TRANSFORMING U.S. ENERGY INNOVATION

EXECUTIVE SUMMARY

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ACKNOWLEDGEMENTS

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Our efforts have been greatly enriched by the time and the wisdom that our ERD3 Board has so generously provided over the course of this project.

We also thank John P. Holdren and Kelly Sims Gallagher for their invaluable guidance and assistance in the early stages of this project; Henry Lee for his thoughtful feedback and helpful suggestions throughout the project; Gregory Nemet both for his feedback on the report and for sharing his time and knowledge so generously while he was with us as a visiting scholar from January through July of 2011; Paul Friley, Tom Alfstad, and Savvas Politis at the Energy Sciences and Technology Department at Brookhaven National laboratory for their work implementing out samples in MARKAL; and Pat McLaughlin for her help with editing and organizing the publishing process, without which this report would not have been possible.

All responsibility for any errors or misjudgments rests solely with the authors.

THE ENERGY RESEARCH, DEVELOPMENT, DEMONSTRATION & DEPLOYMENT (ERD3) POLICY PROJECT

The goal of the ERD3 project, which was funded by a generous grant from the **Doris Duke Charitable Foundation**, was to produce and to promote a comprehensive set of recommendations to help the U.S. administration accelerate the development and deployment of low-carbon energy technologies.

The core members of the ERD3 project are:

Venkatesh "Venky" Narayanamurti, Co-Principal Investigator

Matthew Bunn, Co-Principal Investigator

Laura Diaz Anadon, Director of ETIP group and ERD3 Project Manager

Melissa Chan, Research Fellow (until December 2010)

Charles Jones, Research Fellow

Ruud Kempener, Research Fellow

Audrey Lee, Research Fellow

Nathaniel Logar, Research Fellow

Gabriel Chan, Research Assistant

The ERD3 project began in 2008 with three primary, and related, goals:

> (a) to develop a methodology for assessing opportunities in energy research, development, and demonstration (ERD&D) investment, and to produce a set of comprehensive recommendations for the U.S. administration's investment in ERD&D;
>
> (b) to prepare an annual analysis of and set of recommendations for the Department of Energy's ERD&D budget, including, but not limited to, climate-change-related technologies; and
>
> (c) to understand the private sector's current role in the carrying out and funding of ERD&D, and in the drawing of conclusions about effective structures of public-private undertakings, areas of opportunity, and strategies for international cooperation in energy technology innovation.

Over the past three years, the ERD3 project has worked to develop and to implement a methodology for designing an expanded portfolio of federal ERD&D activities; has investigated the role that the private sector and public-private partnerships play in energy innovation in the United States; has identified ways to improve the effectiveness of public energy innovation institutions; and has analyzed how the U.S. government could improve the effectiveness of its international collaboration efforts on energy innovation. This research was informed by interviews, surveys, modeling exercises, and literature reviews.

In addition to this report, the members of the ERD3 project evaluated the U.S. federal annual spending on energy research, development, and demonstration. The project's assessments were released with policy recommendations on how the appropriations could be improved in order to better align with the national and global need to develop and to deploy clean energy technologies. This effort built on earlier efforts of the Energy Technology Innovation Policy (ETIP) group, which has been monitoring the federal ERD&D expenditures since 1978.

The ERD3 project has benefitted from the advice of a distinguished Advisory Committee with members from academia, industry, and the nonprofit sector (listed below).

This report contains the project's final analysis and recommendations on how to transform U.S. energy innovation.

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EXECUTIVE SUMMARY

The United States and the world need a revolution in energy technology—a revolution that would improve the performance of our energy systems to face the challenges ahead. A dramatic increase in the pace of energy innovation is crucial to meet the challenges of:

- *Energy and national security,* to address the dangers of undue reliance on dwindling supplies of oil increasingly concentrated in some of the most volatile regions of the world, and to limit the connection between nuclear energy and the spread of nuclear weapons;
- *Environmental sustainability,* to reduce the wide range of environmental damages due to energy production and use, from fine particulate emissions at coal plants, to oil spills, to global climate disruption; and
- *Economic competitiveness,* to seize a significant share of the multi-trillion-dollar clean energy technology market and improve the balance of payments by increasing exports, while reducing the hundreds of billions of dollars spent every year on importing oil.

In an intensely competitive and interdependent global landscape, and in the face of large climate risks from ongoing U.S. reliance on a fossil-fuel based energy system, it is important to maintain and expand long-term investments in the energy future of the U.S. even at a time of budget stringency. It is equally necessary to think about how to improve the efficiency of those investments, through strengthening U.S. energy innovation institutions, providing expanded incentives for private-sector innovation, and seizing opportunities where international cooperation can accelerate innovation. The private sector role is key: in the United States the vast majority of the energy system is owned by private enterprises, whose innovation and technology deployment decisions drive much of the country's overall energy systems. Efficiently utilizing government investments in energy innovation requires understanding the market incentives that drive private firms to invest in advanced energy technologies, including policy stability and predictability.

The U.S. government has already launched new efforts to accelerate energy innovation. In particular, the U.S. Department of Energy is undertaking a Quadrennial Technology Review to identify the most promising opportunities and provide increased coherence and stability. Our report offers analysis and recommendations designed to accelerate the pace at which better energy technologies are discovered, developed, and deployed, and is focused in four key areas:

- Designing an expanded portfolio of federal investments in energy research, development, demonstration (ERD&D), and complementary policies to catalyze the deployment of novel energy technologies;

- Increasing incentives for private-sector innovation and strengthening federal-private energy innovation partnerships;
- Improving the management of energy innovation institutions to maximize the results of federal investments; and
- Expanding and coordinating international energy innovation cooperation to bring ideas and resources together across the globe to address these global challenges.

METHODOLOGY

For each of these separate questions, we have used a different approach. To develop recommended portfolios of federal ERD&D investments, we surveyed experts and incorporated their projections into an energy-economic model to assess key outcomes such as greenhouse gas emissions or oil imports, looking for portfolios that would offer the greatest progress against key goals for a given level of investment. This also allowed us to explore the impact of demand-side policies such as a carbon cap or a clean energy standard. The process of energy technology innovation is inherently uncertain; no one, including the surveyed experts, can predict exactly where the most important energy technology breakthroughs may arise. Hence a broad portfolio of investments is essential. Unlike many other studies, we explicitly asked the surveyed experts to assess the uncertainty in their estimates, and incorporated that uncertainty in our modeling and subsequent projections.

To assess private sector innovation, we conducted an initial pilot-scale survey of enterprises engaged in energy innovation—going well beyond previously available data and surveys—and studied partnerships between private firms and the U.S. Department of Energy (DOE) to explore how they might be made more effective.

To examine approaches to managing federal energy innovation institutions, we employed a case-study approach (combined with the experience of some of the actors managing such institutions), looking in depth at the National Renewable Energy Laboratory (NREL) and the Semiconductor Research Corporation (SRC) to draw upon lessons learned.

To explore international cooperation on energy innovation (which we define as including ERD&D and deployment (ERD3)), we developed a number of datasets on current and past collaborations (ranging from energy publications with international authors to joint international energy private sector ventures), examined the state-directed ERD3 investments of major emerging economies, and investigated current U.S. government approaches to international ERD3 cooperation and how they might be improved.

DESIGNING A PORTFOLIO OF FEDERAL ENERGY INNOVATION INVESTMENTS

FINDINGS

> *Finding*: Experts in a broad range of energy technology fields recommend increases of a factor of 3–10 depending on the area in federal research, development, and demonstration investments.

We conducted expert elicitations for four energy supply technology areas (nuclear energy, bio-energy, fossil energy with and without carbon capture and sequestration, and solar photovoltaic (PV) energy), one enabling technology area (utility-scale energy storage), and two key areas of energy efficiency (buildings and vehicles). Experts in each of the technology areas covered recommended large increases in federal ERD&D investments. The average recommended increases over fiscal year (FY) 2009 appropriations ranged from 186% for solar photovoltaic to 963% for utility-scale storage (where the base for comparison is small and the potential is large). In absolute terms, the average recommended increases in spending ranged from $221 million per year for storage to $1.65 billion per year for fossil energy. See Table ES-1. As we discuss later, experts also expressed the opinion that there are points of diminishing returns for investments in each technology—that increasing funds well beyond this particular amount in the short term may not result in significant benefits. Current federal energy ERD&D investments, however, are well below what the experts recommend.

Technology	2009 spending (million $)	2009 ARRA spending (million $)	Average recommended (million $)	Average increase over 2009 recommended by experts in %	Absolute increase over 2009 in $million
Bioenergy	214	777	682	219%	468
Energy storage	23	185	244	963%	221
Nuclear	466	0	1,833	293%	1,367
Fossil	701	3,390	2,354	236%	1,653
Solar PV	143	86	409	186%	266
Vehicles	432	2,839	2,050	375%	1,618
Buildings	144	319	678	371%	534
Total of technologies studied	**2,123**	**7,596**	**8,251**	**289%**	**6,128**

TABLE ES-1. Expert recommended RD&D spending and 2009 federal spending, per technology area (or industry).

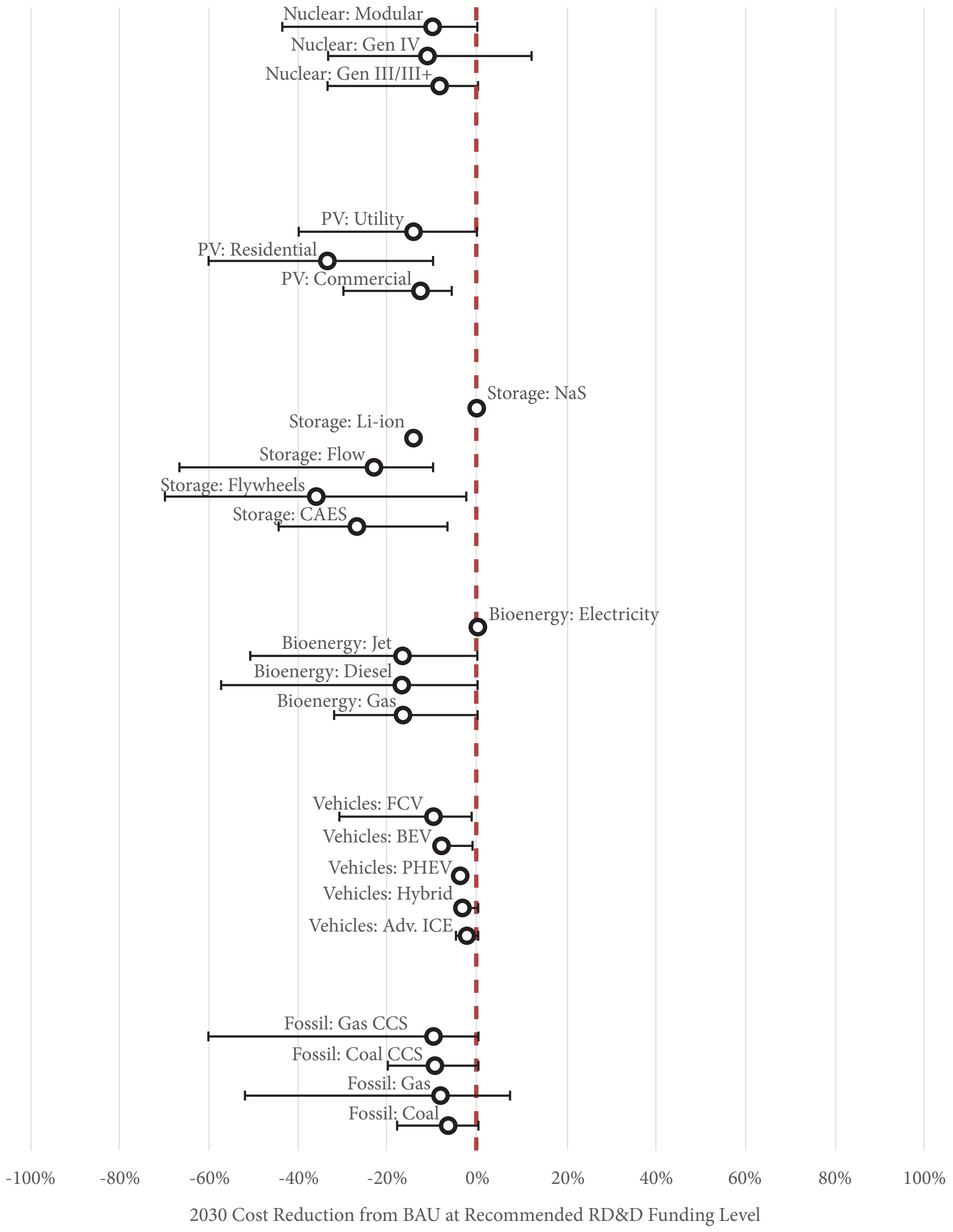


FIGURE ES-1. Range of median cost reduction per technology predicted by each expert under his or her recommended RD&D spending per industry. Costs cover overnight capital costs for SMR, Generation IV, and Generation III/III+ nuclear power plants; overnight capital costs for grid level energy storage technologies; production costs for biomass-based electricity ($/kWh) and substitutes for jet fuel, diesel, and gasoline ($/gallon); unit costs for advanced ICE, hybrid, plug-in hybrid, electric, and fuel cell vehicles ($/unit); overnight capital costs of coal and natural gas power plants with and without CCS ($/kW); and module costs for residential, commercial, and utility scale PV panels ($/kW).

As mentioned earlier, in spite of U.S. fiscal challenges, investments today are essential building blocks for future growth and prosperity. Good mechanisms need to be in place to make decisions about investments, and also to find avenues for paying for essential long-term investments like those for ERD&D. This report aims at beginning to explore those mechanisms.

> *Finding*: Experts in most of the technology areas surveyed believe that federal energy innovation investments, at the levels they recommend, would lead to substantial improvements in performance and reductions in cost by 2030.

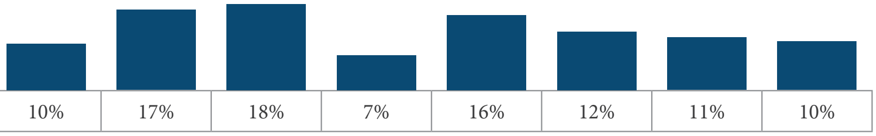
Our surveys asked experts to estimate the cost and performance that technologies in their area would be likely to achieve by 2030 if federal ERD&D investments continued at current levels, and at three levels of potential increased investment. For each technology area and funding level, experts estimated a range of cost and performance improvements that could be achieved over two decades, and judged the uncertainty bounds in those estimates.

For most technologies, the experts projected greater improvements in cost and performance by 2030 with increasing levels of federal ERD&D investments. Figure ES-1 shows the experts' median projections of the additional cost reduction that would result from their recommended ERD&D investments compared to maintaining current levels of federal investment. The figure also shows the range of opinion among the experts surveyed. The median of experts' estimated cost reduction over the cost under a business-as-usual (BAU) ERD&D funding scenario in 2030 ranged from no cost reduction in the case of sodium sulfur batteries (for which only a small number of experts provided estimates), to around 35% in the case of residential-scale solar PV and flywheel energy storage technologies. The cost reduction catalyzed by federal ERD&D funding beyond the BAU scenario is estimated the lowest for vehicle technologies, ranging from a 2% cost reduction for advanced internal combustion engine (ICE) vehicles to a 10% cost reduction for fuel cell vehicles (although this may reflect a judgment that investments by private firms, rather than federal spending, will be the major driver of improvement in vehicle technologies.)

> *Finding*: The surveyed experts recommend a portfolio approach within their technology areas, with investments spread across a range of technologies and a range of technology innovation stages (from basic research to large-scale technology demonstrations).

Within each of the seven technology areas, experts generally recommended supporting a range of technologies. For example, in the case of solar PV, experts recommended funding crystalline silicon, thin film, concentrator, excitonic, and novel high-efficiency technologies (among others) but focused mainly on thin film, concentrator, and novel high-efficiency technologies (see Figure ES-2). Experts also recommended funding efforts across different stages of technology development. In this solar PV example, the average allocation of funding from experts across basic research, applied research, experiments and pilots, and commercial demonstration was 27%, 37%, 25%, and 11%, respectively.

	Crystalline Si	Thin Film	Concentrator	Excitonic	Novel high-efficiency	Inverter	Systems Engineering	Other
Basic Research	2.4%	5.1%	3.6%	3.2%	6.6%	2.8%	1.4%	2.2%
Applied Research	5.5%	6.1%	5.4%	2.2%	5.6%	4.8%	4.4%	3.0%
Experiments and Pilots	2.5%	4.3%	5.1%	1.3%	2.5%	3.4%	3.5%	2.2%
Commercial Demonstration	0.5%	1.4%	3.5%	0.6%	1.1%	1.3%	1.5%	1.5%



Total	10%	17%	18%	7%	16%	12%	11%	10%

FIGURE ES-2. Average allocation of recommended annual federal solar PV technology RD&D budget for 2010-2030 (percentage of total). The percentages may not add to 100% due to rounding.

> *Finding*: Experts in all technology areas expected decreasing marginal returns from federal ERD&D investments in terms of both improved technology costs and performance for very large ERD&D funding increases. These are further reflected in decreasing marginal returns for CO_2 emissions under no policy, CO_2 allowance price reductions under a CO_2 cap-and-trade program, and clean energy standard (CES) credit prices under a power sector CES, illustrated by the energy system modeling results.

Experts generally expected ERD&D increases over current funding levels to lead to cost reductions over a BAU federal ERD&D funding scenario. However, when asked about the impact of a federal ERD&D budget ten times larger than the BAU scenario, almost all experts expected less progress per dollar invested.

Figure ES-3 shows that decreasing marginal returns to ERD&D investment occur when consumer surplus increases resulting from different levels of RD&D funding under the CO2 cap policy scenario (Figure ES-3). The median benefits in investing in RD&D at the full recommended level compared to the BAU level are significant, especially by 2050, though the uncertainties are large. The median result shows that increasing RD&D funding from the BAU to the FULL scenario under a CO2 cap policy results in an increase in consumer surplus in 2050 of about $35 per dollar invested in energy RD&D. Note that, as a measure of the impact of RD&D, consumer surplus is a metric that encompasses more factors than other studies measuring the returns to RD&D, but does not consider the opportunity cost of investing the energy RD&D funds elsewhere in the economy. However, in our models, based on the experts' projections, dramatic further expansions of RD&D beyond the recommended level would offer little benefit.

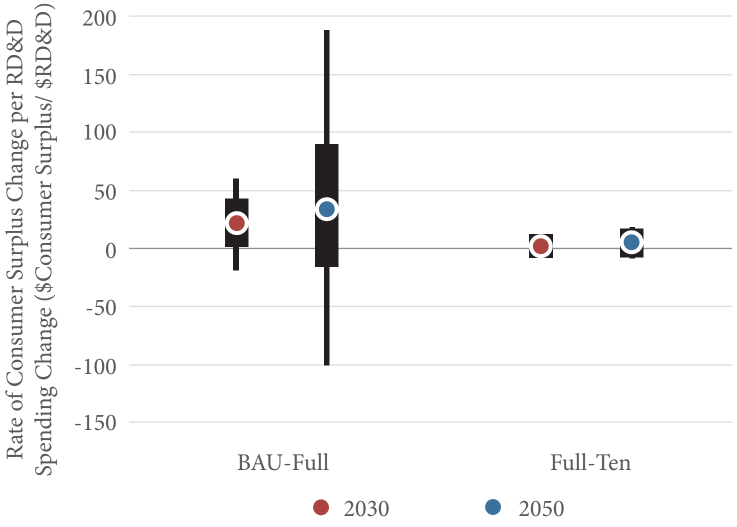


FIGURE ES-3. Average increase in consumer surplus per $RD&D invested when comparing $MFULLCO_2$ with $MBAUCO_2$ and $MTENCO_2$ with $MFULLCO_2$ in 2030 and 2050. The dot corresponds to the 50th percentile, the black rectangle encompasses the 25th and 75th percentiles, and the line encompasses the 5th and 95th percentiles.

> *Finding*: It is very unlikely that the goal of reducing carbon dioxide emissions by 83% below 2005 levels by 2050 can be met without both increased ERD&D investments and policies that price carbon emissions (along with sector-specific demand-side policies) to create strong incentives for the private sector to develop and deploy carbon-reduction technologies.

Modeling results using the technology cost and performance inputs from the experts indicate that, without new demand-side (or deployment) policies—such as an economy-wide CO_2 cap-and-trade program or sectoral policies like a power sector clean energy standard—ERD&D investments are exceptionally unlikely to lead to CO_2 emissions reductions from the U.S. energy sector consistent with the goal of limiting global average temperature rise to about 2°C. An 83% reduction in greenhouse gas emissions when compared to 2005 levels would require emissions in 2050 to be around one billion metric tons of CO_2 or equivalent per year (U.S. greenhouse gas emissions in 2005 were 6.1 billion metric tons). As shown in Figure ES-3, in our models, neither a BAU scenario of federal funding ERD&D for the seven areas covered (around $2.1 billion per year), nor a 23- to 49-fold increase (between $49 billion and $82 billion), even under optimistic technology assumptions, have any significant chance of achieving this level of CO_2 emissions without substantial demand-side policies. In these models, projections from the "middle of the road" experts suggest that even large increases in ERD&D funding, in the absence of any price on carbon, still lead to a roughly 95% probability that emissions in 2050 would be greater than those in 2010, far from the goal of more than five-fold reductions. The uncertainty shown in Figure ES-4 only includes the experts' estimates of the uncertainty around the cost and performance of the seven technology areas covered in our surveys, not the myriad other factors that will affect U.S. emissions between now and 2050.

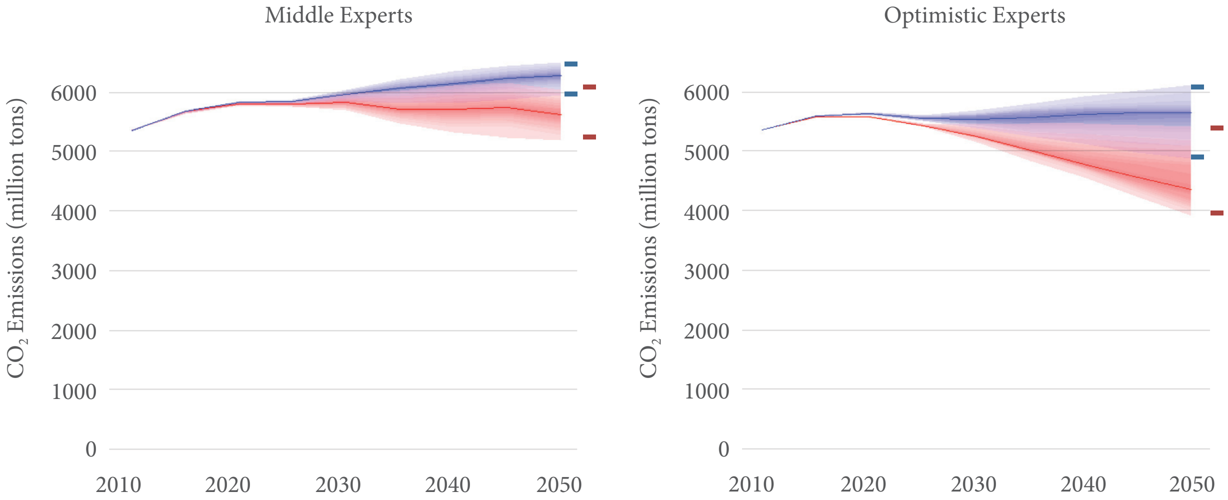


FIGURE ES-4. U.S. energy-related CO_2 emissions under (a) business-as-usual federal energy RD&D investment and no additional demand-side policies (blue) and (b) ten times the experts' average recommended federal energy RD&D investments (somewhere between $49 and $82 billion/year) (red), with no additional demand-side policies, using "middle of the road" and "optimistic" experts' technology cost projections. Note that optimistic experts were optimistic about technological progress in general, and not necessarily optimistic about the effects of RD&D.

Nevertheless, it is clear that necessary ERD&D investments must be complemented with demand-side policies to encourage widespread deployment of new energy technologies.

> *Finding*: The technology improvements projected by the surveyed experts from their recommended ERD&D investments would probably lead to significant, but not dramatic, improvements in the cost and feasibility of fueling a growing U.S. economy while meeting targets for reduced greenhouse gas emissions or oil imports.

Our economic modeling suggests that an investment of a few extra billion dollars a year today could develop technologies that could save the economy over a hundred billion dollars a year by 2050, in scenarios where there are stringent policies limiting how much carbon can be emitted. In our models, a robust ERD&D investment reduces the total cost of the U.S. energy system, expands consumer surplus, and reduces the carbon prices needed to meet a tight cap on carbon emissions. As Figure ES-5 shows, if the projections of the middle-of-the-road technology experts prove to be correct, expanding ERD&D from the BAU level to the full recommended level would reduce carbon prices by over $30 per ton, saving some $30 billion a year in 2050 for those purchasing emission allowances. Under the optimistic technology assumptions, the CO_2 price also declines with higher levels of RD&D funding, but the uncertainty in the price also decreases.

It is important to note that the modeling did not incorporate the results of the expanded private-sector investments in clean energy innovation that would be provoked by a price on carbon emissions or a clean energy standard due to the lack of empirical data on the size of this effect. Private sector innovation is likely to invent new approaches that make complying with stringent carbon policies cheaper than it appears to be in our models. In addition, the modeling did not include benefits that may occur after 2050, when novel technology may have the largest impact on controlling mitigation costs.

> *Finding*: The optimal level of RD&D for many technology areas is highly contingent on adopted policies, which means that having a balanced portfolio across different technology options is very important.

We sought to develop optimized RD&D portfolios by relating projections of future technology costs (from experts' surveys) and resulting economic benefits (from the energy system modeling results) to RD&D portfolios. Optimized RD&D portfolios among six of the seven technology areas are shown in Figure ES-6 at two total budget levels ($5 billion, left; $7.5 billion, right) for three policy scenarios: no climate policy, CO_2 cap and trade, and standards-based sectoral policy (note that the $5 billion and $7.5 billion figures are for these particular six technologies, corresponding to substantially larger ERD&D investments for a complete portfolio of energy technologies). In our modeling, we sought to optimize the three policy scenarios using different outcome metrics: CO_2 emissions, CO_2 allowance prices, CES credit prices, and consumer and producer surplus. Figure ES-6 reveals that investments in some technologies are much more important in some policy scenarios than in others. Given the large uncertainties in both future policies and future progress in each technology, investment in a broad

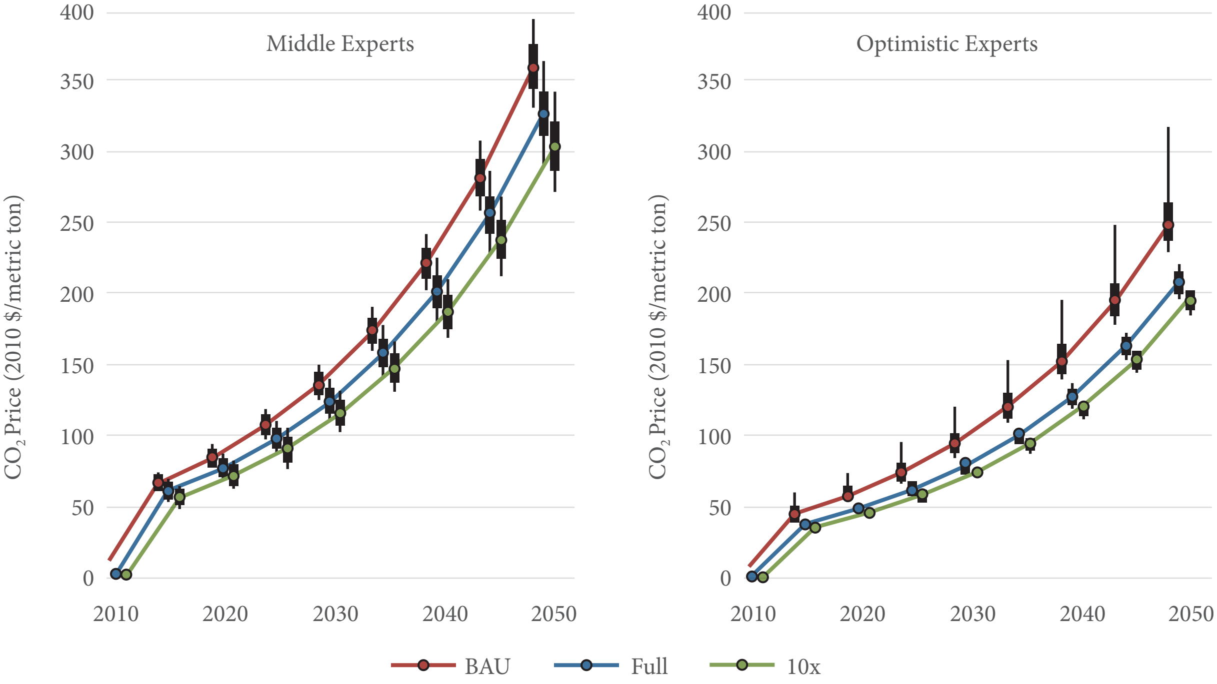


FIGURE ES-5. Trajectory of CO_2 prices ($/metric ton of CO_2) under a CO_2 cap limiting emissions to 83% of 2005 levels in 2050, with no international offsets (note that this is a very stringent policy). Three RD&D funding scenarios are shown—business-as-usual level (red), full recommended level (blue), and ten times the recommended level (green). The "middle-of-the-road" (left) and "optimistic" (right) technology assumptions are compared. The dot corresponds to the 50th percentile, the black rectangle encompasses the 25th and 75th percentiles, and the line encompasses the 5th and 95th percentiles.

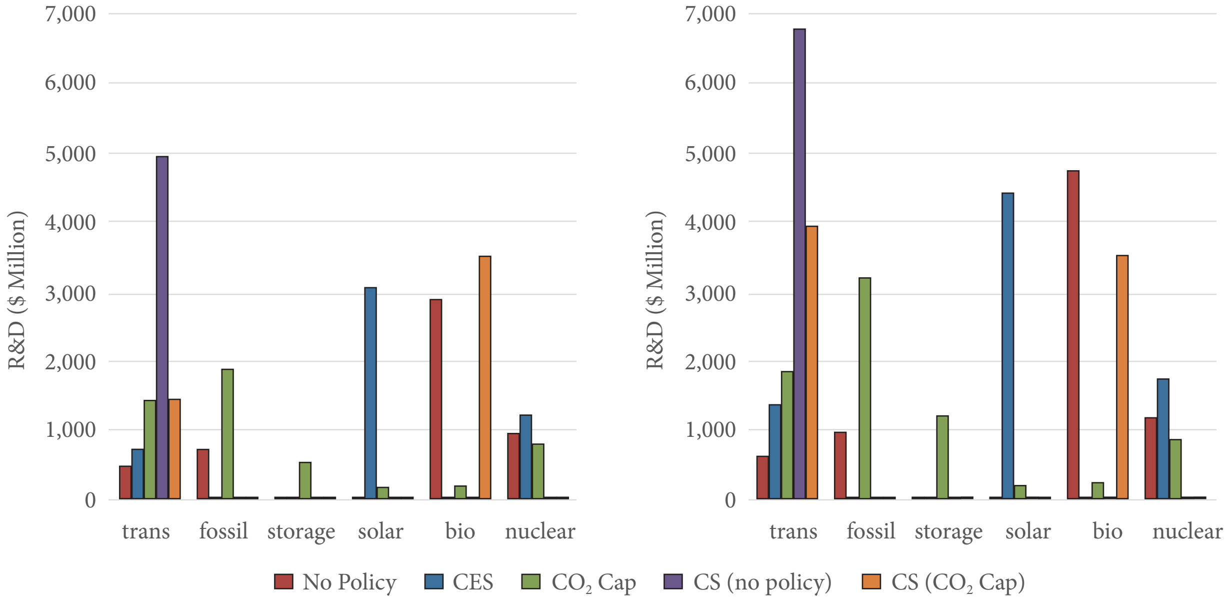


FIGURE ES-6. Optimized budget allocation under different scenarios: no policy optimized for total CO_2 emissions), standards policy (CES) optimized for CES credit price, CO_2 cap and trade (CO_2 cap) optimized for CO_2 price, no policy optimized for consumer and producer surplus (CS (no policy)), and CO_2 cap and trade optimized for consumer and producer surplus (CS (CO_2 cap)). The left figure optimizes in these scenarios under a $5 billion budget and the right figure optimizes the same scenarios under a $7.5 billion budget.

portfolio of ERD&D would provide more confidence in producing substantial results than attempting to pick a few winning technologies.

RECOMMENDATIONS

> *Recommendation*: We recommend that the U.S. federal government increase its annual investment in ERD&D to $10.0 billion, a 92% increase over the FY 2009 appropriations. This increase should proceed at the maximum rate consistent with efficient expenditure of the funds.

The combination of the technology experts' recommendations and our energy-economic modeling (which incorporates the experts' estimates of the uncertainty around the technical outcomes of those investments), suggests that $5.2 billion (2.5 times FY2009 appropriations) in ERD&D funding is necessary for the seven technology areas covered in this report. Recommended increases in funding for Basic Energy Sciences, ARPA-E, and the other technology areas not covered by our expert elicitations (based on a review of other analyses of these programs) total approximately $4.8 billion, a 40% increase from FY 2009 levels, excluding "environmental and biological R&D." We based our recommended allocation (see Table ES-2) on an analysis of technology deployment under different RD&D budget levels and on an optimization of RD&D allocation under different policy scenarios.

While the United States faces a period of severe budget stringency, such long-term investments in the U.S. energy future must not be sacrificed. There are a variety of options for raising additional funds for ERD&D outside the usual appropriations process, some of which have been used with success in the past, as described in a recent report of the President's Council of Advisors on Science and Technology, and these should be explored.

> *Recommendation*: This increased investment should be targeted at a broad portfolio of different technologies and at different stages of technology development, from basic research to large-scale technology demonstrations, implemented by a portfolio of different institutions appropriate for the different stages of innovation.

Tables ES-2 and ES-3 shows our recommended federal ERD&D investment portfolio compared to the FY 2009 budget. The recommendations in Table ES-2 are based on our expert surveys and modeling, combining the experts' recommendations with analyses of which investments offer the greatest returns in terms of reducing CO_2 emissions and oil imports in cases with no new carbon policies or sectoral policies, or the greatest contributions to reducing CO_2 emissions allowance prices in scenarios with a CO_2 cap-and-trade policy. The recommendation to increase funding for DOE's Basic Energy Sciences (BES) program in Table ES-3 from $1.5 billion in 2009 to $2.4 billion going forward

DOE program	FY 2009 appr.	Mean of experts (std. dev.)	Median of experts	Min of experts	Max of experts	Middle expert	Optim. expert	Pessim. expert	ERD3 recs.	Percent change over FY 2009 appr.
Bio-energy	214	680 (286)	640	300	1,000	300	600	680	680	218%
Energy storage	23[a]	240 (391)	120	50	2,000	103	128	103	240	943%
Nuclear	466	1800 (1,397)	1,200	800	8,000	1,200	8,000	1,200	1,200	158%
Fossil and CCS	701	2300 (1,980)	2,000	600	7,500	1,550	1,550	7,500	1,000	43%
Buildings	144	680 (315)	700	200	1,000	900	1,000	500	680	372%
Vehicles (inc. fuel cells)	432	2050 (3,050)	1,000	400	10,000	650	1,000	650	1,000	131%
Solar PV	143	337 (226)	300	200	1,000	200	500	300	400	180%
Total	2,123	8,159	5,960	2,350	29,500	4,903	12,778	10,933	5,200	145%

[a] This includes FY 2009 appropriations for grid-scale storage, which were a total of $6 million, and storage funding through ARPA-E.

TABLE ES-2. Summary information for areas covered by elicitations. From left to right: FY 2009 appropriations from DOE; statistics of the RD&D recommendations of experts in each technology area (mean and standard deviation, median value, maximum value, and minimum value); recommended values of the experts chosen as "middle of the road", "optimistic," and "pessimistic;" recommendations from this report; and percentage change in recommendations over FY 2009 appropriations. All numbers are in millions U.S.2010$.

is driven by the large known benefits of basic research both in terms of spillovers to various technology areas and in terms of training a scientifically capable workforce that can then work in the private sector. Given the large benefits of basic research, in two to five years it would become important to reconsider an additional increase for the BES program.

Table ES-2 shows that while the largest absolute recommended investments would go to nuclear, vehicles, and fossil and CCS (these technologies are capital intensive and some of them are closer to commercialization), the largest increases in terms of percentage change would go to energy storage, buildings, bioenergy, and solar PV. Funding for fossil and CCS should probably be increased further if policymakers do not expect nuclear energy expansion. If the U.S. shale gas industry develops as quickly as some predict, and if gas prices remain low for the next 5-10 years, the U.S. government would need to consider reassessing its investment portfolio, since low-carbon technologies in the electricity sector would have to compete against gas—a cheap and flexible incumbent under this scenario.

Program		FY 2009 appropriation	FY 2012 request	ERD3 recommendation	Percentage change over FY 2012 Request
Applied RD&D programs not covered by elicitations	**Wind**	79	127	127	0%
	Non-PV solar[a]	29	120	120	0%
	Geothermal	43	102	102	0%
	Water power	49	39	39	0%
	Industry	94	320	320	0%
	Transmission and distribution (exc. storage)	117	151	233	55%
	Program direction[b]	371	467	500[c]	7%
ARPA-E		389[d]	550	600	9%
Basic Energy Sciences		1,536	1,985	2,400	21%
Fusion		380	400	400	0%
TOTAL		3,087	4,259	4,841	14%

[a] Includes: concentrating solar power ($50 million), systems integration, and market transformation (standards, operability, training).

[b] Includes direction for EERE, FE, NE, and OE corresponding to RD&D budgets as shown in Gallagher & Anadon (2011).

[c] This value is a placeholder. We are unsure of the economies of scale involved in increasing the size of the research pro grams. Therefore we tentatively recommend an increase over the FY 2012, although this amount should be crafted.

[d] Funding for ARPA-E in 2009 did not come from the normal appropriations process. Instead it came from the American Reinvestment and Recovery Act of 2009, also known as the stimulus package.

TABLE ES-3. Summary of FY 2009 appropriations, FY 2012 request, ERD3 recommendation, and percentage change of recommendation over the FY 2012 request for applied RD&D programs not covered by the elicitations, ARPA-E, Basic Energy Sciences, and Fusion.

We also recommend investing in a portfolio of different technological approaches and stages of innovation within each technology area. Figure ES-2, as an example, showed the experts' recommendations across technological approaches and innovation stages for solar PV. (Similar figures for other technologies are provided in the Chapter 2 Appendix.)

> *Recommendation*: As soon as possible, the U.S. government should put in place policies that have the effect of creating a substantial price on carbon emissions (either through a cap-and-trade system or through a tax on greenhouse gas emissions) to increase incentives for the private sector to invest in clean energy innovation and to encourage large-scale deployment of clean energy technologies. In addition, the U.S. government as well as state and local governments, should adopt a range of sector-specific policies to overcome market failures that are limiting the deployment of energy efficiency and clean-energy technologies as part of a coordinated energy strategy.

As previously indicated, large increases in ERD&D alone are very unlikely to result in the emissions reductions needed to meet climate mitigation goals. Increased ERD&D investments must be complemented by policies that reflect the CO_2 emissions reduction benefits of low-carbon technologies and enable them to compete in the marketplace earlier. Although economy-wide policies such as a cap or a tax on CO_2 emissions would be the most cost-effective approach, this report also considers a clean energy standard such as that proposed by President Obama, as well as vehicle fuel efficiency and commercial buildings standards that go beyond those in place today.

In addition, other market failures will require other policies to address them. In the buildings sector, for example, it is often the case that the business or unit that would get the benefit of lower energy bills is not the same as the one paying the cost of more expensive, energy-efficient designs – one reason why even efficiency measures that would pay for themselves do not get built. Similarly, consumers purchasing energy-efficient products often have insufficient information or expect very short payback times, limiting the adoption of more energy-efficient appliances and vehicles. Labeling, performance standards, and other sector-specific policies will be needed to overcome these barriers.

> *Recommendation*: The U.S. government should match its ERD&D programs and deployment programs to maximize the effectiveness of these policies in leading to large-scale deployment of improved energy technologies.

Currently, the U.S. government is making large investments in deployment policies ranging from tax subsidies to loan guarantees, often with little coordination with energy research and development programs, and using efficiency or other standards (e.g., vehicle economy standards). To maximize the contribution of federal investments and standards to accelerating energy innovation, these efforts should be closely coordinated, with targeted and appropriate support for each phase of innovation from basic research to initial deployment. Federal support should be phased out as technologies become commercially viable, rather than continuing indefinitely. To enable the phase down of government support for programs or specific projects, the U.S. government should have clear goals and mechanisms to collect and evaluate information about the progress and contribution of projects and technologies from the start. Support programs can also be designed to decrease gradually over time and to include covenants that allow for program changes based on new information.

Increasing Incentives for Private Sector Innovation

Findings

> *Finding*: Private sector investments and approaches are critical to energy innovation in the United States.

Though the Department of Energy is the largest single investor in energy technology innovation, the private sector collectively funds and carries out the majority of ERD&D in the United States. New energy technologies can only make significant contributions to the major energy challenges if they are adopted on a broad scale by the private sector. From the information available on private-sector investments in ERD&D (which is limited to utilities and oil companies) it would seem that these investments are low compared to energy expenditures and to R&D in other industries. Government policies that shape private sector incentives for energy innovation investments are particularly important in determining the pace at which new energy technologies will be developed and deployed. The long-term stability and predictability that private sector actors need to make investments is currently lacking.

> *Finding*: Previously available data on private sector energy innovation are insufficient as a basis for policy decisions.

Data on private sector energy innovation are limited, incomplete, and superficial. The surveys of energy innovation performed for the National Science Foundation include only a little over 100 of the largest firms, which collectively invest a total of about $3 billion per year in ERD&D. These surveys do not provide the information needed to understand ERD&D investment beyond these largest firms, or to identify funding gaps by industry sector. Estimates based on venture capital spending for new energy startup companies do not distinguish between research and development and other spending by new ventures. No data source offers detailed information on the key drivers of private sector energy innovation decisions or on the role government policies play in shaping them.

> *Finding*: Private sector energy innovation activities are more widespread than previously understood.

The pilot-scale survey performed for this report provides a lower-bound estimate that at least 2.4% (± 1.3%) of the ten million non-farm business establishments in the United States (about 240,000 business establishments) are involved in energy technology innovation. (The true figure is very likely higher than this lower bound, which assumes that the rate of energy innovation among non-respondent firms is zero.) These establishments cover the spectrum from small start-ups to massive multinational corporations. A larger survey would be very useful to provide estimates of total private sector ERD&D investment by industry sector, and to help identify trends by industry, but total private ERD&D investment is certain to be larger than previously known, although still low compared to the technology opportunities and society's need for improved energy technologies.

> *Finding*: **Costs are more important than other factors in promoting private sector decisions to invest in energy innovation. Lack of market demand and specific innovation process issues are also important barriers.**

Firms react to price signals by innovating and shifting their investments. The survey of energy innovation in U.S. businesses revealed that cost-related issues, most importantly energy prices, are the most important drivers of energy innovation. Market opportunities and market-creation policies also drive innovation. Private-sector respondents often cited the absence of market opportunities as a barrier to innovation in new energy technologies. Along with poorly-functioning markets, the difficulties and uncertainties inherent in the innovation process are the most commonly mentioned barriers to investing in innovation.

> *Finding*: **Private firms are overwhelmingly focused on short-term returns in making their energy innovation investments.**

Many of the energy innovators participating in the survey do not formally measure the economic impacts of their energy innovation investments. Of those that do, two-thirds expected to recoup investments in only two to three years. For a large fraction of the establishments engaged in energy innovation, there appears to be little room for long-term investment—reinforcing the rationale for the U.S. government to make long-term investments toward improved energy technologies for the long haul. As mentioned earlier, the U.S. energy system is owned by private firms, that have profit-making (and not the provision of public good) as their main objective. Thus, firms will not invest in developing or deploying new energy technologies contributing to security, competitiveness, and environmental goals unless government policies structure market incentives so that they see prospects for creating a business around these technologies.

> *Finding*: **Government, academia, and the national labs play a major role in shaping private sector energy innovation decisions.**

Participants in the survey cited government, academia, and the national labs as important sources of funding, information, and innovation. On average, they report that 25% of the funding for the ERD&D work they do comes from the government, and government grants and contracts are the next most important drivers of innovation after costs. Some 60% of firms use government or university information to make their own investment decisions. As sources of innovation, 65% of respondents cite universities or national labs as being next in importance after their own industry. Cooperation with government and cooperation with universities are reported as the two most beneficial trends in energy innovation. Therefore, private and public-sector decisions regarding energy technology are fundamentally connected.

> *Finding*: **Various forms of partnership with the private sector account for a major portion of DOE ERD&D funding and attract substantial private sector investment.**

The two main mechanisms DOE uses to fund or collaborate with non-federal partners are grants and cooperative agreements, which together make up over 99% of DOE's energy innovation expenditure with the private sector. As a whole, funding to private firms and universities is a large fraction of the DOE budget for ERD&D, at about 30% of the funding in the applied DOE offices and 55% of the funding in the Office of Science, making it important to treat it strategically. Most of the funding from the Office of Science goes to universities, but a greater fraction of the applied DOE office funding goes to private firms.

From 2000 through 2009, the DOE awarded $9.1 billion to support science, and $7.2 billion to support applied ERD&D. ERD&D projects attracted $9.5 billion in outside matching funds, more than matching the federal investment, which represents a measure of the value placed on these projects by the private sector (Fig. ES-7). There is little information available regarding the outcomes of these projects.

> *Finding*: **The DOE does not collect sufficient data on the approaches its programs take to working with the private sector, and their successes and failures, to serve as the basis for policy-making and learning. The DOE appears to have no focused strategy shaping its energy innovation partnerships with the private sector.**

The DOE's own program managers cannot readily determine from the available data systems how many projects have been funded with which private sector firms, for what amounts of money—much less the technologies, development stages, processes, and outcomes associated with them. Record-keeping and reporting requirements are more burdensome than in the private sector, but still do not produce the data and analysis that would be most useful to managers for planning future projects. DOE strategic plans, budget documents, and multi-year program plans all state the importance of the public-private partnership, but none provide guidance on selecting or managing partnerships in practice.

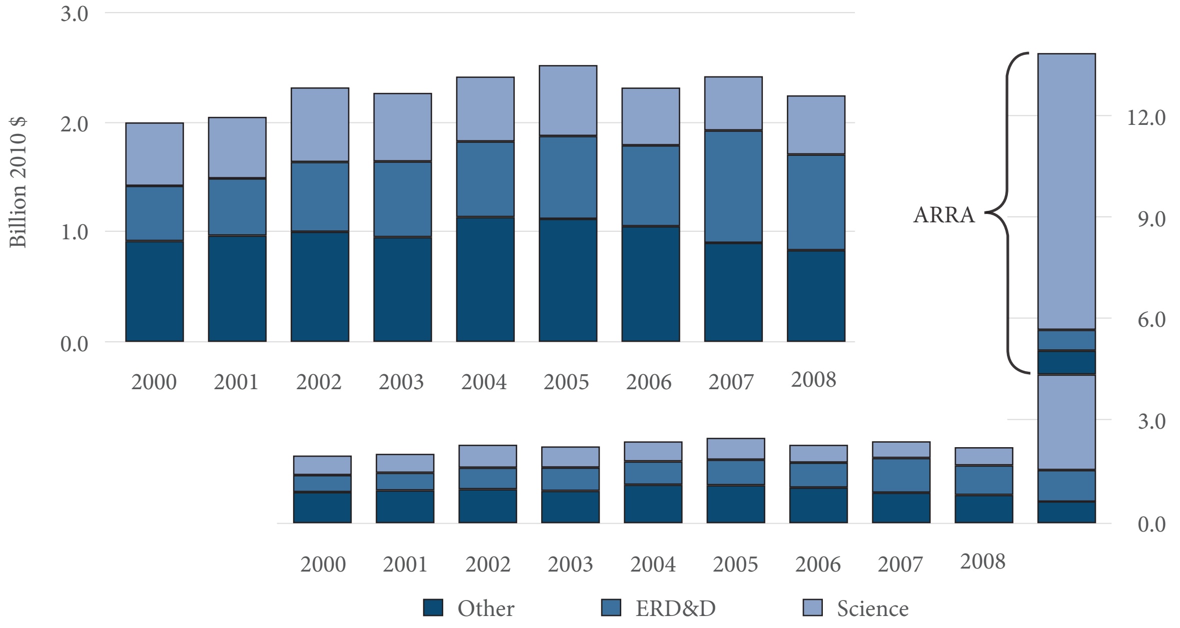


FIGURE ES-7. Funding for assistance, mostly in the form of cooperative agreements and grants, to private firms, academic institutions, and other institutions, by DOE in major categories (ERD&D, Science, and "other").

RECOMMENDATIONS

> *Recommendation*: The U.S. federal government should implement policies that create market incentives to develop and deploy new energy technologies, including policies that have the effect of creating a substantial price on carbon emissions, and sector-specific policies to overcome other market failures. These policies should be aggressive enough to create substantial incentives for private-sector innovation.

Substantial and lasting prices on carbon emissions are needed to increase private incentives to invest in inventing, developing, and deploying new approaches to avoiding emissions. Additional sector-specific policies will be needed to overcome particular market failures and maximize the net benefit to society from new energy technologies.

> *Recommendation*: The U.S. government should provide additional incentives for private-sector investments in energy innovation.

Given the many market failures impeding private sector investment in energy innovation, additional incentives are justified if they could cost-effectively leverage additional private sector spending. Our survey indicated that government cost-sharing and deployment-related incentives (such as production tax credits) are generally more important in private sector innovation investment decisions than R&D tax credits, but further research is needed to design the optimal package of incentives for private sector energy innovation.

> *Recommendation*: **The U.S. government should establish an Energy Innovation Advisory Board (EIAB) with representation from the private sector, academia, the national laboratories, and other key stakeholders, to advise on how best to accelerate private sector energy technology innovation.**

This advisory board would supplement the existing Secretary of Energy Advisory Board by providing a specific focus on policies to accelerate the pace of improvement in energy technologies in collaboration with the private sector. It would also complement and inform the Quadrennial Technology Review, which is currently being undertaken. It should include private sector innovators from both large and small firms. The board's mission should include consideration not only of DOE investments in energy technologies but also of the broader set of U.S. government policies that affect the pace of energy technology innovation.

> *Recommendation*: **The Department of Energy should develop and implement an integrated strategy for its partnerships with the private sector, which should include the data collection and analysis needed for the effort to learn over time.**

To enable managers to incorporate strategic priorities into project decisions, the DOE should articulate how each of its functions contributes to its missions and goals, and set forth principles for when and how to use different mechanisms of support. The ongoing Quadrennial Technology Review is potentially a good start, but more focus in needed on how to use different types of cooperation mechanisms (e.g., cooperative agreements, CRADAs, work-for-others, etc.). The portfolio of support mechanisms that are used should in turn be accounted for during budget development and other strategic planning. To support continuous improvement of its programs, the DOE must improve its data collection and analysis system to include information on practices, problems, solutions, and outcomes for partnerships with the private sector.

> *Recommendation*: **The U.S. government should establish a mechanism for working with the private sector to financially support and implement large-scale energy technology demonstrations, where such demonstrations are essential to enable private sector adoption of clean energy technologies that have the potential to significantly contribute to reducing CO_2 emissions and oil imports.**

Commercial scale demonstrations of unproven technologies are currently the rate-limiting step in the commercialization of some important energy technologies, and they provide critical information to all stakeholders (government, financial community, and industry) by testing not only technologies but also new business models. The Department of Energy, as currently constituted, does not appear to be well-suited for carrying out commercial-scale technology demonstrations in close partnership with the private sector. The creation of some new office or institution may be necessary to achieve this goal. One option is the proposed Clean Energy Development Administration (CEDA), which has already received some bipartisan support. The DOE Quadrennial Technology Review, which was underway at the time of the writing this report, may be able to help outline the necessary institutional arrangements, the level of funding required, and some of the most promising technology areas that could be supported.

MANAGING ENERGY INNOVATION INSTITUTIONS

FINDINGS

> *Finding*: The United States government is supporting a range of energy innovation from basic research to deployment, and has recently established a number of new energy innovation institutions focused on particular technology states, although some gaps remain.

In the past, the U.S. government has not only provided too little funding for energy innovation, but it has left major gaps in the innovation chain, reducing the effectiveness of its investments. The creation of several new institutions at the DOE—namely, the loan guarantee program, the Advanced Research Projects Agency - Energy division (ARPA-E), the Energy Frontier Research Centers (EFRCs), and the Energy Innovation Hubs—since 2005 were intended to fill some of these gaps in the innovation system. Figure ES-8 includes a visualization of the older institutions (depicted in blue) and the newer institutions (depicted in red).

> *Finding*: There has been insufficient systematic study of the effectiveness of U.S. energy innovation institutions, and how their effectiveness might be improved.

Many funders, other decision makers, and scholars have assumed that there is a strong relationship between research funding and societal benefit. This is certainly the case when innovation institutions are managed effectively and focused on meeting major societal needs. But in-depth, independent assessments are needed to identify areas that are being managed effectively and those that are not, and what new steps are needed to improve these institutions' effectiveness so that the U.S. government gets the maximum return on its investments into these institutions. Of course, funders and other parties already undertake some assessments of energy innovation institutions. For example, several groups regularly evaluate the National Renewable Energy Laboratory (NREL), the subject of a case study in this report, including technical advisory boards and decision-makers at the DOE. These reviews certainly help, bringing outside knowledge and perspective to the organization reviewed. However, one limitation of them seems to be that the participants conducting the reviews rarely have the time, resources, or incentives needed for in-depth, comprehensive evaluation—including challenging existing U.S. government approaches where necessary.

> *Finding*: ARPA-E has won strong reviews for its focus on high-risk, high-payoff energy technology concepts, and it fills an important gap in U.S. energy innovation.

ARPA-E was authorized in 2007 and funded with the 2009 Recovery Act. As designed, ARPA-E is a nimble organization, free of some of the hiring and contracting hurdles encountered at the DOE, and possesses experienced and knowledgeable employees. In addition to the projects it has chosen to fund, it has launched several new initiatives, such as the ARPA-E Summit, in which winners and finalists of ARPA-E awards are showcased to attract further funding. In funding both early-stage innovation and facilitating pathways for its awardees to reach commercialization, it is attempting to take a more holistic view of innovation. Finally, ARPA-E has worked to communicate its mission and progress to Congress, and has collected metrics, such as follow-on data on the VC funding its projects attract, that help to build its legitimacy.

> *Finding*: The U.S. national laboratories play a critical role in energy technology innovation and are likely to continue to do so in the future.

The U.S. national laboratories contain an enormous amount of talent and knowledge, and are an asset to the United States. Some examples of ways in which the national labs contribute to energy technology innovation include: (a) the support from national labs personnel during the oil spill in 2010; (b) the fact that international researchers generally value the U.S. national labs and attempt to collaborate with them; (c) reports and expertise from the national labs are often used by private companies; and (d) test facilities at the labs are generally considered to be useful in reducing costs for private firms.

However, as may be indicated by the range of institutions created outside the labs, there are areas in which the labs are lacking, such as funding for some research areas, undertaking high-risk, long-term, application-inspired research, bridging the basic and applied research divide, and managing large-scale demonstration projects. In spite of these flaws, the national labs have made contributions to developing and commercializing energy technologies (e.g., they played a key role in the development of the thin film technology underlying First Solar, the largest U.S. photovoltaic company). And over time, it is likely that some of the investments made in the labs throughout the years will result in more benefits, particularly if some of their barriers to working efficiently are removed.

> *Finding*: Programs funded by the DOE and, in turn, the national laboratories are faced with volatile funding that often impedes research programs' ability to move forward effectively.

DOE programs (e.g., solar, wind, industrial technologies, vehicle technologies, nuclear, hydrogen, etc.) have experienced very volatile funding over the past few decades. This translates to an uncertain funding environment for national labs, private firms, and other research performers. In particular, NREL has faced severe budget cuts or shortfalls over the years (in 1981, 1996, and 2006, for example), which

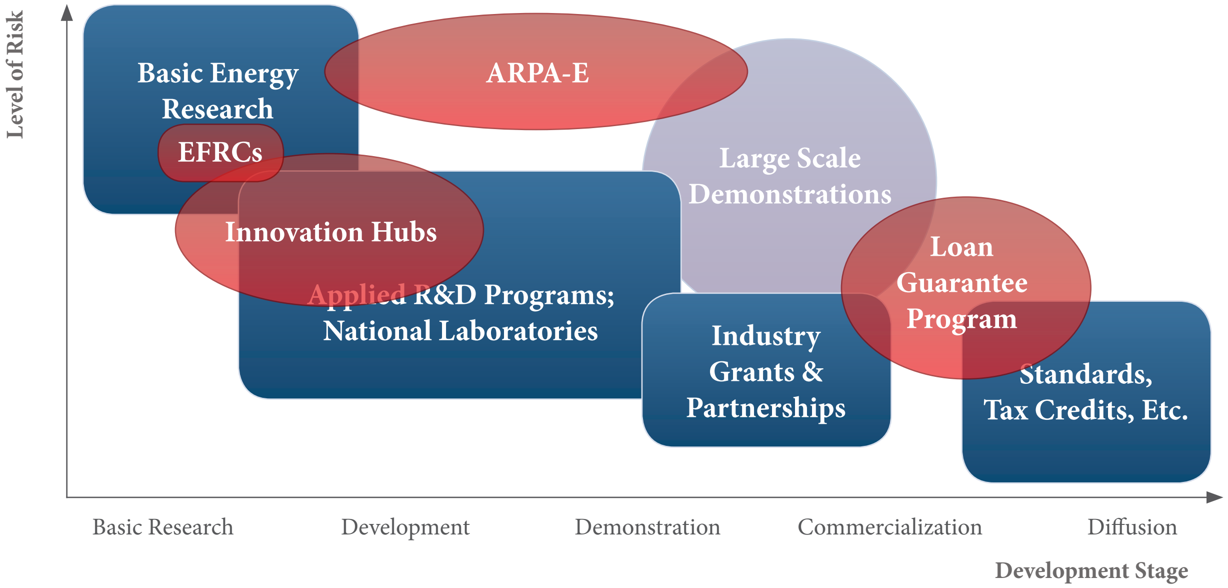


FIGURE ES-8. Schematic of the current U.S. government institutions and policies whose primary mandate is to accelerate energy innovation. Blue boxes denote programs that existed before 2005. The other institutions (with the exception of the "large scale demonstrations", which is an area we have identified as a gap) are more recent: the EFRCs, the Hubs, and ARPA-E were funded in 2009, and the loan guarantee program was instituted in 2005, although the first loan guarantee was issued in 2009. (Adapted from various presentations from the U.S. Department of Energy.)

led to several rounds of layoffs, significant impact on morale, and a reduced ability to attract the best researchers. While research programs should be closely evaluated and phased out if they are not working, or if they have not achieved enough success that the private sector can carry the technology forward without further federal help, the overall effectiveness of the national labs will be improved with more stable funding.

> *Finding*: To be effective, energy innovation institutions require a clearly defined mission; strong leadership with proven technical and managerial excellence; an entrepreneurial culture that accepts risk and encourages both competition and collaboration; sufficient flexibility for the leadership to build the right culture and seize opportunities as they arise (including a significant fraction of lab-directed funds); reasonably stable and predictable funding; balance and linkages between basic and applied research; and strong connections to the private sector.

For too long, U.S. policymakers have focused too little attention on these essential steps to maximize the performance of U.S. energy innovation institutions, including the national laboratories.

An analysis of NREL in particular, the primary national lab for renewable energy and energy efficiency, shows that the above principles are not currently as prominent as they should be. NREL's mission implementation has been volatile over time and its structure does not sufficiently integrate basic and applied research efforts. In addition, the lab director does not have enough flexible funding to take advantage of important opportunities as they arise, and the lab employees have to deal with constantly shifting budgets imposed from outside the lab. Finally, NREL employees' technical knowledge and experience with the private sector activities are not sufficiently utilized at the DOE.

We complemented our case study of NREL with a case study of the Semiconductor Research Corporation (SRC) in order to explore alternative models of coupling research between the government and private sector. The study of the SRC indicates that a stronger connection with industry contributes to technology relevance and private sector uptake. The SRC's efforts to build the future workforce of the semiconductors industry also provide a useful model for the DOE and other innovation institutions.

Recommendations

> *Recommendation*: The U.S. government should restructure its management of the national laboratories to maximize their innovation potential, based on the principles just described.

The original design of the national labs had a clear mission, stellar leadership, an entrepreneurial culture, block funding, and a structure that allowed researchers to be accountable and independent, yet connected. Over time, the mission of the multiprogram national labs has become more diffuse. Arguably, for-profit management of some labs has increased the emphasis on corporate priorities, sometimes at the expense of national priorities. In the case of NREL, even though its mission has remained stable, the lab has not had the ability to make decisions about how to best serve the mission and has had a volatile budget. Moreover, it has been subject to control from decision-makers in Congress and the Executive branch, with sometimes conflicting priorities. In some periods, decision makers have pushed the laboratory's focus toward basic research, while at other times, they have expected NREL to work mainly on technology deployment and commercialization.

Of course, the DOE must also take steps to ensure that its other innovation institutions and processes, such as ARPA-E, its partnerships with industry, the Joint BioEnergy Institute (a partnership of national labs, universities, and NGOs with a mission to advance the development of the next generation of biofuels), and the Energy Innovation Hubs, are all operating as effectively as possible. But the role of the national labs is particularly important, both in energy technology and in other areas. Indeed, the national labs are the repository of most of the technical expertise available to the DOE. The bottom line is that, in addition to creating new important institutions, the DOE should also try to better utilize the national laboratories. Although this task will require a large effort, it could yield large returns.

> *Recommendation*: The administration and Congress should provide support for a portfolio of energy innovation institutions designed to ensure that all stages of the innovation chain have appropriate support, avoiding technology gaps and finding "valleys of death." In particular, the administration and Congress should provide sustained support for ARPA-E to pursue the high-risk technologies that could lead to major energy breakthroughs.

To meet the energy challenges the United States faces, from climate change to oil dependence and beyond, it will be necessary to use a wide range of technologies, including some that are close to being commercialized and some that may not be commercialized for decades to come. Major gaps at any point in the innovation chain can disrupt the process of developing and deploying a new technology, reducing investment throughout the innovation chain. Hence, the U.S. government must provide appropriate support for a broad range of technologies and stages of innovation.

ARPA-E has a clear mission and has shown technical and managerial excellence. It also has a unique organizational model that allows it to act quickly, identifying areas of opportunity, hiring staff, and making decisions about how to allocate funding. In its task to fund potentially transformative energy technologies and to pave the way for their commercialization, it has been effective and innovative in forming partnerships with the private sector and other government departments. The number of meritorious, innovative proposals ARPA-E has received is far larger than it has been able to support with the budgets it has had available thus far. The U.S. government should substantially increase funding for ARPA-E, and maintain stable support for at least 10 years to give it a fair chance to succeed in some areas of study. This is because innovation takes time, and not all of the high-risk technologies ARPA-E is pursuing will succeed. The value of the successful technologies developed with ARPA-E funds, combined with the value of lessons learned from the projects that do not reach commercialization, is likely to far outweigh the cost of supporting ARPA-E.

The Energy Innovation Hubs are an important initiative to create a critical mass of researchers working on problems requiring an integration of fundamental science breakthroughs and inventive engineering. Because of their likely contributions to technological progress and to developing the science and technology workforce of the future, the U.S. government should also expand funding for the Energy Innovation Hubs, and provide stable support for an extended period of time.

The Energy Frontier Research Centers (EFRCs) comprise another relatively new and focused initiative that could make a large contribution to meeting the world's energy challenges and should also be expanded and provided with stable funding. The EFRCs are located within universities, national laboratories, nonprofit organizations, and for-profit firms, singly or in partnerships, and are selected by scientific peer review and funded for a 5-year initial award period. EFRCs add to the portfolio of mechanisms supporting energy RD&D by conducting fundamental research with stable funding for 5 years, encouraging multiple investigators to work together, and focusing on one or more of the "grand challenges" and "basic research needs" identified in a major strategic planning effort by the scientific community.

> *Recommendation*: The U.S. government should strengthen the connections between its energy innovation institutions and the private sector throughout the innovation chain, but particularly as technologies move toward the development, demonstration, and deployment phases.

The case study of the SRC highlighted the value of involving private sector members in developing technology roadmaps and in the high-level direction of the institution. As technologies get closer to commercialization, private sector input is even more crucial. Advisory boards, workshops, and incorporating members of the user community into the research process are ways to increase private sector participation in decisions. Additionally, finding ways to build relationships beyond the structured mechanisms can facilitate informal, mutually beneficial partnerships. User facilities, either for research and development or for demonstrations, have proven their value at several institutions, allowing laboratory and private-sector employees to work together and understand each other's priorities and approaches. Cost-sharing and more complex financial mechanisms involving an even closer public-private partnership (e.g., equity stakes or reverse auctions) could play important roles in technology demonstrations and early deployment.

Strengthening Energy Innovation Cooperation with Other Countries

Findings

> *Finding*: Energy technology innovation is a global undertaking with a larger number of countries engaging in scientific, private, and public energy innovation activities than ever before. This creates both new competitive threats and new opportunities for cooperation.

In many technological areas, including some nuclear reactor, solar, battery, and advanced coal technologies, the United States' share of the scientific and technological output of new energy technologies is slowly decreasing and the United States is no longer the clear technological leader.

> *Finding*: Collectively, the investments in energy RD&D by governments and state-owned enterprises in the emerging economies of Brazil, Russia, India, Mexico, China, and South Africa (the BRIMCS countries) are now as large or larger than those of the developed countries in the Organization for Economic Cooperation and Development (OECD). Out of these emerging economies, the bulk of the energy RD&D investment is being made by state-owned enterprises in China.

> *Finding*: Global energy technology markets have changed dramatically in the last two decades, with both energy demand and manufacturing capabilities of clean energy technologies expanding rapidly in emerging economies.

Over the past decade, China has become the largest energy consumer in the world, and several other emerging economies (such as Brazil, Russia, India, Mexico and South Africa) have become major energy consumers and producers, and major players in energy technology innovation. In addition, nearly all of the projected growth of energy demand over the next quarter of a century will take place in developing countries, making their markets—and the cooperation needed to help ensure the U.S. role in them—particularly crucial.

Countries are not only cooperating but are also competing in global energy markets. The import and export values of energy technologies continue to increase, and the value of U.S. exports is growing at a slower rate than that of other countries. China, in particular, has clearly made a strategic decision to compete aggressively in the markets for solar, wind, nuclear, and other clean-energy technologies, and the United States must respond to that competitive challenge—yet the opportunities for cooperation are enormous as well. Choosing where to work together and where to compete is difficult, and must be decided on a case-by-case basis.

> *Finding*: The most important forms of international energy technology cooperation are not directed by governments but arise organically from the activities of private firms, academic and research institutions, and individual scientists and engineers. Governments have key roles to play in facilitating and supporting, rather than hindering, these forms of cooperation.

Much international cooperation on ERD3 takes place without direct government involvement. Private sector cooperation efforts will generally be larger, more dynamic, and more responsive to immediate private-sector needs than government efforts. One of government's most important roles is to enable this bubbling flow of bottom-up cooperation and avoid creating unnecessary barriers. This can be achieved by limiting the obstacles posed by tariffs, export controls, visa restraints, and the like (the surest way to stop any technical cooperation is to require that governments must negotiate a legally binding agreement covering every step to be taken before it can begin).

Because environmental protection and energy security are public goods and are not priced in the market, and because firms cannot capture all the benefits arising from their innovations, private firms alone will always invest less in energy technology innovation than would be best for society, overall. For this reason, governments should support cooperation with other countries through agreements, programs, or individual projects; particularly in cases where such cooperation results in:

- shared or lower costs in research, development, and demonstration projects through the sharing of information, facilities, and personnel;
- access to complementary expertise and facilities;
- increased business prospects for American companies through a better understanding of new markets and their needs; or
- environmental, security, and economic benefits to the United States from an accelerated development and deployment of advanced energy technologies globally.

> *Finding*: **The U.S. government undertakes international cooperation on energy technologies for many different reasons. No single set of criteria can adequately capture all of the different motivations for cooperation on energy technology.**

A brief historic analysis of the drivers of international cooperation on energy technology innovation revealed that new political drivers for international cooperation appear over time, and that old drivers, and the networks formed to support them rarely completely disappear. As a result, U.S. government decisions to engage in international cooperation are shaped by multiple objectives: (1) accessing knowledge on high-tech energy technologies; (2) retaining or gaining technological competitiveness; (3) increasing energy security; (4) accelerating the commercialization of new energy technologies; (5) reducing the negative environmental impacts of the production and consumption of energy; (6) promoting reforms in the energy sector; (7) providing energy access to the poor; and (8) increasing U.S. access to emerging markets.

> *Finding*: **The U.S. government does not appear to have an overall strategy for its international energy technology cooperation efforts; has no systematic approach to coordinate the many different efforts underway; and does not collect or analyze data on the successes and failures of international energy technology cooperation that would make it possible to strengthen these programs over time by learning from experience.**

There are several factors that make it difficult for the U.S. government (and many other governments throughout the world) to undertake an effective and flexible effort on ERD3 international cooperation. These factors include: (1) the multiplicity of objectives that drive ERD3 cooperation; (2) the wide range of activities involved (e.g., information sharing, standard design, joint R&D projects, etc.); (3) the large number of platforms and channels through which it takes place; (4) the large number of government stakeholders; (5) the lack of information about the activities taking place within existing bilateral and multilateral platforms; (6) the growing number of non-government international cooperation activities by scientists, national laboratories, industry, and non-governmental organizations; (7) the wide range of technologies that are needed to meet the energy challenge; (8) the difficulty of balancing cooperation versus protecting intellectual property and potential competitive advantages.

There are at least nine U.S. government departments and at least ten U.S. agencies involved in international cooperation on ERD3. Some coordination of international cooperation activities takes place within the different U.S. agencies and across agencies through a network of personal contacts, but a coordination effort that encompasses the majority of the relevant government activities has not yet been found.

This complexity has contributed to a lack of direction and systematic coordination among government agencies, which results in:

- Little continuation and follow up between activities;
- Duplication and repetition of activities supported across governmental organizations;
- Restructuring of existing projects with little evaluation;
- A large number of inactive agreements; and
- Limited efforts to extract lessons from international cooperation activities and provide them to the wider community.

> *Finding*: **Funding for most U.S. energy technology cooperation efforts is limited and comes with administrative and procedural burdens. Most of these cooperation programs focus on very limited objectives such as outlining standards for new technologies. In most cases these programs do not have the resources for actual joint technology development.**

An analysis of the activities taking place in each of the international cooperation platforms—the International Energy Agency, the Global Environmental Facility, the Asia Pacific Partnership, and others—shows that the focus of the cooperation programs is limited in most cases. Most international cooperation projects focused on energy technology supported by the U.S. government are small-scale deployment activities for existing technologies in developing countries. They include cooperation on the development of databases, handbooks, best practice examples, state-of-the-art literature reviews, standards and codes, computer models, regulatory issues, or policy reform advice. This is to be expected, because generally these activities are cheaper and easier to arrange than projects in which equipment is being purchased and new processes are being developed. There are several international cooperation projects that support the exchange of experimental data and the coordination of experimental testing in facilities, but only a small number of international cooperation projects actually work on the development of new energy technologies.

Recommendations

> *Recommendation*: **The expanding and increasingly diversified global ERD3 landscape implies that the United States needs to develop and implement an effective strategy for cooperation with other countries, to pursue global sources for the best ideas and innovation opportunities, while also targeting investments to maintain its competitive position and future market share.**

The changes in global energy technology markets in the last two decades, with both energy demand and manufacturing capabilities of clean energy technologies expanding rapidly in emerging economies, require U.S. policy makers to take the global interdependence of ERD3 activities into consideration, and to evaluate their actions in the context of the global market.

> *Recommendation*: The U.S. government should expand funding for international energy technology cooperation in three ways: (a) by setting aside a portion of the budgets of each major energy RD&D program for international cooperation to finance efforts identified bottom-up by program officers or project managers involved in international energy RD&D efforts; (b) by providing incubator funding to support the procedural aspects for creating technology-focused cooperation projects; and (c) by providing funding for programs that represent strategic priorities identified top-down by a new interagency committee.

In an increasingly complex, diverse, and fast-changing global landscape of ERD3 activities, innovators who are connected to international networks must be relied upon to identify new opportunities for international ERD3 cooperation. These bottom-up projects (which are already taking place to some extent), increase the ability of both U.S. policy makers and U.S. innovators with contacts in other countries to respond to needs and opportunities in a flexible and timely manner. We therefore recommend instructing departments and agencies to set aside a portion of their ERD3 program funding to support bottom-up energy technology innovation cooperation projects. This approach would significantly increase the total funding directed to international cooperation efforts.

Simultaneously, the United States needs a more prioritized and efficient approach to international energy technology cooperation to meet the challenges of energy innovation in a rapidly changing international landscape. We recommend that the U.S. government adopt a two-track approach designed to create coherence and synergies between bottom-up activities through a top-down strategic planning process. This top-down process requires a more diligent and systematic effort of collecting information about what projects are currently supported, what problems they address, and what solutions they may provide. The next two recommendations detail the top-down portion of our proposal.

> *Recommendation*: The U.S. government should establish an interagency working group under the National Science and Technology Council (NSTC) to coordinate international energy technology cooperation.

The U.S. government should create a working group focused on international energy technology cooperation that would be co-chaired by the DOE and the Office of Science and Technology Policy (OSTP) and have active participation from the other agencies involved, including the State Department, the U.S. Department of Agriculture, and the U.S. Agency for International Development, as well as private sector actors. The Working Group would be housed under the Committee on International Science, Engineering, and Technology (CISET) within the (NSTC). The Working Group should be guided by an "adaptive strategy" that (1) compares existing international ERD3 cooperation activities and instigates projects that create coherence between them; and (2) identifies activities that create synergies or seize opportunities between U.S. national ERD3 activities and those of its partnering countries. It would be responsible for identifying and communicating strategic guidelines for cooperation on energy technology innovation every year, and produce a report to Congress, the White House, and the different departments.

Moreover, the working group should work with agencies, the Office of Management and Budget, and Congress to ensure that these recommendations are included in agency budgets.

> *Recommendation*: The U.S. government should establish a focused effort to collect and analyze data on its international energy RD&D cooperation activities, creating an information platform at the Energy Information Administration (EIA).

To aid the work of the Working Group at NSTC, as well as the other departments engaged in ERD3 and other stakeholders who may be interested in cooperating with other parties internationally, a platform to share information on international ERD3 cooperation projects should be created. This platform could be hosted by the EIA. The platform should collect information about the technical and strategic dimensions of existing international cooperation projects, programs, and high-level agreements at different government levels across the different U.S. agencies, and how they relate to each other. Incentives should be put in place to ensure that those responsible for the projects consistently introduce information on the details of the projects and their progress on a yearly basis. Incentives could include follow-up funding for projects being contingent upon providing information, and/or including information sharing in personnel evaluations. The platform should also enable private firms and not-for-profit organizations to share information about their projects, and should make it possible for information to be made comparable at different levels and across agencies, and accessible to both U.S. policy makers and U.S. organizations who may be interested in cooperating with other parties internationally.

CROSS-CUTTING ISSUES

As we pursued our research, several themes arose repeatedly. We believe these principles are important to improve the effectiveness of U.S. energy innovation policy.

The first of these themes is the need for *stable long-term policies* that allow the private sector to plan and make investments and that provide researchers with time to collect sufficient information and to explore different research avenues efficiently. The Quadrennial Technology Review that the DOE was undertaking at the time of writing this report is a first step that can help provide more stability by identifying multi-year programs for different technologies. Long-term stability is also needed for policies to pull technologies into the market place, such as standards or carbon prices.

The second theme is the need for *improved coordination* between agencies. Again, the Quadrennial Technology Review will help provide coordination within the DOE, but ultimately, a government-wide review (such as the Quadrennial Energy Review recommended by the President's Committee of Advisors in Science and Technology) will be needed to align DOE programs with government-wide initiatives. For example, a price on carbon or a clean-energy standard will affect private sector activity in energy innovation and therefore the investments that the DOE should make.

The third theme that emerged is the need to have *a balanced portfolio* of: (a) investments in different technologies, (b) investments in different stages of technology development, and (c) mechanisms to interact with the private sector and universities. The outcome of innovation is uncertain, and, as a result, managing risks requires spreading bets across a range of projects while expecting failures. At the same time, given that budgets are constrained, and that bets that are too small are unlikely to yield results, not everything can be supported.

A fourth theme that emerged was the need to *strengthen the interaction between government and the private sector*. Although members of the private sector testify to Congress, participate in advisory boards, and respond to requests for information, it would be useful to integrate private sector perspectives more fully in the design of policies and research programs. An extended use of advisory boards—such as the Energy Innovation Advisory Board we propose—could help strengthen connections between the public and private sectors.

Finally, a fifth theme our research indicated is that there is a lot of work to be done to design an *energy technology innovation strategy that is guided by learning*. Today, program managers are often unaware of which approaches worked and which did not in areas of research related to their own, making it difficult to strengthen or expedite their efforts by learning lessons from past experience. Much more work can be done to collect and analyze data on the different approaches that are being implemented and to determine which ones seem to work best, and under what circumstances. For example, better information is needed for program planning and the budget process. Information required includes: (1) the portfolio of mechanisms and projects that are in place; (2) multi-year program plans that take into account what capabilities and resources will be needed; (3) managers' experience with what partners are able to contribute and what the DOE has to contribute (this is as important as the state of technology in deciding what actions to take); (4) the pace of technology development and the challenges that are being encountered by those involved in projects; and (5) the impacts of the programs. ARPA-E is placing an increased emphasis on self-evaluation and data collection, and is an example of an institution that is adopting this "learning" principle.

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