that the agency funds efforts based on full, open, and fair competition; and that the agency interact with proposers and contractors in a respectful manner. The agency must comply with federal law. The agency must avoid both real and perceived conflicts of interest. It is in the agency's interest that R&D contractors understand that they will receive a fair hearing for their ideas and that their intellectual property will be protected. Only in this way will ARPA-E have access to the best ideas to accomplish its missions. Good governance also requires that funds be executed in a manner that is both timely and designed to give the maximum benefit to the taxpayer by optimizing the programs and program portfolio to best achieve the agency goals.

Oversight Role

The Office Director is a key player in the agency governance strategy. In an ARPA-style organization, upon approving the start of a new program, the Director delegates authority for detailed oversight of the program to the Office Director. The agency Director approves the top-level goals and strategy of the program, the milestones, and program metrics, and then delegates the funding authority to the Office Director. The Program Manager determines which efforts should be funded and then asks for concurrence from the Office Director, who looks at a variety of factors. These factors include whether the effort was selected by a fair competition of ideas and is:

- Technically sound;
- Consistent with program goals and delegated authority;
- Staffed by a capable performer or team of performers; and
- Showing good, up-to-date performance for incremental funding.

Documentation of Selections and Funding Decisions

There should be an agency-wide process for documenting the information underlying a funding decision and recording both the Program Manager's request and the Office Director's approval. The Comptroller must also agree that the funding documentation shows funds are consistent with the agency appropriation and within the funds delegated to the Office for that program. The Office Director is responsible for ensuring timely execution of funds. The Office Director also usually serves as the Source Selection Authority in competitions, ensuring that a fair process yielded a set of selected proposals that is most likely to meet program goals. If the Office Director, in the role of the Source Selection Authority, determines that the competition and selection process were not executed properly, then remediation actions will be required up to restarting the competition.

Oversight of Programs within the Office

In addition to having oversight of contract selection and detailed financial execution, the Office Director has first-level oversight to ensure that the programs are being managed optimally for the stated program goals. The Office Director must therefore maintain an awareness of the programs within the Office. In addition, all good programs evolve as the R&D is performed. Technical development paths are pruned as they prove unsatisfactory and others may be added as promising alternatives arise. It is the responsibility of the Office Director to determine if these normal excursions are cumulatively large enough to take the program outside the original definition of the program authority delegated to the Office. If so, the Office Director must schedule a meeting for the Program Manager to re-brief the Director on the new, updated program.

If a program is in trouble, the Office Director supervises the Program Manager in taking corrective action. If necessary, the Office Director (or the Program Manager through the Officer Director) may recommend the early termination of a program. In the type of high-risk research that an ARPA-style organization manages, it is not considered a failure to identify a failing program. It is only a failure if the problem should have been identified earlier or was not dealt with appropriately.

Communicating Effectively

Finally, the Office Director must be an effective communicator of the office strategy, goals, and accomplishments. The Office Directors will be called upon to support the budget justification submitted to Congress. The Office Director will also represent the agency to the technical community, communicating the ARPA-E strategy and motivating them to participate in ARPA-E programs.

The Agency Director

The Director's job is multifaceted, looking both outside and inside the agency. If the ARPA-E Director has a deputy, the Director may make the choice to focus more on the external relationships and delegate more of the inward focus to the Deputy Director. The Director must:

- Be the primary agency contact for and report to the Secretary of Energy.
- Understand the national priorities important for the ARPA-E mission areas of energy security, energy efficiency, and climate change and have access to critical energy policy issues.

- Understand the context for the agency and maintain the relationships that provide information about the critical policies.
- Remain informed on national energy priorities through interactions with the Secretary of Energy and appropriate Congressmen and Senators.
- Develop a strategic vision for the agency; understand how best to accomplish the agency's missions; and align the internal structure and processes to best accomplish this work.
- Maintain a view of future worlds and invest accordingly.
- Be responsible for what the agency will do internally, as well as ensure that all internal aspects are aligned and optimized for executing the transformational R&D work.
- Gain the trust of the Secretary and Congress that the agency is organized and performing well. (Heavy external oversight leads to detailed bureaucratic processes and lots of documentation that will cause the agency to be inefficient and will lead to failure of the ARPA-style of R&D management.)

Agency Portfolio Investor

- Be the portfolio manager for the agency's investments by deciding which programs to initiate.
- Be responsible for approving specific programs within the overall strategy.
- Ensure a program plan and strategy is fully formed before delegating the program authority. (See Heilmeier Catechism, p. 59)
- Drive the agency to seek solutions to critical national problems, favoring such programs in the portfolio mix.

Oversight

- Execute high level oversight of programs and thrusts. The Office Directors are responsible for detailed day-to-day oversight.
- Carry out yearly review to maintain awareness of how programs are progressing and how they fit in the overall portfolio. (The review will determine that programs are within acceptable risk and performance profile, and whether corrective action is needed. The Director's annual review will serve to reauthorize the programs, including any changes made during the last year.)
- Institute processes with sufficient controls and documentation, but as light-weight as possible to maintain the non-bureaucratic, nimble functioning of ARPA-E.

Budget

- Work with the Secretary of Energy, the DOE departmental budgeting process, and the Congressional authorizing and appropriating committees to explain and defend the annual budget request, including the out-year implications of that budget.
- Plan the agency budget to leave financial flexibility to create programs in the most promising areas and where there are currently gaps in the program portfolio supporting the agency strategy.
- Build understanding about the multi-year nature of program budgeting within ARPA-E and the strong negative consequences of unpredictable future budget swings.

Leadership and Culture

- Be responsible for leading the agency, instilling the right culture and work ethic.
- Establish a culture of brutal honesty. High risk R&D can only be managed effectively when all the risks are identified, monitored and dealt with. Problems must never be hidden, but must be confronted and managed. The Director should reward honesty, even reward those that report failure if they do so in a timely manner, and punish those that hide critical information.
- Ensure an exceptionally high standard of conduct for the agency's individuals and the processes of the agency – because ARPA-E is a government agency executing funds on behalf of the American public.
- Organize the structure and processes to support the delivery-oriented program-based approach of an ARPA-style R&D organization. The Director should not accept only progress toward a goal as a justification for a program. The Director must require specific programmatic goals that cross a threshold for transition.
- Reward Office Directors and Program Managers who take appropriate risks and manage those risks prudently.
- Establish a reputation for ARPA-E as a flexible, nimble organization that is open to new ideas and all performers (old and new to DOE). The reputation must also include technical quality of the staff, excellent program objectives, fairness in evaluation, and respect for proposers and performers.
- Gain the awareness and trust of the technical community so that they bring transformational energy R&D ideas to ARPA-E.

Organizer

- Create sub-units (Offices) when appropriate to aid the development and execution of programs and strategic thrusts.
- Allow flexibility of the Offices to start programs outside their specific strategic thrusts if these ideas contribute to the agency.
- Monitor the Office evolutions and re-organize as appropriate.

- Develop policies that are derived from the law and the agency mission and proven methods of managing transformation R&D, not just accept policies because other elements within DOE use those methods (which have been optimized over time to support their missions).

- Be aware that ARPA-E is a government agency, not an industrial one, and align policies, processes, and organizational structures to fulfill the unique attributes of government R&D organizations.

Characteristics Of An Ideal First Director

The Director must have deep technical knowledge in some area relevant to the ARPA-E mission, be savvy about technology transitioning, be aware of the various types of energy industries and how they use and adopt new technologies, and have experience with starting up an organization. Start-up requires experience with and knowledge of organizational structure, processes, reward systems, culture, recruiting, and policies, how government operations differ from industry (can be covered by getting an experienced deputy). The Director must be an effective planner and communicator of the ARPA-E mission, strategy, and priorities to the Secretary of Energy and Congress. The Director can only be effective with the full faith and support of the Secretary of Energy.

Control of Support Functions

- Establish the necessary support functions within ARPA-E: contracting, general counsel, and human resources.

- Communicate to the support functions their value and contribution to the agency.

- Communicate also that their role is to support the mainline function, not to interfere with it nor limit it beyond what the law requires.

- Appoint a senior manager for support functions and charge with finding experienced creative, flexible people for the support functions. The mainline technical people specify what needs to be done and why, while the support functions help them find the best way to execute these strategies. This creative interaction requires seasoned professionals who understand the full flexibilities allowed by the law as well as what is prudent to do and not do.

- Establish the new hiring authority in a way that allows ARPA-E to bring in the best people as ARPA-E technical staff and rewards them for their work.

- Think deeply about in what areas ARPA-E should follow standard DOE procedures and where the procedures must be altered to optimally support the agency function, communicating these reasons to the Secretary and other DOE leaders.

- Establish policies to prevent organizational conflicts of interest from agency support contractors, allowing an entity to either be a support contractor or an R&D performer, but not both.

Chapter 8: Start-Up Issues and Recommended Plan for ARPA-E[18]

ARPA-E will need to balance expectations for a fast "hit-the-ground-running" start-up against the specter of past government failures to provide appropriate oversight and execution when trying to react rapidly to urgent needs. ARPA-E must establish a credible process for selecting and managing the first contracts and contractors while moving forward to simultaneously do all the other start-up tasks. This will require an understanding of what these tasks are and how to sequence them for optimal start-up.

Strategic Vision and Competing Road Maps

ARPA-E will need to craft a strategic vision and plan for how to accomplish missions as laid out in the establishing legislation. This will require access to in-depth, rigorous analyses of the sources of carbon emissions from energy-related technologies in order to satisfy the climate change mission. Also required will be a thorough understanding of the various roles of imported petroleum in our energy mix and economy in order to satisfy the energy security mission, and how these missions interact. Much of this work has been accomplished by others and must be absorbed and assimilated by ARPA-E. In addition, when considering the initiation of a program, the Director must compare that program outcome against what would likely happen without this investment. To be able to make this comparison, ARPA-E must accumulate and understand road maps for current technologies and likely future developments in existing technologies.

Plan for Executing Funds

Although an ARPA-style organization runs best when it is built around transformational R&D programs created by the rigorous process described previously, ARPA-E can start by soliciting one-off ideas. The first set of individual contracts can be selected from an initial solicitation. These obligations would occur during the first seven to ten months from start-up. A small amount of funding would also be spent on determining the potential for new programs. The remaining start-up funds would then support contract initiation for the first set of programs. These later obligations would occur during the first 10 to 18 months.

ARPA-E could start with a set of individual stand-alone contracts, while a staff of Program Managers is hired and more complex interactive programs are developed. For this first tranche of contracts, ARPA-E should immediately seek potentially high-return ideas that can be acted on with single efforts rather than interactive programs of multiple contracts. The efforts should be of a duration limited to a maximum of 24 months, and be fully funded at the time of contract initiation. Fully funding the efforts at initiation limits the burden on ARPA-E Program Managers to process second-year incremental funding at a time when they will be intensely developing new programs. To prevent the fledgling agency from becoming inundated with inappropriate proposals, the key element for the solicitation will be to articulate the threshold of transformational innovation required.

To save some time in the evaluation process, the initial solicitation for projects could go directly to full

18 Note that the material for this section of the report was written before the start-up of ARPA-E. ARPA-E has chosen to follow a similar, but not identical start-up path.

proposals, skipping the more typical white-paper phase. Because the agency will be new – and word must get out to the technical community that ARPA-E is seeking proposals – it will be best to allow longer than the normal period for proposal preparation. Reviewers assembled from multiple government agencies would evaluate programs in a process lasting between 30 and 60 days, depending on the number of proposals received and availability of technical evaluators.

The solicitation should not depend solely on the normal government listing (FedBizOpp) to get the word out to the technical community, but should be advertised widely through press releases to the technical and trade press and through mailing lists and newsletters of technical and professional societies and industry organizations. Before the solicitation is issued, the process for evaluation should be in place, including panels of both outside (non-ARPA) reviewers for technical review and internal reviewers to evaluate transformational impact.

One possible time line for procuring initial proposals would be for initial solicitations to be released within three months after ARPA-E is formed, followed by:

- 60 days for receipt of proposals;
- 45 days for review and external evaluation board meeting;
- 30 days for further analysis of transformational impact and selection of proposals for contracting;
- 2 to 6 months for contracting.

An agency website should go live as soon as possible and allow the posting of information on agency missions, goals, method of doing business, and a copy of the solicitation. A key element in the design of the electronic proposal submission website will be the protection of intellectual property.

Internal Organization and Recruiting ARPA-E Staff

The types of mainline technical staff that ARPA-E will need for success are rare individuals. Locating and recruiting these individuals must begin immediately. Recruitment at this early stage will be a major time commitment for the Director. Hiring should occur with the cooperation of DOE human resources, until ARPA-E can create its own human resources function.

During the agency's start-up phase, all Program Managers will report directly to the Director until 10 to 15 Program Managers have been hired. By the time the organization reaches that level of staffing, many program ideas will have been identified and investigated and some will have already been initiated. At that point, clusters of good ideas and program directions will be apparent. The Director's tasks will include being able to:

- Discern and emphasize the clusters of programs that seem to have the greatest potential for more breakthrough work;
- Emphasize program clusters in areas of greatest national priority and where synergies across programs are most important.

Once these clusters are articulated as areas of strategic thrust and clearly identified, the ARPA-E Director will recruit Office Directors who will develop a more detailed strategic plan within each thrust area (Office Directors will be charged with recruiting additional Program Managers to develop the specific programs that will support the strategic thrusts).

Start-Up of Projects and Programs

Good programs typically take between three and 12 months of development before they are ready for formal approval and actual initiation. After a program is approved, it typically takes an additional five to nine months for the competitive evaluation and contracting phases before the R&D starts. Therefore, while the process of investigating and developing good programs must begin very early, few contracts from new ARPA-E programs will be started in the first fiscal year. This is why the initial general solicitation is so important.

The Director must have a portfolio of started projects to report on at the end of the first year when testifying before Congress. Although the Director is unlikely to have any technical accomplishments to report from the first solicitation, he will be able to project the collective impact on curbing climate change and reducing petroleum imports if all the first projects are successful. The Director will also be able to report on the ability of the technical community to respond to the challenge of creating transformational energy-related R&D projects. All of this information will be important in discussing the agency's top-line budgets.

Contracting and Legal Expertise

In order to solicit, evaluate, select, contract, and manage R&D efforts, ARPA-E must have access to qualified technical evaluators and managers, as well as R&D contracting officers and contract lawyers. In the long term, these experts must be internal staff of ARPA-E. However, in the start-up phase, ARPA-E may be able to borrow staff on a part-time or full-time basis, until it can build its own internal resources. ARPA-E should tap all available DOE resources as well as form agreements with other government agencies to provide contracting services to ARPA-E on a fee basis.

Management and Oversight of Performers

After contracts begin, there must be both technical Program Managers to oversee the technical work as well as administrative contracting officers to manage the contracts. In the longer term, these people will be internal ARPA-E staff. However, in the initiation phase, other options should be explored, including the short-term hiring of detailees and IPA staff.

Financial Plans and Controls

Because ARPA-E is spending taxpayer dollars, the agency is accountable for properly handling the funds. First, the agency must spend funds in ways that are transparent and consistent with appropriations. Controls must be in place so that funds are never obligated beyond those appropriated. In addition to insuring that the agency does not exceed appropriations, ARPA-E must also have clear plans for timely obligation and expenditure of its funds while maximizing benefit to its mission.

Physical Location

The kind of physical space the agency occupies is critical to furthering the mission. ARPA-E will need closed, secure spaces for discussions of proprietary information with potential and current contractors. In addition, storage of proprietary information and proposals will require locked areas. The needs for actual working space for the ARPA-E team will change over time. Initial work will require staff to be very fluid in their work assignments and very interactive. The team will thus need a large enough space that they can be co-located and move around and communicate easily – but also have ready access to the secure areas as well. These are the minimum initial requirements for physical space. However, within six months, ARPA-E needs to move to a location that is optimal for the longer-term execution of its mission.

The order in which these key elements of ARPA-E are realized is also important to the most orderly and effective creation of the agency. Recommendations for how to phase this work follow.

Recommended Start-Up Plan

Phase I (Urgent – Months 0 to 2)

The following activities should run in parallel.

1. Nominate ARPA-E Director. The Secretary of Energy should work quickly with the White House to identify and nominate an outstanding candidate for the Senate-confirmed position of Director of ARPA-E.

2. Assemble a team of government people and contractors to lay the groundwork for ARPA-E. The minimum team would include the following:

   - **3 to 10 technical Program Managers**
     These managers would be loaned from within DOE or other federal agencies, possibly including DARPA, which should be contacted to see if they are willing to loan or reassign some or all of their energy-related Program Managers.

   - **Human resources person**
     This staff member would be loaned from within DOE until ARPA-E can hire their own. Although the special hiring authority for ARPA-E resides with the Director, recruiting activities can begin before the Director is confirmed. ARPA-E should contact DARPA to provide advice and lessons learned from their use of specialized hiring authorities.

   - **Contracting officer**
     The contracting officer would be loaned immediately on a full-time basis so a solicitation can be released, and a team of three to five contracting officers available within three months of ARPA-E start-up. It is very important that these contracting officers be experienced with R&D contracting, not just the procurement of services and supplies. R&D contracting is about allocating and managing risks, while most other government contracting is about minimizing the risk to the Government. Loaned staff will be replaced with permanent ARPA-E contracting officers within a year of start-up.

   - **Government attorney**
     This team member would be available on a part-time basis immediately to assist in launching the first solicitation. A permanent attorney will be needed on a full-time basis within three months as the first contract negotiations begin.

   - **Facilities specialist**
     This is someone who will identify specific physical needs for ARPA-E and find suitable candidate locations.

- **Expert advisors on R&D organizations**
  These advisors would be experts in particular federal ARPA-style organizations.

3. Identify an existing contract that can provide Scientific, Engineering and Technical Assistance (SETA) support to the formation and early execution of ARPA-E. Bring on board 20 to 40 SETA contractors immediately to support both technical, programmatic, and support functions.

4. Request access to existing SETA contracts for DOE. If this route is not available, fund a task on another government agency's task order for SETA support. Since the agency will be new and policies, procedures, and functions will likely evolve, it is best to delay the first competition for SETA support until the agency is stabilized, probably at the end of six months. SETAs will be needed to:

   - Create and support the website, to research program opportunities and support program execution;

   - Create the agency's electronic proposal submission website and provide support for the first solicitation;

   - Identify and evaluate program opportunities while additional Program Managers are hired to complete the job.

5. Write and release first solicitation.

6. Establish mechanisms for receiving and handling proposals.

Phase II of Start-Up (Months 3 to 6)

1. Run a competition among DOE laboratories to support climate modeling and energy-security models. These models will be called upon in evaluating how effective various competing program candidates will be in meeting the mission of the agency.

2. Analyze SETA support requirements and prepare statement of work for contractor competition.

3. Continue recruiting Program Managers and support staff for the agency. Although the mandatory government hiring processes (JOBS U.S.A) will bring in some good candidates, active recruiting will be required for Program Managers and Office Directors. They are highly qualified and rare individuals. They will need to be identified and approached to determine their interest in government service. Passive recruiting (through advertising) will not be sufficient to get the number and quality of individuals required. The first Program Managers will report directly to the ARPA-E Director until there are approximately 10 to 15 on board, at which point they will be organized into Offices.

4. Begin contracting proposals selected under first solicitation.

5. Begin process of visits, literature surveys, and workshops to identify high-return program candidates.

Phase III of Start-Up (Months 6 to 12)

1. Organize into Offices with specific strategic thrusts.
2. Continue hiring highly qualified technical and support staff.
3. Recruit Program Managers through personal contact by Director with industry and technical leaders. To assemble a good cadre, the Director will need to spend between one and two hours daily seeking and screening technical people. In addition to direct recruiting, the Director may use a technical recruiting firm, as well as get the word out to the community through technical societies, technical energy conferences and industry newsletters, and contacts at venture capital groups.
4. Compete the ARPA-specific SETA contract.
5. Approve first set of programs for execution. Conduct education to make the technical community aware of specific program goals. Release program-specific solicitations to the technical community.
6. Continue the process of new program formation. Ask the venture capital community for high-potential project ideas deemed to be in too early a stage for investment.

Reasonable Expectations for the First Year

Congress should judge the first-year success of ARPA-E in several ways.

First, the agency should have in place a Director and a beginning cadre of Program Managers. These Program Managers will not necessarily be those with national name recognition, but will be entrepreneurial technologists with the combined experience and expertise to create and manage transformational R&D programs.

Second, the Congress should expect that ARPA-E was able to run its first solicitation in a way that the technical community responded with a batch of excellent proposals. The agency should be expected to have many, if not all of these first contracts signed by the end of the first year. The Congress may want to monitor whether ARPA-E is being given the resources (including contracting and legal staff) and the flexibility to negotiate and sign these first contracts rapidly and with the full flexibility that will probably be required for optimal projects. Also, the ARPA-E Director should be consulted on whether any modifications of the laws are required to allow ARPA-E to function optimally.

As with any start-up organization, ARPA-E should be expected to experience glitches and learn lessons from the first solicitation. The key point will be whether ARPA-E can learn from and adapt after its initial successes and failures.

ARPA-E must have established trust with the technical community. If the community does not perceive ARPA-E as open to transformational new ideas from all technologists – regardless of whether they have worked with DOE in the past – ARPA-E will have failed. ARPA-E must also develop a reputation for sound technical judgment, aggressive goals, challenging but feasible programs that have the potential for major mission impacts, protection of proposer's intellectual property, and respectful treatment of proposers and performers. ARPA-E should also be seen as flexible, nimble, visionary but practical, and demanding of the best, while accepting and managing risk.

ARPA-E should have a high-level strategy on how to meet its mission. The agency should be able to demonstrate at the end of the first year that there is a contractor community ready and willing to work on ARPA-style energy programs that is large and robust enough, with sufficient transformational ideas, to justify the top-level budget of the agency. ARPA-E should not be expected to report technical accomplishments by the end of the first year, but it should be able to show an initial portfolio of projects and programs worthy of the mission it was given.

Summary

The start-up phase will be difficult because so many activities must proceed in parallel and there is no agency structure in place. An analogy is trying to build an airplane as it taxis down the runway for takeoff. However, it is possible to get the agency up and functioning within a year of initiation, with the first contracts occurring well within that period. Of course, this can only happen with:

- A clear set of start-up strategies;
- A defined plan and timeline for execution;
- The support of the Secretary of Energy and other key individuals.

Chapter 9: Potential Barriers to Success for ARPA-E

There are various potential organizational, staffing, and management errors that can lead to the failure of an ARPA-style agency. The reasons these errors can lead to failure have been discussed in previous chapters. They are brought together here at the end of the report to echo the importance of avoiding them. The following recommendations are ways to prevent the various kinds of failure:

- **Hire a strong Director**
  ARPA-E needs a strong Director. The Director is the portfolio investor for ARPA-E. The Director needs deep technical knowledge, and must know about R&D and how to manage research portfolios. The first Director should have experience with starting up an organization.

- **Hire qualified Program Managers**
  Without the multi-dimensional knowledge and experience of seasoned, entrepreneurial Program Managers, the risk of failure for transformational R&D becomes extremely high. Their expertise and vision shapes the understanding of how the future can be changed to meet national energy objectives through the development and transition of transformational new technologies and systems. Their technical expertise and knowledge of R&D identifies problems early and finds solutions. They understand how far the technology must be matured so that industry will accept the risk of using the new technology. Their knowledge and experience lets them identify the right programmatic strategies tailored to the specific technology being developed. It also helps avoid creating a “poison pill” effect for a seemingly technically successful program but that cannot transition for other reasons.

- **Execute transformational R&D in complete programs**
  Due to the nature of transformational R&D, development must be done in complete programs. Unlike improvements made to current technologies, transformational technologies only transition after they cross a particular threshold. A half-way result is a waste of money. A program encompasses the complete strategy and execution of R&D to overcome all the key barriers to transition. ARPA-E needs multi-year budgeting to allow programs to complete without unnecessary re-planning. Part of empowering and holding a Program Manager accountable is the fact that the Program Manager must focus on delivering on all aspects of a program. Because ARPA-E’s mission is to deliver transformational new capabilities, it must be program-based.

- **Keep contracting, general counsel, and political factors in bounds**
  While contracting and general counsel are key support functions for a program, they must not be allowed to determine the program strategy elements. They assist the Program Managers in embodying the program strategy in competitive evaluations, contracting vehicles, and intellectual property clauses. They do not determine them, unless there is a specific legal impediment. The political process should dictate top level objectives, but politics must not dictate specific programs and projects. ARPA-E must be allowed to establish program objectives, schedules, and deliverables based on real opportunities rather than political desires.

  Congressional earmarking is particularly damaging to an ARPA-style organization. The most valuable resource an ARPA agency owns is the Program Manager’s time. Earmarked programs require vast amounts of a Program Manager’s time in attempting to align the earmarked program’s objectives with optimal value to the Government. The biggest damage is not caused by loss of money from the existing programs, but the diversion of a Program Manager’s time from high-priority programs.

- **Be willing to take appropriate risks**
  Internal processes and the reward system must support prudent risk-taking.

- **Limit bureaucratic drag**
  ARPA-E bureaucracy should be limited to the minimum required by law and by good governance. The complexity of ARPA program management does not lend itself easily to detailed procedures and rules, nor to requirements for detailed documentation. However, some documentation is essential; good governance requires a track record of what was decided and the basis for that decision.

- **Conduct a rigorous program generation and selection process**
  ARPA-E must have a rigorous process for generating and selecting programs. A good program requires many factors such as:

  - Technical opportunity
  - High mission impact
  - Market acceptance strategy
  - Transition strategy to next-stage developer
  - Understanding of maturity needed at transition
  - Program strategy consistent with above factors – proper competitive evaluation and contracting and intellectual property strategies.

If programs are initiated before proper planning, key elements of a successful program will likely be missing. If ARPA-E does not generate programs by a rigorous process that ties it back to national priorities, then it leaves itself open to accusations of favoring particular technologies, per se, rather than picking the specific technologies it does because they have the largest potential to meet the agency's mission.

- **Keep evolutionary and revolutionary R&D separate**
  It is not a good idea to mix evolutionary and revolutionary R&D within the same organization. Revolutionary R&D requires different people and processes to succeed.

- **Maintain trust of R&D technical community**
  ARPA-E must maintain the trust of the R&D technical community. ARPA-E does not perform its own R&D; it meets its R&D objectives through funding others. ARPA-E must be perceived to be open to new ideas, fair in its evaluation and decisions, expert in technical opinion and understanding of industry absorption of new technologies, and able to protect prized intellectual property. ARPA-E should be valued for more than funding. It should provide active technical advice, help identify problems early, identify solutions, and advise on the future.

- **Be flexible and agile**
  ARPA-E must be flexible and agile. It should own no fixed facilities. It should rotate technical staff to allow the agency to move into promising areas and out of ones with less potential.

Appendix I: Appropriate Roles for Government Funding of R&D

In discussing the role of the Federal Government in R&D, several distinctions must be made. The role of government as funder of R&D is distinct and separate from the role of the Government (through federal laboratories or government-sponsored Federally Funded Research and Development Centers [FFRDCs]) as possible performers of the research. For any one particular R&D effort, the Government may fund and/or perform the research, or carry out neither role. The following discussion is about the Government's role as a funder of R&D.

1. **Science and discovery**

   Often, the science and discovery that lead to innovative new technologies is years – and sometimes decades – ahead of the application of these discoveries for commercially viable use. For this reason, few companies can afford or are willing to invest in this discovery phase, when the potential return on the initial research investment appears to be too far in the future and the benefit of early-stage research may be reaped by their competition as well. In other words, it is difficult for companies to justify investment in R&D unless it is clear that the investment will ultimately yield a profit.

   Beyond its value to industry, however, the science and discovery phases of innovation provide a robust source of fresh ideas that can lead to a plethora of public benefits – including discoveries that are capable of improving the health and lives of citizens. This is the basis for Federal Government funding R&D through such agencies as the National Science Foundation, the National Institutes of Health, and the DOE Office of Science. In general, the Government supports R&D on a very wide variety of topics, with greatest emphasis on areas that might lead to basic and dramatic improvements for the health and well-being of the general public. A side benefit of government support for science and discovery activities is that these efforts provide the training ground for the next generation of scientists and researchers. (See # 6 Workforce Development).

2. **Technology maturation**

   After a discovery has been made and scientists have developed a fundamental knowledge of how it works, there is still a great distance to travel before the emerging technology is mature enough to attract industry investment. Part of a new discovery's journey towards commercial viability is assessing whether it can be applied beyond laboratory conditions in real-world situations where, for example, the technology might be subjected to temperature extremes or rough handling. If the technology is not currently robust, paths for improvement must be identified. In addition, as a technology's potential commercial and industrial applications become clear, business or private industry must determine if it can be manufactured cost-effectively, whether it is reliable enough for the foreseen application, and whether it can be maintained in the field at a reasonable cost.

   Before industry can invest in developing and manufacturing products that incorporate a new technology, the key technical risks must be identified and lowered. This phase – often called the "Valley of Death" – refers to the intermediate period when it is too early to attract industry or venture capital investment and, at the same time, it is at a point where robust government support is lacking.

In general, the Federal Government invests in efforts to bring technologies to maturity in areas that it perceives are critical to national needs and priorities. When it makes such a designation, the Government then invests only to the point where an industry will begin to invest its own funds in technology maturation and product development. For some technologies, this transfer from government to private investment development happens when the major technical risks, but not all technical risks, are reduced and understood. In other cases, a large-scale demonstration phase is necessary to provide data essential to determining a technology's commercial viability. Examples of situations where the Government has played a role in promoting maturation of a technology is DOD's support for electronics and materials, and the DOE's support for the development of alternative energy technologies and large-scale energy demonstration projects.

3. **Technologies and systems for government use**

The Federal Government sometimes requires technologies and systems that have no immediate commercial application. In such cases, the Government must bear the full cost of R&D investment. Technologies that fall under these parameters would include DOD's development of military aircraft and the support of nuclear weapons development and testing. In these instances, it is in the interest of the United States to control and limit the technology's dissemination.

4. **Options for future policies**

If the Government determines that the key to addressing a certain issue is a policy path dependent on technologies that are non-existent or still in the formative stages, then it may decide to invest in R&D. By making these investments, the Government could ensure that these technologies are brought to maturity to implement the policy, or are available to reduce the impact of the policies on the economy as a whole or on a specific economic sector. Technologies developed in this way probably will not be competitive in the marketplace until regulations are implemented that make their adoption essential. At this point, industry likely would take the reins of R&D and invest in refining and making the technology more efficient and cost-effective. This type of policy-driven R&D both informs the future political debate over, and lessens the shock of, policy implementation.

Other Functions Associated with Government R&D Funding

5. **User facilities**

Once the Government determines it will support a particular area of scientific discovery and knowledge development, it may determine that the overall program will benefit from common access to expensive, and specialized equipment and expertise. A government-sponsored user facility enables many scientific teams to share equipment that no one group could afford to create and maintain. Plus, government funding allows other scientists to continually improve the capabilities of the shared resource. Examples of this approach are the NSF-supported National High Magnetic Field Laboratory and the DOE-supported high-energy accelerators at SLAC National Accelerator Laboratory and Fermilab, the Fermi National Accelerator Laboratory.

6. **Scientific workforce development**

The United States enjoys a robust cadre of trained scientists and engineers. Many completed their graduate training working on government-sponsored R&D. Although scientific and technical workforce training may not be the primary objective of government R&D, the budget and program planning process for new R&D efforts – particularly ones focused on science and discovery – can include identifying potential workforce needs as an important consideration.

7. **Critical technical advice**

When it grapples with new policies, regulations, treaties, or future technology acquisitions, the Government must have access to sound technical advice. In many cases, the Government can seek this advice from the private sector. However, there are cases where it is to the Government's advantage to have access to dedicated FFRDCs or federal laboratories, especially when industry has a vested interest in the outcome of the analysis. Although this retention of expert advice is not strictly speaking an R&D function, the Government often calls on its in-house R&D experts to fulfill this role. Examples of this kind of expertise are found among the federal and contract employees at such laboratories as the Naval Research Laboratory and the DOE National Laboratories.

8. **Testing and evaluation**

The government often must evaluate competing claims of prospective technology vendors and developers. In these cases, the Government may choose to fund – either at its own laboratories or through an independent contractor – the development and performance of tests to ascertain the qualities of prototypes and products. Testing and evaluation may also be part of the acceptance process for deliverables under other R&D contracts. In some cases, the Government funds and maintains specialized test facilities. Examples of this kind of support include White Sands Missile Range for the DOD and the EPA Test and Evaluation Center in Ohio.

Appendix II: The Dual Energy Challenges – Curbing Climate Change and Improving Energy Security

By Dan Rizza and Jane Alexander

The United States faces two major challenges in meeting today's energy demands:

- Improving energy security
- Curbing climate change caused by energy-related emissions

In order to solve these paired problems, it is important to understand the factors driving energy supply and demand and in particular, to understand the potential capabilities of new technologies to make a significant contribution to reducing energy use or increasing clean energy supply. This appendix provides additional information to the interested reader on the scope of these challenges.

The Challenge of Energy Security

The United States consumes roughly 100 quadrillion BTUs of energy annually – over 20% of global energy consumption.[19] In order to achieve energy security, the United States must have reliable access to the energy it needs at a reasonable price. The heart of this problem is that the United States currently imports roughly one-third of the energy it consumes.

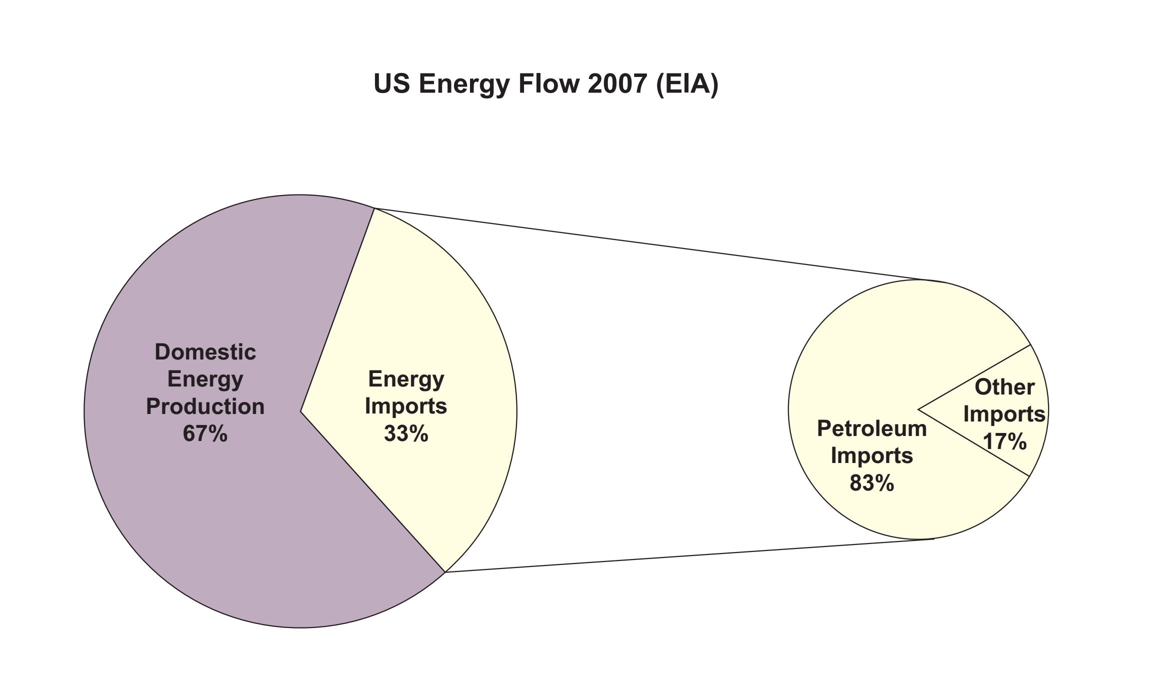

Figure AII-1. Source: Energy Information Agency (EIA) Annual Energy Review 2007

19 Energy Information Agency (EIA). *Annual Energy Review 2007*

Petroleum accounts for 83% of this imported energy; and the transportation sector accounts for approximately 69% of U.S. petroleum consumption through a combination of land vehicles (cars, trucks, buses, and trains) and air transport.

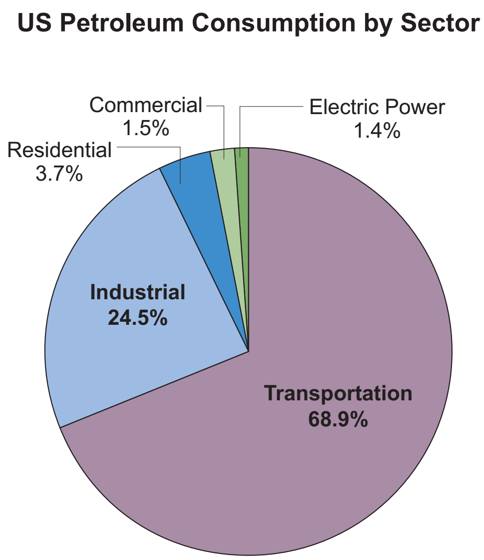

Figure AII-2. Source: Energy Information Agency (EIA) Annual Energy Review 2007

This reliance on imported energy has two negative impacts on the United States. First it adds significantly to the net trade deficit. While the total cost of energy imports varies depending on the fluctuating price of petroleum, Congressional Research Service reports that in 2008 energy-related imports made up as much as $386 billion of the $821 billion U.S. trade deficit.[20] Second, U.S. dependence on imported energy leaves the nation vulnerable to foreign pressures and manipulation. Moreover, much of the imported energy comes from countries with strained or uncertain relations with the United States. Reliance on such sources is clearly risky and a potential threat to national security. Understanding the overall picture of domestic production and utilization of petroleum is central to any effort to improve energy security.

Domestic Production and Utilization of Petroleum

Currently, the United States produces about 10% of the world's petroleum but consumes 25%[21]. Although increasing domestic production could help offset a portion of this disparity, altering consumption patterns to reduce demand – particularly in the transportation sector – will likely have an even greater impact. Lowering U.S. demand for petroleum can be done via several avenues:

20 Jackson, James K. U.S. Trade Deficit and the Impact of Changing Oil Prices. *Trade and Finance,* April 2009.

21 EIA energy brief, Aug 22, 2008

- Improving energy efficiency;
- Reducing the activities that use petroleum; and
- Shifting away from petroleum altogether by transitioning to alternative domestic energy sources.

In order to determine where the greatest opportunities lie for improvement, one need look at the details of petroleum use (see Figure AII-2.). Clearly, the focus of efforts to reduce demand needs to be the transportation sector, which currently accounts for roughly two-thirds of all petroleum use.

Alternatives for the Main Petroleum Usage Categories

The major uses of petroleum in the transportation sector break into three primary categories: air transportation, and light-duty, and heavy-duty vehicles – each having different technological implications. For example, substituting electricity for jet fuel is not feasible because energy per unit weight of batteries is not suitable for air flight. Therefore, to reduce the use of petroleum in air transportation, a substitute liquid fuel produced from a domestic feedstock is needed.

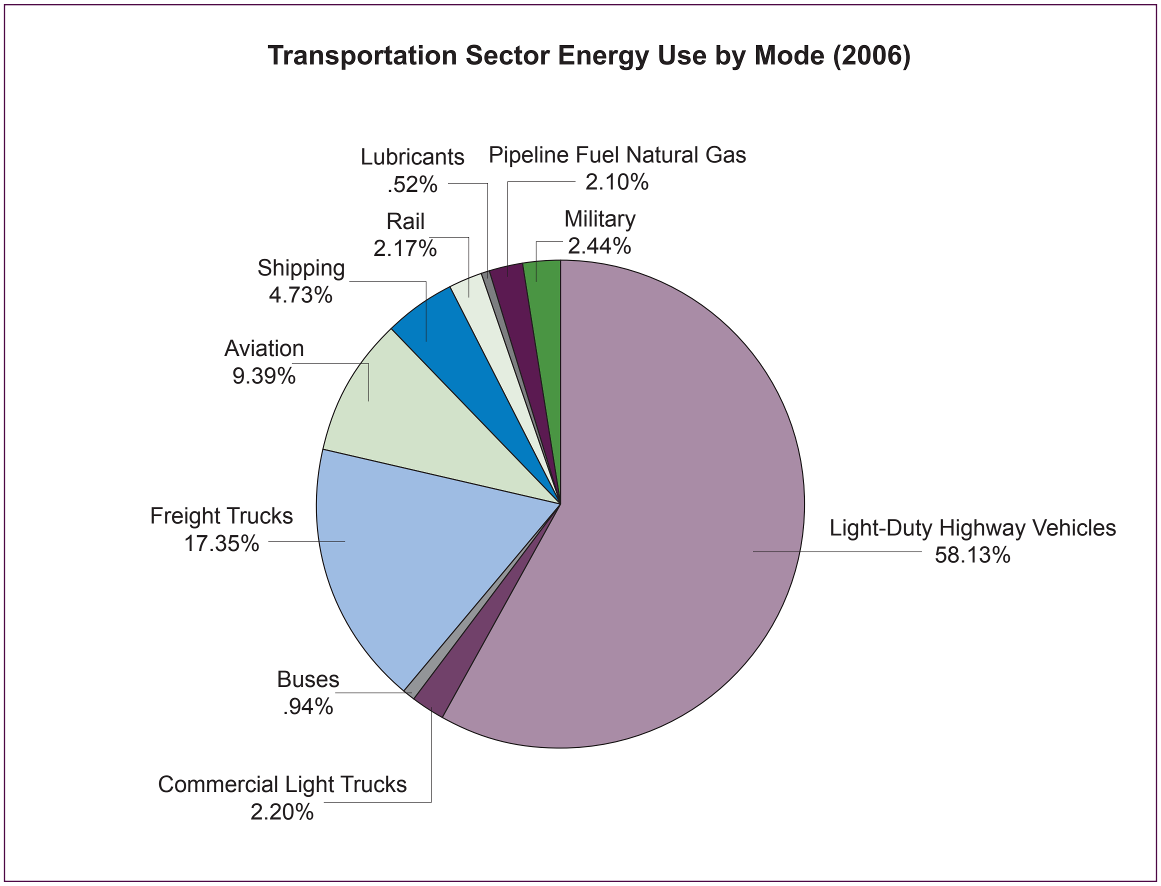

Figure AII-3. Source: Energy Information Agency (EIA) Annual Energy Outlook 2008, Table 35

Transportation sector energy use by mode (2006)	Trillion BTUs
Light-duty highway vehicles (auto, light trucks, motorcycles)	16,407.20
Freight trucks	4,892.20
Aviation	2,647.00
Shipping	1,333.40
Military	688.20
Commercial light trucks	617.90
Rail	611.40
Pipeline fuel natural gas	592.10
Buses	263.60
Lubricants	147.00
Total consumption (trillion BTUs)	28,200.00

Table AII-1. Source: EIA Annual Energy Outlook 2008, Table 35

Transportation sector energy use by type (2006)	Trillion BTUs
Motor gasoline	17,195.00
Diesel	6,182.00
Jet fuel	3,190.00
Residual fuel oil	832.00
Pipeline fuel natural gas	592.10
Lubricants	147.00
Aviation gasoline	33.00
Electricity	21.70
Compressed natural gas	20.70
Liquefied petroleum gases	17.50
Ethanol	1.30
Total consumption (trillion BTUs)	28,232.30

Table AII-2. Source: EIA Annual Energy Outlook 2008, Table 35

While ARPA-E is meeting the objectives of one mission area (energy security or climate change), it must remain mindful that it should not harm the other mission area. For example, if ARPA-E were to address jet fuel replacements, the agency would need to select approaches that are at least carbon-neutral per passenger mile compared to current jet fuel. Ideally, ARPA-E will support approaches that have positive impacts on both mission areas, while being truly transformational in one or more mission areas.

For the light-duty vehicle transportation sector, petroleum is consumed primarily in personal vehicles on trips lasting less than 40 miles. Technology options to reduce dependence on imported petroleum could include higher-efficiency vehicles, liquid fuels from domestic sources,and plug-in electric and hybrid vehicles.

Most transportation using heavy-duty vehicles is long-haul. Given the current state of battery technology and expectations for the foreseeable future, purely electric plug-in vehicles may not work for long-haul trucking. However, substitute biofuels, and synthetic fuels as well as higher-efficiency vehicles – including hybrids – are possibilities for improvements in this sector.

Summarizing the needs for technological improvements and breakthroughs to support improved energy security, the biggest needs are in the transportation sector, in particular the development of liquid fuels from domestic sources, plug-in hybrid and electric personal vehicles, and improved efficiency. These are areas in which the Department of Energy (DOE) and the Department of Transportation (DOT) have long-standing investments. The challenge for ARPA-E will be to find truly transformational opportunities in areas that have already been so thoroughly investigated.

The Challenge of Climate Change

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), issued in February, 2007, further solidified the body of research showing that human-induced (anthropogenic) greenhouse gas emissions have very likely contributed significantly to the global increase in average temperature since the mid-20th century. Rising concentrations of greenhouse gases in the atmosphere are reducing the amount of infrared radiation that passes out through the Earth's atmosphere into space, altering the Earth's energy balance and warming the planet.[22,23] While natural climate forcing certainly affects the Earth's climate, analysis of output from a suite of global climate models shows that the extent of Earth's recent warming can only be explained by including anthropogenic forcing of the Earth's climate system.[24,25] Anthropogenic greenhouse gas emissions stem primarily from burning fossil fuels, land use changes (for example, deforestation), and agriculture.[26]

22 IPCC 2007: *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Chapter 2, p. 136.

23 To learn more about the Earth's energy balance see the presentation of Dr. James G. Anderson, *The Frame and Scale of the Climate/Energy Challenge: Issues and Implications* given at the Environmental Science Seminar Series (ESSS) of the American Meteorological Society, December 18, 2007. See: http://www.ametsoc.org/atmospolicy/71218ESSS.html

24 Volcanic activity and solar radiation variability are examples of natural climate forcing. The IPCC states that models fail to reproduce observed warming when run using only natural factors in its response to frequently asked question 9.2 of its 2007 report. (IPCC 2007: *op. cit.*, FAQs, p. 120) http://ipcc-wg1.ucar.edu/wg1/FAQ/wg1_faq-9.2.html. Learn more by viewing the presentation of Dr. Caspar Ammann of NCAR at the Environmental Science Seminar Series (ESSS) of the American Meteorological Society, March 24, 2008. See http://www.ametsoc.org/atmospolicy/80324ESSS.html.

25 According to Boden, T.A., G. Marland, and R.J. Andres of the Carbon Dioxide Information Analysis Center, since 1751 humans have emitted into the atmosphere over 1200 billion metric tons of carbon dioxide (330 billion tons of carbon) from the consumption of fossil fuels and cement production - *half of this since the mid 1970s.*

26 IPCC 2007: *op. cit.*, Summary for Policy Makers, p. 2. The major fossil fuels are petroleum, natural gas and coal. In its 2007 report IPCC states "the largest growth in GHG emissions between 1970 and 2004 has come from energy supply, transport and industry, while residential and commercial buildings, forestry (including deforestation) and agriculture sectors have been growing at a lower rate."

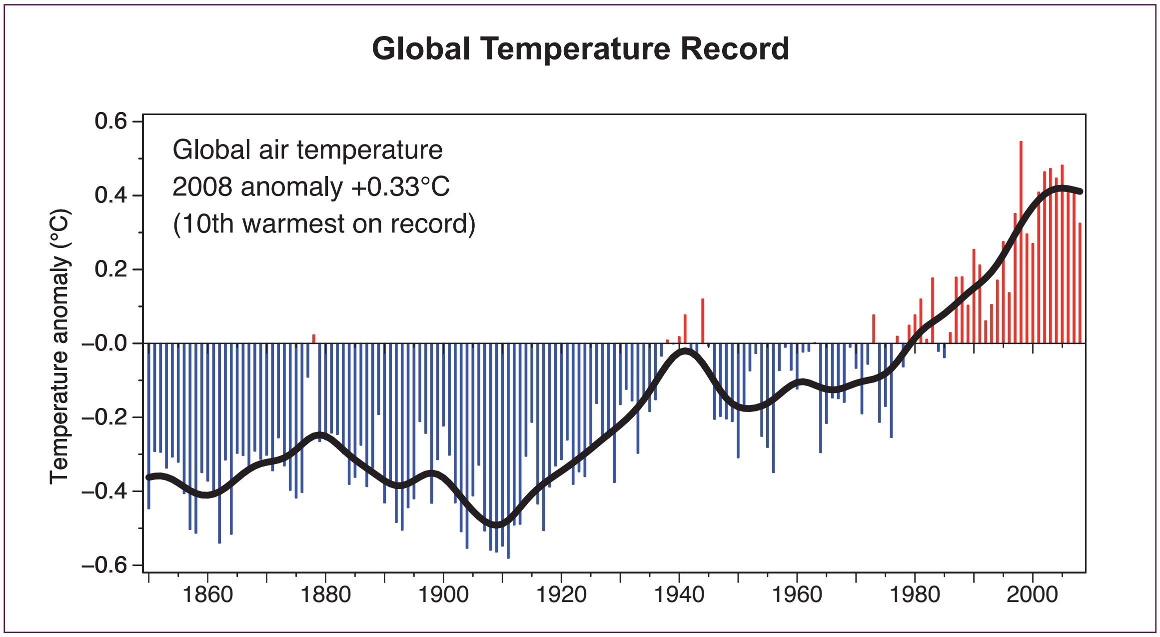

Figure AII-4. The combined global land and marine surface temperature record from 1850 to 2008. Source: The Climatic Research Unit, School of Environmental Sciences at the University of East Anglia.[27]

Carbon Dioxide: The Most Significant Greenhouse Gas

Carbon dioxide is the largest radiative forcer of all greenhouse gases (GHGs). Once emitted, it stays in the atmosphere for 100 years or longer. According to the IPCC, the combustion of fossil fuels and the processes used in cement manufacturing have produced 75% of anthropogenic CO_2 emissions since the preindustrial era. Deforestation and other land-use changes are responsible for most of the remainder.[28] In 2007, the global economy emitted about 31 billion metric tons of CO_2[29] into the atmosphere from the burning of fossil fuels and the manufacturing of cement.[30] In 2007, the CO_2 component of atmospheric concentrations was 383 parts per million (ppm), 37% above preindustrial levels.[31] Despite the dominance of CO_2 compared to other GHGs, it has contributed only about 55% of the post-industrial additional radiative forcing from all GHGs (including methane, nitrous oxide, tropospheric ozone, CFCs and others).[32,33] (Including not only CO_2 but all greenhouse gases, the atmosphere is at

27 http://www.cru.uea.ac.uk/cru/info/warming

28 IPCC 2007: op. cit., *Frequently Asked Questions,* p. 115.

29 Carbon Dioxide Information Analysis Center (CDIAC) http://cdiac.ornl.gov/ftp/trends/emissions/Preliminary_CO2_Emissions_2006_2007.xls (31 billion metric tons of CO_2 is approximately equal to 8.5 billion metric tons of carbon because 1 billion metric tons of carbon = 3.67 billion metric tons of carbon dioxide). (1 billion metric tons of carbon = 1 Gigaton (GtC) of carbon = 1 petagram (PgC) of carbon = 3.67 Gigatons of carbon dioxide)

30 Land use adds an additional 5.5 billion tons of CO_2 (1.5 GtC) of emissions for 2007, according to the Global Carbon Project.

31 *Carbon Budget 2007.* Global Carbon Project: www.globalcarbonproject.org

32 Carbon Dioxide Information Analysis Center: http://cdiac.ornl.gov/pns/current_ghg.html (Recent Greenhouse Gas Concentrations); National Oceanic and Atmospheric Administration, Earth System Research Laboratory: http://www.esrl.noaa.gov/gmd/aggi (Annual Greenhouse Gas Index); IPCC AR4 WG1 Summary for Policy Makers http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_SPM.pdf (Intergovernmental Panel on Climate Change, Working Group I)

33 Greenhouse gases besides CO_2 include methane, nitrous oxide, tropospheric ozone, CFCs, HCFCs, Halocarbons, among others.

approximately 460 ppm-CO_2-equivalent.)[34,35] Other climate forcers, such as black carbon, also warm the planet, including the Arctic. [36, 37]

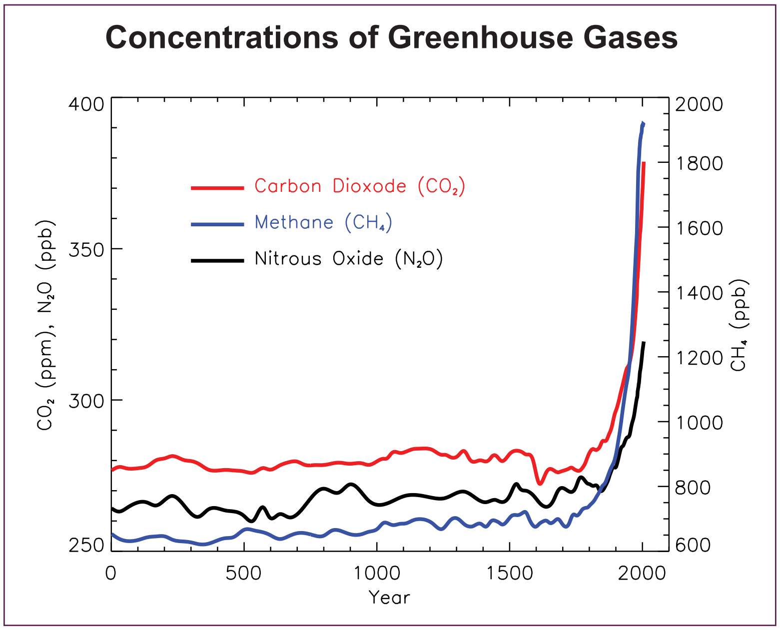

Figure AII-5. Concentrations of Greenhouse Gases from 0 to 2005[38] **Source: IPCC, 2007.**

From trace gas measurements of bubbles in Antarctic ice cores, scientists have determined that, for the past 650,000 years, the CO_2 component of greenhouse gas concentrations has ranged from 180-300 ppm[39]. Carbon dioxide is listed by the IPCC as the most significant anthropogenic radiative forcing component over the next 100 years, meaning that its accumulation in the atmosphere will alter earth's energy balance more than any other anthropogenic or natural influence.[40]

To date, earth's natural carbon cycle has lessened the impact of these emissions on the environment. Since 1959, oceans, plants, and soil have absorbed an estimated 45% of human CO_2 emissions.[41] Without the absorption of CO_2 by these natural sinks, atmospheric concentrations would be much higher. However, land and ocean sinks are absorbing less CO_2 each year.[42] As human activities produce more greenhouse gases and ocean and land sinks absorb less, the balance between sources and sinks is further strained, leading to an increase in atmospheric concentrations. In addition,

34 In other words, the concentration of CO_2 increased by about 100 ppm since pre-industrial times to about 380 ppm, but additional emissions of other greenhouse gases since pre-industrial times have also contributed about 80 ppm-CO_2-eq to total greenhouse gas concentrations. Adding the 100 ppm of CO_2 increase to the 80 ppm-CO_2-eq from other gases brings today's greenhouse gas concentration total to about 460 ppm-CO_2-eq, and additional radiative forcing from preindustrial concentrations other GHGs would make today's total CO_2-eq concentrations higher still. Sources: CDIAC, NOAA, IPCC as mentioned in earlier footnote.

35 IPCC defines carbon dioxide equivalent (CO_2-eq) as "the amount of CO_2 emission that would cause the same radiative forcing as an emitted amount of a well mixed greenhouse gas or a mixture of well mixed greenhouse gases, all multiplied with their respective GWPs to take into account the differing times they remain in the atmosphere." See http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-spm.pdf, Also see IETA: http://www.ieta.org/ieta/www/pages/index.php?IdSitePage=123

36 AMAP / Quinn et al., 2008. The Impact of Short-Lived Pollutants on Arctic Climate. AMAP *Technical Report No. 1* (2008), Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

37 IPCC 2007, *op. cit.*, Chapter 2, p. 184.

38 *ibid.*, p. 135. Atmospheric concentrations of important long-lived greenhouse gases over the last 2,000 years. Increases since about 1750 are attributed to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion air molecules, respectively, in an atmospheric sample.

39 IIPCC 2007, *op. cit.*, Frequently Asked Questions, p. 114.

40 IPCC 2007, *op. cit.*, Chapter 2, p. 136.

41 IPCC 2007, *op. cit.*, Frequently Asked Questions, p. 115.

42 Global Carbon Project reports the efficiency of natural sinks has decreased by 5% over the last 50 years and will continue to do so.

carbon dioxide is not only causing warming, but also making ocean waters more acidic as they absorb more carbon dioxide.[43] Ocean acidification makes it difficult for marine organisms, such as coral[44] and shellfish[45], to create and maintain their shells.

According to the Global Carbon Project, since 2000 the growth of atmospheric CO_2 has accelerated 33% faster than in the previous 20 years, and anthropogenic CO_2 emissions have been growing at a rate four times faster than during the previous decade (and faster than the IPCC's highest greenhouse gas emission scenario). In addition, developing countries (non Annex B Countries under terms of the Kyoto Protocol) have now become larger emitters than developed countries (Annex B). Finally, while the carbon intensity of the global economy (carbon emitted/unit of GDP) has been decreasing since 1980, from 2003 - 2005 it increased due to contributions from developing countries.

Underlying Drivers of Climate Change Long Lived

THE UNDERLYING DRIVERS OF CLIMATE CHANGE, SUCH AS POPULATION GROWTH AND PER CAPITA GDP GROWTH, WILL NOT DISAPPEAR AFTER 2030 OR EVEN 2050.

Given current energy sources, a growing global population increases the demand for energy, which in turn leads to rising CO_2 emissions. The UN's Population Division of the Department of Economic and Social Affairs estimates that world population is expected to peak at around 9.2 billion people in 2075 and remain near that level through 2300, according to medium-level projections of its 2004 report.[46] While it is estimated that China's population will peak in 2030 at around 1.5 billion people, it is expected to stabilize at 2000 levels (around 1.3 billion). India's population, however, is expected to peak in 2065 at around 1.6 billion people and level out around 1.4 billion. However, even small changes in the projected global population growth rate could lead to a situation where population does not stabilize until after this century.

One must consider not only the potential increase in population, but the desire and ability of an increasing number of people to participate in economic activity with the energy consumption approaching that of highly developed nations. Should current trends continue, ongoing economic and industrial growth in China, and other countries with rapidly modernizing economies, will contribute to steady increases in global greenhouse gas emissions.

The Energy Information Administration's (EIA) 2007 *International Energy Outlook* makes it clear that the impact of the United States and China on global emissions will be profound in the next 30 years. According to the report reference case, in 2004 the United States accounted for 4.6% of the global population and 22% of global emissions. In 2004 with 20.5% of the world's population, China accounted for 17.5% of global CO_2 emissions. According to the report's reference case projections, by 2030, the U.S. population and the country's production of greenhouse gas emissions are expected to drop to 4.5% and 18.5% of the global total respectively. While China's population is expected to decrease to 17.6% of global population, its greenhouse gas emissions are projected to increase to 26.2%

43 Caldeira, K, Wickett, ME. 2003. Anthropogenic carbon and ocean pH. *Nature* 425:365

44 O. Hoegh-Guldberg, et al. *Science* 318, 1737 (2007)

45 Miller, AW, Reynolds, AC, Sobrino, C, Riedel, GF. Shellfish Face Uncertain Future in High CO2 World: Influence of Acidification on Oyster Larvae Calcification and Growth in Estuaries. *PLoS ONE* 4(5): e5661, 2009.

46 United Nations (UN). *World Population to 2300.* New York, NY: UN, 2004.

of global emissions. China's population is expected to increase only 11% by 2030 from its 2004 level. However, its per capita energy consumption is projected to soar 121% and its per capita emissions rise 116% – compared to projected global rates of 22 and 24%, respectively.

The International Energy Agency (IEA) states that "a level of per-capita income in China and India comparable with that of the industrialized countries would, on today's model, require a level of energy use beyond the world's energy resource endowment and the absorptive capacity of the planet's ecosystem."[47] Based on 2007 EIA *International Energy Outlook* data, had the 2004 per capita consumption of China and India been at the same level as U.S. per capita consumption, then world demand for energy and world emissions would have been over 250% higher. The reference scenario of IEA's recent *World Energy Outlook* report predicts world primary energy demand (with oil as dominant fuel) will increase 45% by 2030, with India and China accounting for over half of this increased demand.[48]

Potential Scale of the Climate Problem

The impacts of climate change are already being felt in the United States[49] and elsewhere. For example, climate change is contributing to weather extremes, and more frequent wildfire and insect outbreaks. It is stressing ecosystems, putting more species in danger of extinction[50], as well as impacting agriculture, industry, and human health.[51] Warming in the Arctic is occurring more rapidly – causing summer Arctic sea ice to retreat and thin with low probability of recovery[52] and creating infrastructure problems as the Alaskan permafrost thaws, [53,54,55] impacting the lives of indigenous peoples. Additional global warming will worsen these impacts.[56]

Due to positive climatic feedback mechanisms already occurring – such as the aforementioned melting of Arctic sea ice that reduces reflective ice cover and allows sunlight to reach and warm the darker ocean waters, causing more melting, and thus more warming[57] – many scientists believe the world has little time to reverse emission trends in order to avoid worsening existing impacts, and to avoid the risk of setting Earth's system onto a warming trajectory that would be difficult to reverse, causing serious impacts.

For example, should the Greenland ice sheet disintegrate over the next few centuries, sea levels would

47 IEA ,*World Energy Outlook 2007: China and India Insights,* p. 215

48 IEA, *World Energy Outlook 2008*

49 *Global Climate Change Impacts in the United States,* Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson, (eds.). Cambridge University Press, 2009.

50 Parmesan C, Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42. To read more about which species are threatened, see the presentation of Dr. Camille Parmesan entitled *Ecosystem Health in a Climatically-Altered World – Is 'Species Rescue' Part of the Prognosis for the Future* given at the Environmental Science Seminar Series (ESSS) of the American Meteorological Society on October 10, 2008: http://www.ametsoc.org/atmospolicy/81010ESSS.html

51 IPCC 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Chapter 14: North America. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

52 International Polar Year, *Arctic sea ice will probably not recover,* February, 19, 2009. http://www.ipy.org. Arctic sea ice could recover several thousand years from now, but this is not within a timeframe relevant to today's climate problem.

53 For further information on permafrost thaw in Alaska, see Dr. Vladimir Romanovsky's essay entitled *How rapidly is permafrost changing and what are the impacts of these changes?* http://www.arctic.noaa.gov/essay_romanovsky.html

54 Arctic Climate Impact Assessment (ACIA), 2004

55 www.arcticwarming.net

56 IPCC 2007: *op. cit.*,Working Group II, Summary for Policy Makers, p18.

57 This is called the ice-albedo feedback. Learn more about Arctic sea ice levels at the National Snow and Ice Data Center (NSIDC) website: http://nsidc.org/arcticseaicenews

rise several meters[58,59]. Scientists are already observing that the Greenland ice sheet is melting faster than expected.[60] Water runoff from Greenland could alter ocean currents and raise sea levels, especially along the coasts of the northeastern United States and Canada.[61] More warming could also cause additional mountain glacier melting, further altering hydrological cycles and stressing water resources – such as in the Himalayas where glaciers are the source of water to very large populations.[62, 63] The water supplies of the western United States will also be affected as mountain snowpack declines.[64] Further warming could also increase the rate at which the large amounts of organic carbon stored in the soils and permafrost of Alaska and the rest of the northern circumpolar zone is released in the form of carbon dioxide or methane into the atmosphere as the ground thaws[65,66] – further warming the planet.

As anthropogenic atmospheric CO_2 concentrations increase, along with levels of other climate forcers such as methane, tropospheric ozone, and black carbon, so does the risk of serious economic and ecological damage in the future. The longer action to curb global warming is delayed, the more widespread the impacts of climate change will be felt - and the higher the chances will be of setting the planet onto a warming trajectory hard to reverse, making it difficult to restore a stable climate, similar to today.

IPCC models suggest that in order to stabilize the CO_2 component of atmospheric greenhouse gas concentrations at 450 ppm[67], global cumulative emissions over the 21st century may have to be reduced to about 1800 billion tons of CO_2 (490 billion tons of C)[68], which would average out to about 18 billion tons of CO_2 (4.9 billion tons of C) per year. The world is significantly above this average with 2007 carbon emissions at about 31 billion tons[69] of CO_2 (8.5 billion tons of C).[70] Given that China's

58 Dr. David Carlson, Director of the Program Office of the International Polar Year (IPY), in testimony before the U.S. Senate Foreign Relations Committee on May 5, 2009, stated that a consensus has developed among polar researchers that it is probable the Greenland ice sheet will disappear as a result of current global warming, and that it is plausible sea levels will rise one meter or more from Greenland by 2100.

59 Experts estimate that should all of Greenland melt, it could raise global mean sea level by 5-7 meters. According to the Cooperative Institute for Research in Environmental Sciences (CIRES), Greenland contains 8% of all of Earth's fresh water. See: http://cires.colorado.edu/steffen/greenland/journal/part1.html.

60 Mernild, Sebastian H., Glen E. Liston, Christopher A. Hiemstra, Konrad Steffen, Edward Hanna, Jens H. Christensen. Greenland Ice Sheet surface mass-balance modelling and freshwater flux for 2007, and in a 1995-2007 perspective. *Hydrological Processes*, 2009.

61 Hu, Aixue, Gerald Meehl, Weiqing Han, and Jianjun Yin. Transient Response of the MOC and Climate to Potential Melting of the Greenland Ice Sheet in the 21st Century. *Geophysical Research Letters,* May 29, 2009.

62 Kehrwald, N. M., L. G. Thompson, Y. Tandong, E. Mosley-Thompson, U. Schotterer, V. Alfimov, J. Beer, J. Eikenberg, and M. E. Davis (2008), Mass loss on Himalayan glacier endangers water resources, *Geophysical Research Letters,* 35, L22503, doi:10.1029/2008GL035556.

63 T. P., Barnett, Adam, J. C. & Lettenmaier, D. P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438, 303–309 (2005).

64 Mote, P. W., Hamlet, A. F., Clark, M. P. & Lettenmaier, D. P. Declining mountain snow pack in western North America. *Bulletin of the American Meteorological Society,* 86, 39–-49 (2005).

65 This study estimates the amount of organic carbon in frozen terrestrial soils and permafrost in the northern circumpolar zone: Schuur, E. A. et al.: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *BioSciences,* 58, 701–714, 2008.

66 Schuur, E. A. G. et al. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature* 459, 556–559 (2009).

67 Some scientists believe CO_2 concentrations needs to be reduced to 350 ppm "if humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted". Hansen, J., et al. "Target Atmospheric CO_2: Where Should Humanity Aim?" *The Open Atmospheric Science Journal,* Volume 2: 2008.

68 IPCC 2007: *op. cit.*, Summary for Policy Makers of Working Group I, p. 16.

69 Carbon Dioxide Information Analysis Center

70 For further discussion read Dr. Joseph Romm's blog at ClimateProgress.org

emissions have already surpassed those of the United States and will rise rapidly as China's economy grows and more of its citizens increase consumption, offsetting energy efficiency gains, there is little hope of achieving the kinds of emission reductions we need to achieve 450 ppm stabilization of atmospheric CO_2 - let alone 350 ppm - without significant new strides in renewable energy production and energy efficiency.

Need for a Long-Term Strategy

One useful way to view the climate change challenge is by using the "stabilization wedge" approach proposed by Robert Socolow and Stephen Pacala of Princeton University.[71] Socolow and Pacala describe an approach using a combination of existing technologies, each representing a piece of what is needed to achieve immediate, large overall reductions in CO_2 emissions over the next 50 years. While this approach can help to postpone near-term climate change impacts, a more long-range strategy is needed that will encourage the development of truly transformational technologies that are low-cost, non-polluting and renewable.

Society needs to deploy available non-carbon and low-carbon technologies now, but this single wave of deployment will not be enough. As the underlying drivers of the problem continue for many decades into the future, society must plan for and implement many generations of new technologies to combat the problem.

The analysis of Socolow and Pacala shows that no widespread deployment of a single technology will be sufficient to solve the climate change problem by itself. The wedge approach shows that many different technologies are necessary, as are changes in many industrial sectors, to limit the impact of climate change. Technological breakthroughs are also needed to reduce the cost of early stage deployments envisioned in the wedge approach.

The IEA states that "existing technologies can take us some of the way down the path towards more sustainable energy use…. But technological breakthroughs that change profoundly the way we produce and consume energy will almost certainly be needed to achieve a truly sustainable energy system in the long term."[72]

Worldwide Problem

World population growth paired with rising economic development will spur continued growth in annual CO_2 emissions. Although the United States and Europe are responsible for a large portion of the existing greenhouse gases in the atmosphere, nations with rapidly expanding economies and appetites for fossil fuels have become the greatest emitters of greenhouse gases.

While the United States cannot solve the climate change problem alone, there is an opportunity for the U. S. to lead a renewable revolution if it comes up with low-carbon products and processes, especially ones whose prices can compete directly with products and processes from elsewhere. At that point, the world market will absorb them and make a difference.

71 Pacala, S., and R. Socolow (2004), Stabilization wedges: Solving the climate problem for the next 50 years with current technologies, *Science*, 305, 968–972.

72 International Energy Agency (IEA), 2007. op. cit., p. 235. IEA's 2008 *World Energy Outlook* also states: "Current global trends in energy supply and consumption are patently unsustainable – environmentally, economically, and socially… Preventing catastrophic and irreversible damage to the global climate ultimately requires a major decarbonisation of the world energy resources."

Energy Security and Climate Change: A Significant Overlap

The technologies that enable the United States to achieve energy security likely overlap significantly (with a few exceptions)[73] with technologies that can help curb global warming. ARPA-E's challenge will be to develop transformational technologies that can and will have significant, large impacts on climate change and energy security. The need for multiple generations of new technologies is overwhelming if the United States is to truly address the looming crises.

73 In a few cases, efforts to achieve energy security and address climate change are not complementary. For example, the United States could exploit its existing and extensive coal reserves to achieve energy security by ramping up the generation of coal-based power that doesn't use carbon sequestration technology. An energy future based on this strategy would significantly increase, rather than lower, U.S. greenhouse gas emissions. Alternatively, the United States could lower its greenhouse gas emissions by replacing imports of petroleum with imports of biofuels. While this strategy would address climate change, it would not necessarily improve energy security.

(2) Funding.—Funding of the appointment of the distinguished scientist for the second 3-year allotment shall be determined based on the review conducted under paragraph (1).

(i) Cost Sharing.—To be eligible for assistance under this section, an appointing institution of higher education shall pay at least 50 percent of the total costs of the appointment.

(j) Authorization of Appropriations.—There are authorized to be appropriated to carry out this section—

(1) $15,000,000 for fiscal year 2008;

(2) $20,000,000 for fiscal year 2009; and

(3) $30,000,000 for fiscal year 2010.

SEC. 5012. ADVANCED RESEARCH PROJECTS AGENCY—ENERGY. 42 USC 16538.

(a) Definitions.—In this section:

(1) ARPA-E.—The term "ARPA–E" means the Advanced Research Projects Agency—Energy established by subsection (b).

(2) Director.—The term "Director" means the Director of ARPA-E appointed under subsection (d).

(3) Fund.—The term "Fund" means the Energy Transformation Acceleration Fund established under subsection (m)(1).

(b) Establishment.—There is established the Advanced Research Projects Agency—Energy within the Department to overcome the long-term and high-risk technological barriers in the development of energy technologies.

(c) Goals.—

(1) In general.—The goals of ARPA-E shall be—

(A) to enhance the economic and energy security of the United States through the development of energy technologies that result in—

(i) reductions of imports of energy from foreign sources;

(ii) reductions of energy-related emissions, including greenhouse gases; and

(iii) improvement in the energy efficiency of all economic sectors; and

(B) to ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies.

(2) Means.—ARPA-E shall achieve the goals established under paragraph (1) through energy technology projects by—

(A) identifying and promoting revolutionary advances in fundamental sciences;

(B) translating scientific discoveries and cutting-edge inventions into technological innovations; and

(C) accelerating transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty.

(d) Director.—

(1) Appointment.—There shall be in the Department of Energy a Director of ARPA-E, who shall be appointed by the President, by and with the advice and consent of the Senate. President.

(2) Qualifications.—The Director shall be an individual who, by reason of professional background and experience, is especially qualified to advise the Secretary on, and manage research programs addressing, matters pertaining to long-term

and high-risk technological barriers to the development of energy technologies.

(3) RELATIONSHIP TO SECRETARY.—The Director shall report to the Secretary.

(4) RELATIONSHIP TO OTHER PROGRAMS.—No other programs within the Department shall report to the Director.

(e) RESPONSIBILITIES.—The responsibilities of the Director shall include—

(1) approving all new programs within ARPA-E;

(2) developing funding criteria and assessing the success of programs through the establishment of technical milestones;

(3) administering the Fund through awards to institutions of higher education, companies, research foundations, trade and industry research collaborations, or consortia of such entities, which may include federally-funded research and development centers, to achieve the goals described in subsection (c) through targeted acceleration of—

(A) novel early-stage energy research with possible technology applications;

(B) development of techniques, processes, and technologies, and related testing and evaluation;

(C) research and development of manufacturing processes for novel energy technologies; and

(D) coordination with nongovernmental entities for demonstration of technologies and research applications to facilitate technology transfer; and

(4) terminating programs carried out under this section that are not achieving the goals of the programs.

(f) PERSONNEL.—

(1) PROGRAM MANAGERS.—

(A) IN GENERAL.—The Director shall designate employees to serve as program managers for each of the programs established pursuant to the responsibilities established for ARPA-E under subsection (e).

(B) RESPONSIBILITIES.—A program manager of a program shall be responsible for—

(i) establishing research and development goals for the program, including through the convening of workshops and conferring with outside experts, and publicizing the goals of the program to the public and private sectors;

(ii) soliciting applications for specific areas of particular promise, especially areas that the private sector or the Federal Government are not likely to undertake alone;

(iii) building research collaborations for carrying out the program;

(iv) selecting on the basis of merit, with advice under subsection (j) as appropriate, each of the projects to be supported under the program after considering—

(I) the novelty and scientific and technical merit of the proposed projects;

(II) the demonstrated capabilities of the applicants to successfully carry out the proposed project;

(III) the consideration by the applicant of future commercial applications of the project, including the feasibility of partnering with 1 or more commercial entities; and

(IV) such other criteria as are established by the Director;

(v) monitoring the progress of projects supported under the program; and

(vi) recommending program restructure or termination of research partnerships or whole projects.

(C) TERM.—The term of a program manager shall be 3 years and may be renewed.

(2) HIRING AND MANAGEMENT.—

(A) IN GENERAL.—The Director shall have the authority to—

(i) make appointments of scientific, engineering, and professional personnel without regard to the civil service laws; and

(ii) fix the compensation of such personnel at a rate to be determined by the Director.

(B) NUMBER.—The Director shall appoint not less than 70, and not more than 120, personnel under this section.

(C) PRIVATE RECRUITING FIRMS.—The Secretary, or the Director serving as an agent of the Secretary, may contract with private recruiting firms for the hiring of qualified technical staff to carry out this section.

(D) ADDITIONAL STAFF.—The Director may use all authorities in existence on the date of enactment of this Act that are provided to the Secretary to hire administrative, financial, and clerical staff as necessary to carry out this section.

(g) REPORTS AND ROADMAPS.—

(1) ANNUAL REPORT.—As part of the annual budget request submitted for each fiscal year, the Director shall provide to the relevant authorizing and appropriations committees of Congress a report describing projects supported by ARPA-E during the previous fiscal year.

(2) STRATEGIC VISION ROADMAP.—Not later than October 1, 2008, and October 1, 2011, the Director shall provide to the relevant authorizing and appropriations committees of Congress a roadmap describing the strategic vision that ARPA-E will use to guide the choices of ARPA-E for future technology investments over the following 3 fiscal years.

(h) COORDINATION AND NONDUPLICATION.—

(1) IN GENERAL.—To the maximum extent practicable, the Director shall ensure that the activities of ARPA-E are coordinated with, and do not duplicate the efforts of, programs and laboratories within the Department and other relevant research agencies.

(2) TECHNOLOGY TRANSFER COORDINATOR.—To the extent appropriate, the Director may coordinate technology transfer efforts with the Technology Transfer Coordinator appointed under section 1001 of the Energy Policy Act of 2005 (42 U.S.C. 16391).

(i) FEDERAL DEMONSTRATION OF TECHNOLOGIES.—The Secretary shall make information available to purchasing and procurement programs of Federal agencies regarding the potential to demonstrate technologies resulting from activities funded through ARPA-E.

(j) ADVICE.—

(1) ADVISORY COMMITTEES.—The Director may seek advice on any aspect of ARPA-E from—

(A) an existing Department of Energy advisory committee; and

(B) a new advisory committee organized to support the programs of ARPA-E and to provide advice and assistance on—

(i) specific program tasks; or

(ii) overall direction of ARPA-E.

(2) ADDITIONAL SOURCES OF ADVICE.—In carrying out this section, the Director may seek advice and review from—

(A) the President's Committee of Advisors on Science and Technology; and

(B) any professional or scientific organization with expertise in specific processes or technologies under development by ARPA-E.

(k) ARPA-E EVALUATION.—

(1) IN GENERAL.—After ARPA-E has been in operation for 4 years, the Secretary shall offer to enter into a contract with the National Academy of Sciences under which the National Academy shall conduct an evaluation of how well ARPA-E is achieving the goals and mission of ARPA-E.

(2) INCLUSIONS.—The evaluation shall include—

(A) the recommendation of the National Academy of Sciences on whether ARPA-E should be continued or terminated; and

(B) a description of lessons learned from operation of ARPA-E.

Public information.

(3) AVAILABILITY.—On completion of the evaluation, the evaluation shall be made available to Congress and the public.

(l) EXISTING AUTHORITIES.—The authorities granted by this section are—

(1) in addition to existing authorities granted to the Secretary; and

(2) are not intended to supersede or modify any existing authorities.

(m) FUNDING.—

(1) FUND.—There is established in the Treasury of the United States a fund, to be known as the "Energy Transformation Acceleration Fund", which shall be administered by the Director for the purposes of carrying out this section.

(2) AUTHORIZATION OF APPROPRIATIONS.—Subject to paragraphs (4) and (5), there are authorized to be appropriated to the Director for deposit in the Fund, without fiscal year limitation—

(A) $300,000,000 for fiscal year 2008; and

(B) such sums as are necessary for each of fiscal years 2009 and 2010.

(3) SEPARATE BUDGET AND APPROPRIATION.—

(A) BUDGET REQUEST.—The budget request for ARPA-E shall be separate from the rest of the budget of the Department.

(B) APPROPRIATIONS.—Appropriations to the Fund shall be separate and distinct from the rest of the budget for the Department.

(4) LIMITATION.—No amounts may be appropriated for ARPA-E for fiscal year 2008 unless the amount appropriated

for the activities of the Office of Science of the Department for fiscal year 2008 exceeds the amount appropriated for the Office for fiscal year 2007, as adjusted for inflation in accordance with the Consumer Price Index published by the Bureau of Labor Statistics of the Department of Labor.

(5) ALLOCATION.—Of the amounts appropriated for a fiscal year under paragraph (2)—

(A) not more than 50 percent of the amount shall be used to carry out subsection (e)(3)(D);

(B) at least 2.5 percent of the amount shall be used for technology transfer and outreach activities; and

(C) no funds may be used for construction of new buildings or facilities during the 5-year period beginning on the date of enactment of this Act.

TITLE VI—EDUCATION

SEC. 6001. FINDINGS.

20 USC 9801.

Congress makes the following findings:

(1) A well-educated population is essential to retaining America's competitiveness in the global economy.

(2) The United States needs to build on and expand the impact of existing programs by taking additional, well-coordinated steps to ensure that all students are able to obtain the knowledge the students need to obtain postsecondary education and participate successfully in the workforce or the Armed Forces.

(3) The next steps must be informed by independent information on the effectiveness of current programs in science, technology, engineering, mathematics, and critical foreign language education, and by identification of best practices that can be replicated.

(4) Teacher preparation and elementary school and secondary school programs and activities must be aligned with the requirements of the Elementary and Secondary Education Act of 1965 (20 U.S.C. 6301 et seq.) and the requirements of the Higher Education Act of 1965 (20 U.S.C. 1001 et seq.).

(5) The ever increasing knowledge and skill demands of the 21st century require that secondary school preparation and requirements be better aligned with the knowledge and skills needed to succeed in postsecondary education and the workforce, and States need better data systems to track educational achievement from prekindergarten through baccalaureate degrees.

SEC. 6002. DEFINITIONS.

20 USC 9802.

(a) ESEA DEFINITIONS.—Unless otherwise specified in this title, the terms used in this title have the meanings given the terms in section 9101 of the Elementary and Secondary Education Act of 1965 (20 U.S.C. 7801).

(b) OTHER DEFINITIONS.—In this title:

(1) CRITICAL FOREIGN LANGUAGE.—The term "critical foreign language" means a foreign language that the Secretary determines, in consultation with the heads of such Federal