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Chapter 10: Concepts in Integrated Analysis
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Issues and RDD&D Opportunities

The goal of energy technology development programs, whether in the private sector or in government institutions, is to maximize the positive impact of research, development, demonstration, and deployment (RDD&D) portfolio investments. To evaluate total impacts, research institutions must consider multiple impact metrics that address energy-linked economic, security, and environmental goals from business and public perspectives. Portfolio analysis is widely employed, but at varying levels of thoroughness, analytic rigor and transparency. Many tools for technology planning and projection, analysis, metrics calculation, and impact evaluation exist already, but are not necessarily fully developed or packaged in a way that can be used directly for evaluating energy portfolios. This chapter accomplishes the following:

- Provides a suggested, iterative process to shape an energy portfolio and estimate the potential impacts of particular RDD&D activities on key national goals
- Articulates the current state of integrated technology assessment
- Gives examples of sector-specific applications of metrics and tools for technology analysis in use in various organizational contexts (i.e., corporate, nonprofit, academic, and government)
- Identifies gaps in technology assessment capabilities

10 Concepts in Integrated Analysis

10.1 Introduction

The goal of a technology program's allocation and prioritization approaches is to identify research, development, demonstration, and deployment (RDD&D) opportunities with the greatest benefits while also considering their risks. The technology challenges and opportunities presented in the technology sector chapters (3–8) on energy-related RDD&D, together with integrated analysis approaches outlined in this chapter, can provide key insights on how to provide decision makers with information that will enhance their ability to understand trade-offs among various energy portfolios.

The purpose of this chapter is to articulate the current state of integrated technology assessment and identify gaps in technical assessment capabilities needed for integrated analysis. The chapter does not provide a definitive process nor perform any of the calculations necessary to begin to evaluate the many RDD&D investment opportunities that have been explored in the preceding technology sector chapters; but instead, provides a framework that can be utilized to conduct such analysis.

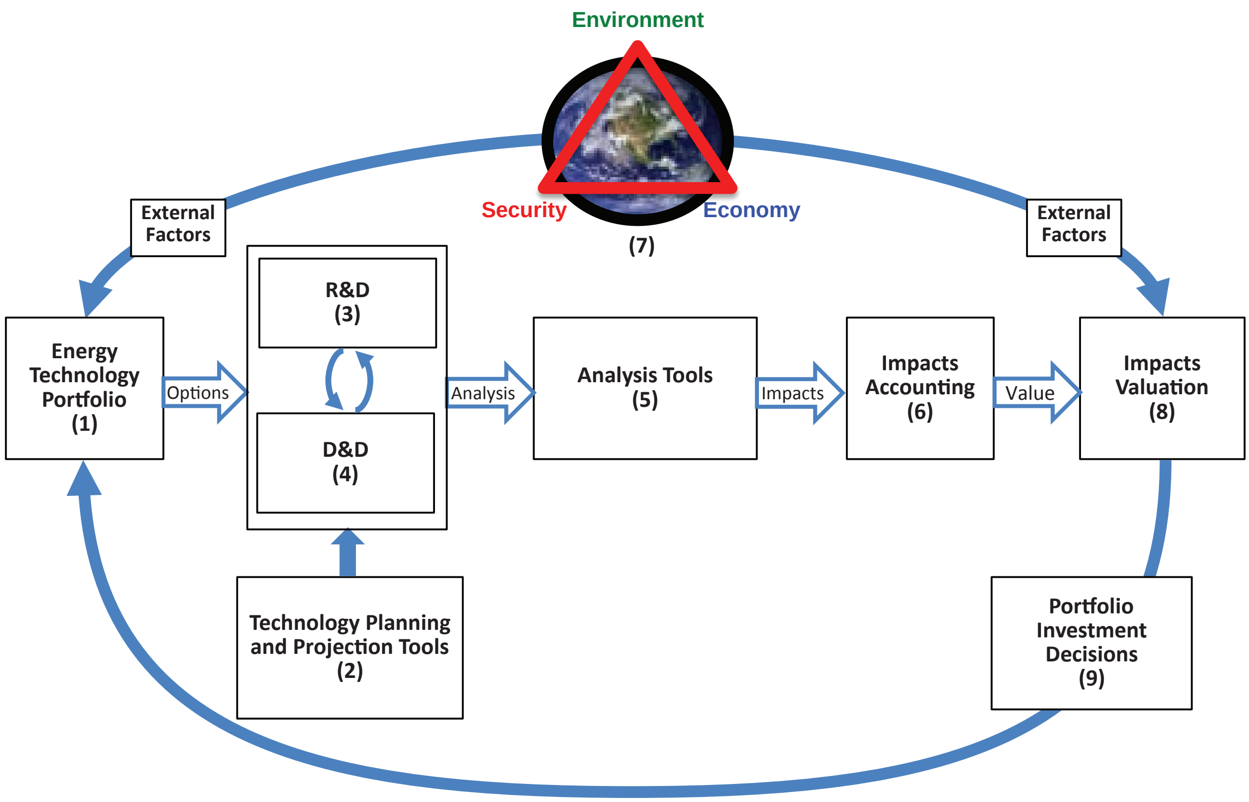
In particular, Figure 10.1 indicates the overall flow of the chapter and provides a suggested, iterative decision-making process to shape an energy portfolio and estimate the potential impacts of particular RDD&D activities on key national goals. It shows nine distinct steps in the RDD&D decision-making process, with each step numbered sequentially: 1) Starting with a portfolio of energy technologies, 2) a combination of technology planning and projection tools is used to 3) estimate the potential advance in capabilities through research and development. These tools are discusses in Section 10.2.2 of this chapter and include approaches ranging from simply stating a research and development (R&D) goal, to providing a subjective range of cost and performance metrics, to a formal elicitation of probabilistic risk estimates. Included are a number of tools and concepts described briefly below in this section and developed more fully in the rest of the chapter.

4) Demonstration and deployment (D&D) activities have several interactions with R&D. First, R&D progress will largely determine when and how much D&D activity is warranted, as deployment is substantially driven by costs that are dependent upon technical progress. Second, D&D activities that drive economies of scale and inform experience or learning processes may require further research activity in certain areas, stimulating feedbacks to R&D.

5) Estimates of the potential impact of overall RDD&D activities are developed next using analysis tools. Approaches include creating a range of potential growth outcomes over time, quantitatively modeling market penetration within a particular sector, or using an economic model to forecast market penetration and examine cross-sector impacts.

6-7) The deployment of energy technology RDD&D will have a variety of impacts on national security, economics, and the environment, illustrated in the figure as a triangle around the image of Earth.[1] Each high-level concept represents a number of impacts, quantified as metrics, that are discussed in Section 10.2.3.

Figure 10.1 Overall Flowchart of an RDD&D Decision-Making Process



Determining appropriate metrics at the individual technology, technical system, sector, and integrated (systemwide) levels is a non-trivial task, but is vitally important to fairly assess portfolio impacts across a wide range of dimensions.

8) Evaluation tools such as options space and wedge analysis allow decision makers to consider multiple alternative approaches to achieve their high-level goals (see Section 10.2.4). Another type of evaluation tool is integrated assessment modeling (IAM), which takes environmental impacts into account in energy and economic models. This must be done in the context of a complex and evolving "background" of economic, political, institutional, and social forces that interact with and are shaped by energy technologies. Moreover, stochastic analysis is needed to overlay all of these approaches to take into account a wide range of factors that impinge upon outcomes. The wider the range of outcomes considered, the more that portfolios can be evaluated for robustness. The latter quality, robustness, should be quantified as a key high-level metric.

Technology outcomes depend critically on the human element at all levels, including individual consumers, building managers, energy suppliers, product designers, and high-level R&D program managers. Decision science tools can help our understanding, are critical to realistic modeling, and can lead to better RDD&D design. These concepts are also discussed in Section 10.2.4. Example applications of tools for technology analysis are provided at the end of this section.

9) A proposed approach of modeling, visualizing, interpreting, and ultimately making RDD&D portfolio investment decisions is discussed in Section 10.4. Reducing the volume of data to a level that provides insight to decision makers, while avoiding paralysis from "information overload" and the potential for bias arising from too narrow a range of considered data, is a formidable challenge.

The tables found in Section 10.5 enumerate the issues, questions, and metrics that might be considered in evaluating or planning portfolio investments. This section also includes a summary of RDD&D activities needed to improve these tools and decision-making capabilities.

10.2 Technology Assessment

Various tools, metrics, and concepts that can inform portfolio analysis are discussed here. This section describes their capabilities separately although for decision-making purposes one would likely use more than one to assess a portfolio.

10.2.1 Risk and Uncertainty

Risk and uncertainty are key characteristics of R&D programs. Attempting to do what no one has done before may sometimes end in failure, just as it may sometimes lead to extraordinary success. There are important distinctions, connections, and dependencies between different types of risks (i.e., technical versus market risk).

As considered here, risk can be characterized by the total uncertainty about a future cost and performance of a technology under RDD&D and its impact (usually assessed along multiple dimensions; see discussion on metrics in Section 10.2.3). Sometimes risk is colloquially used to refer only to bad outcomes, but risk refers to—and considers the weighted effects of—all outcomes. Understanding the relative risk and potential benefits of different projects is important in assigning value to RDD&D opportunities within a portfolio. Moreover, risks occur over different time horizons, further complicating a comparison of relative value. For example, an outcome with a potential impact in five years will be judged differently than one whose impact is evaluated over twenty or fifty years. Such time trade-offs are common in energy RDD&D investments, as some are focused on short-term benefits, while others may be multidecadal, but the potential impacts are typically larger. Simple economic discounting is sometimes appropriate, but the resulting risk calculation will depend on the choice of discount rate and the time horizon under consideration. Trade-offs between public (e.g., DOE) and private investment must also be evaluated.

10.2.2 Technology Planning and Projection

This section discusses four assessment tools as they are applied to technology RDD&D. Technology Readiness Levels are used to indicate the status of the technology. Technology roadmapping is used to plan, usually quantitative, goals for technologies and chart RDD&D pathways to achieve them. Expert elicitation is used to develop projections of the potential future cost and performance of technologies. Finally, experience curve analysis uses observed past rates of improvement in a technology to project its potential future cost and performance. Each of these assessment tools is discussed briefly in turn.

Technology Readiness Levels

Technology Readiness Levels (TRLs) identify the maturity level of a technology as well as its planned progression during the course of a project's execution. TRLs first employed by the National Aeronautics and Space Administration (NASA) and formalized to nine levels, denoted TRL 1 through TRL 9.[2] This scale has since gained widespread acceptance outside of NASA.[3, 4] The lowest level, TRL 1, indicates that basic principles have been observed and reported, and it is the first step in taking an idea toward practical application. On the other end, a technology that has achieved TRL 9 has been built and "flight proven" through successful mission operations. While TRLs have proven useful to many agencies, they also suffer from drawbacks, most notably the lack of quantitative or physical characteristics in defining TRLs, exposing them to potential user bias. In addition, TRLs typically encompass many subsystem technologies that can exist at multiple levels of development, raising the question of what TRL an overall technology system should receive. Also, TRLs do not allow ready comparisons across disparate technologies and time frames, and they do not adequately characterize early stages of applied RDD&D.

Technology Roadmapping

Technology roadmapping (TR) provides information to support technology investment decisions by identifying critical technologies and technology gaps, tracking the performance of individual and potentially disruptive technologies, and identifying opportunities to leverage RDD&D investments.[5] Research institutions commonly use TR to create flexible RDD&D investment strategies that address complex barriers.[6] According to Garcia and Bray (1997),[7] technology roadmapping is "critical when the technology investment decision is not straightforward," which could be due to the availability of multiple alternatives, the need for coordinating the development of multiple component technologies (e.g., as part of a system), or the time horizon in which a technology is needed.[8]

Expert Elicitation

Expert elicitation is used to address risk and uncertainty in forecasts of future technology costs by relying on experts familiar with the technology. The method emphasizes both quality and diversity of expertise. Collectively, the experts represent a large breadth of knowledge to inform where "observable data [are] sparse or unreliable, and potentially useful data [are] unpublishable or proprietary."[9] Expert judgment can fall prey to a number of biases, but these can be moderated with appropriate questioning techniques.[10]

Expert elicitation has been used extensively in some fields—with acknowledged challenges in its application[11] —but it has been used relatively little in energy technology RDD&D. Examples of such expert elicitation for energy technologies have included photovoltaics, nuclear power, and carbon capture and storage.[12] One approach that has had some initial testing is to conduct expert elicitation on potential improvements in physical (and cost) characteristics baselined against known physical phenomena, and to then use these in a reduced form energy-economic model on which Monte Carlo simulation is done to generate probability distributions of potential performance and cost improvements over time.[13] Portfolio analyses can then be developed across dimensions of risk, return, time frame, and other metrics. Challenges include controlling various biases, and limiting the cost of and time required for the expert elicitation process. These costs should be considered in the context of the scale of investment in the research. Further development and testing of this type of expert elicitation approach in conjunction with reduced form system modeling to provide early estimates of the potential of particular RDD&D pathways could be done to determine its utility as an interim step before a full system engineering analysis is possible.

Experience Curve Analysis

Experience (or technology learning) curve analysis models the widely accepted mechanism through which technology cost reductions can occur, a concept originating from observations that manufacturing processes improve as production volume increases.[14] This has important implications for understanding past technology developments and program benefits, as well as a potential tool for forecasting technology growth for policy planning and modeling scenarios.

Economies of scale, R&D, regulatory environments, supply/demand, and material and component prices all affect the price of a given technology. Efforts have been made to distinguish the individual importance of these factors, which is useful when projecting forward based on learning rates derived from historical data as well as R&D investment and deployment activities. At a minimum, R&D and incentives that support deployment are often necessary to get early stage technology to the marketplace.

Overall, learning or experience curve analysis can be a useful tool for modeling and planning, but the limitations and uncertainties of these methods must be well-understood and incorporated into any decision-making process. This approach is most applicable to commercialized, non-commodity, scalable, component-level technologies, because manufacturing processes and production and cost histories are in principle readily available. It is also useful to consider how forecasts of technological progress (e.g., costs, performance metrics) can be an input to forward-looking expert elicitation.

10.2.3 Analysis Tools and Metrics

Quantitative assessment tools can provide rigor and robustness to portfolio decision making. These tools often rely on metrics, such as levelized cost of energy and greenhouse gas (GHG) emissions. Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals. To evaluate the extent to which different RDD&D portfolios and component activities can meet diverse goals, it is important to employ a consistent and common set of tools and metrics to enable effective comparison.

Metrics will differ at the level of an individual technology, technology category (e.g., technologies that provide a similar type of service but may differ in details such as gasoline vs. electric vehicle), sector, and overall energy system. However, it is challenging to compare technologies that provide different types of services; a good example is comparing modes of personal transportation (e.g., walking, bicycling, driving, and flying).

All choices of metrics contain implicit value-related judgments such as type of effect considered and weighting of effects over time.[15] Moreover, estimating these metrics requires common methodologies across all technologies. There is no single metric that can be used to comprehensively assess and compare RDD&D opportunities. Moreover, all metrics do not carry equal weight; the issue of weighting or combining metrics is discussed in Section 10.4.

In this section, brief discussions of metrics that have been identified as most relevant to energy technologies will be presented, along with quantitative examples.

Life-Cycle Assessment Overview

For effective comparison of RDD&D opportunities, many metrics are defined in a way that accounts for the entire life cycle of a process or product as part of a life-cycle assessment (LCA). LCA is a methodology that assesses the inputs, outputs, and impacts of a product or process from raw material extraction through end-of-life management (e.g., disposal, recycling, or repurposing). There are typically four steps in completing an LCA: goal definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation of results.[16] Although energy and material-related metrics are often generated during the LCI step (e.g., energy required to convey one person a distance of one kilometer), many of the environmental metrics are determined in the LCIA step, which characterizes and assesses the environmental burdens identified in the LCI (e.g., global warming potential). The final step, interpretation of results, determines the level of confidence of the results through identification of significant parameters for each impact category, assessment of completeness of the study, and effectively communicates conclusions that are reflective of the original goal of the LCA.[17] The principles of LCA are described in ISO 14040:2006, and the steps and framework are described in ISO 14044:2006.

The above mainly describes the approach used in retrospective LCA that is generally applied to existing technologies. Another type is prospective (or anticipatory) LCA that can be applied to emerging technologies that do not yet exist.[18] Both types of LCA are important and valuable, but prospective LCA has additional challenges, such as data uncertainty and availability, the rapid pace of technological innovation, thorough understanding of environmental impacts, and the need for stakeholder engagement, that inhibit its widespread application.[19,20]

Key LCA metrics for energy RDD&D include costs, material flows, GHG emissions, water consumption, and land use. These metric categories are discussed in subsequent sections below.

Levelized Cost of Energy

The levelized cost of energy (LCOE) represents the projected cost of providing one unit of energy for a particular energy service over the lifetime of the asset (for example, $/kilowatt-hour (kWh) for electricity, or $/megajoule for fuel). The LCOE calculation typically includes the capital investment cost, fixed and variable operation and maintenance costs, and fuel costs. [21] LCOE is an easily understood metric that can be useful in developing research goals for a particular technology, evaluating investments and trade-offs in alternative pathways to achieve those goals, and tracking progress in that technology towards those goals. Waterfall charts of cost and performance are commonly used. Other factors may include the weighted average capital cost (WACC), annual capacity factor, and incentives such as accelerated depreciation and federal or state level tax credits.

Although LCOE is useful in illustrating the economics of technologies with similar characteristics (i.e., dispatchability or load profiles), for electricity gerneration LCOE can be misleading when comparing technologies with different operating characteristics. This is because LCOE does not account for certain important attributes for power generation. It is especially problematic to compare dispatchable with variable generation technologies, [22,23] or to compare baseload capacity with those used for peaking or for reliability purposes. For example, LCOE does not account for the value of capacity for meeting peak demands, ability to dispatch generation, differences in the value of energy at different times of the year or day (i.e., on-peak, off-peak, etc.), ancillary services, or other costs for grid integration. Furthermore, LCOE is very sensitive to the assumptions for WACC, installation costs, fuel prices, materials costs, tax or other incentives, interconnection costs, and capacity factors.[24] Finally, regional conditions can impact LCOE, particularly for renewable generation technologies whose capacity utilization is governed by factors such as solar insolation or weather patterns. In real-world applications, technologies in a given region with substantially different LCOEs can often be competitive with one another for reasons other than cost. At the system level, the overall cost of providing electricity is used to compare different portfolios, taking into account the level of reliability.

For new technologies, it is also necessary to evaluate what their cost will be with significant deployment, e.g., for the "Nth" plant. Empirical learning curves are typically used to represent long-term cost projections, but the actual experience across technologies varies widely, from strongly positive learning curves (often 20% or more cost reduction per cumulative capacity doubling) to negative values (sustained cost increases, despite continued deployment).[25] The underlying assumptions for these factors thus can have a significant impact.

Greenhouse Gas Emissions

Most energy-consuming processes generate GHG emissions that contribute to global climate change. While carbon dioxide (CO_2) is the best-known GHG and is fairly long-lived, other gases including methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs) also induce net radiative forcing effects (that is, atmospheric warming). GHG emissions are usually expressed in terms of "CO_2-equivalent" (CO_2e) emissions, a quantity that is obtained by scaling each gas emission according to its global warming potential (GWP), which in turn is defined as the cumulative radiative forcing per unit mass over a specified timescale relative to an equal mass of CO_2.[26] The choice of timescale has a large effect on the value of GWP: for CH_4 or HFC-134a, with atmospheric lifetimes of about twelve years, the twenty-year GWP is approximately three times as large as the corresponding one hundred-year GWP, whereas for longer-lived gases (e.g., N_2O), the twenty- and one hundred-year GWP values are almost identical. The United Nations Framework Convention on Climate Change adopted the time horizon of one hundred years for GWP, and this choice has been widely replicated in U.S. policies and analysis at the federal, state, and local levels.[27] The selection of time horizon depends upon what impacts are to be evaluated and does not otherwise have scientific significance. [28,29]

In terms of climate change impact, processes are often characterized in terms of "GHG intensity," that is, a mass (e.g., metric ton[30] of carbon dioxide equivalent [tCO_2e]) emitted per unit energy consumed (or other suitable metric). In this way, the GHG impact for an equivalent amount of energy service can be assessed. Another common GHG metric is the cost per tCO_2e reduced or avoided, which allows cost comparison of different GHG abatement strategies.

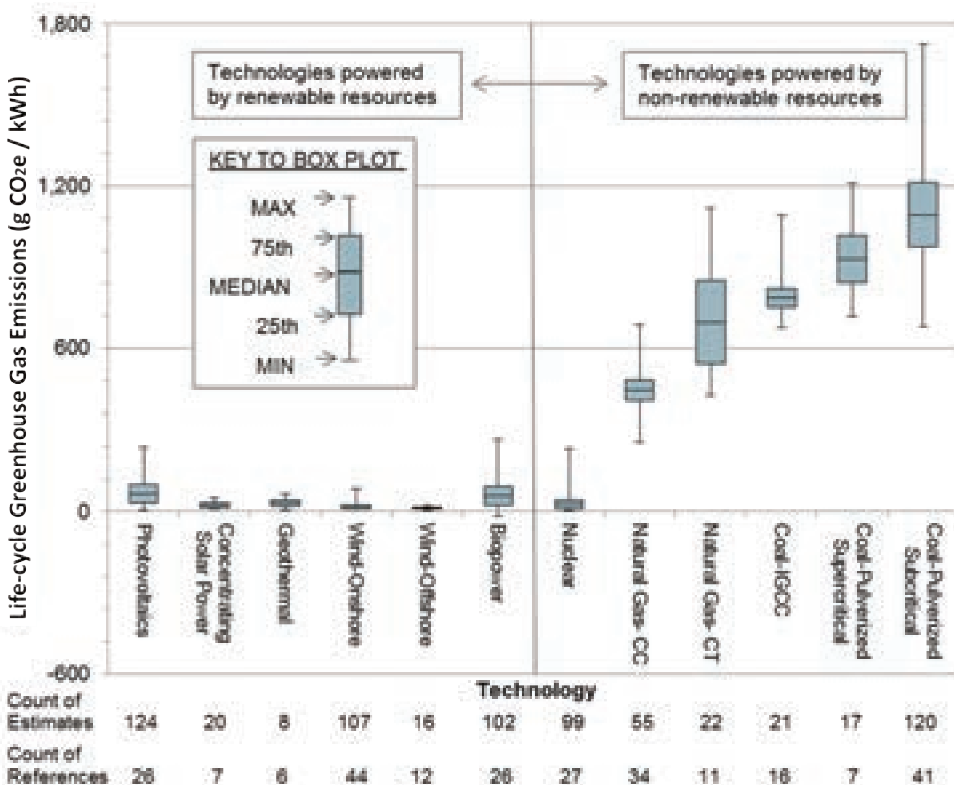
In Figure 10.2, GHG emissions for various electric generation technologies are compared.[31] In particular, two types of uncertainty bounds are shown, along with the number of estimates and references upon which each reported value is based, illustrating the relative uncertainty in GHG emissions for many technologies.

Other Emissions

In addition to GHGs, other emissions, such as criteria pollutants,[33] persistent organic pollutants,[34] and hazardous air pollutants[35] have negative impacts on the environment and human health. Moreover, some pollutants are typically emitted to water and soils.

Each year's version of the U.S. Energy Information Administration's Annual Energy Outlook[36] incorporates the projected impacts of existing air quality regulations on emissions. Emissions of nitrogen oxides (NO_X), sulfur dioxide (SO_2), and mercury (Hg) are tracked by this effort, although particulate matter (PM) and

Figure 10.2 Illustrative Comparison of Life-Cycle GHG Emissions of Various Electricity Generation Technologies[32]



Note: Reference has "harmonized" original data to correct for differences in a number of input assumptions, resulting in reduced variance. "Count of estimates" refers to the number of separate sources of data. "Count of references" refers to the number of separate studies used to provide data. Key: **CC** = combined cycle; **CT** = combustion turbine; and **IGCC** = integrated gasification combined cycle.

numerous other substances are also of concern to human health. Table 10.1 presents average emissions factors resulting from national and regional air pollution regulations for the six criteria air pollutants for selected combustion technologies.

Table 10.1 National Average Energy Efficiencies, Technology Shares for Each Fuel Type, and Criteria Air Pollutant Emission Factors (g/kWh) of the U.S. Power Sector in 2010[37]

Fuel type, combustion technology	Efficiency	Technology shares	NO_x	SO_x	PM_{10}	$PM_{2.5}$	CO	VOC
Biomass, ST	21.9%	100.0%	0.9267	0.603	2.814	1.9763	4.7546	0.1349
Coal, IGCC	34.8%	0.1%	0.1167[a]	0.0403[a]	2.4693	0.7198	0.02191	0.0012
Coal, ST	34.7%	99.9%	1.141	3.1998	0.2836	0.1994	0.1221	0.0147
NG, CC	50.6%	82.1%	0.1175	0.0041	0.0009	0.0009	0.098	0.0018
NG, GT	31.6%	5.5%	0.3452	0.0172	0.0386	0.0386	0.4458	0.0114
NG, ICE	32.8%	0.9%	3.0829a	0.0061[a]	0.4718	0.4718	3.8187	1.1102
NG, ST	32.3%	11.5%	0.8653	0.1745	0.0426	0.0426	0.4821	0.032
Oil, GT	29.4%	18.2%	2.9759	0.9438	0.3011	0.0763	0.0181	0.003
Oil, ICE	36.3%	4.6%	4.7442a	0.2274[a]	0.0138	0.013	0.0315	0.0119
Oil, ST	33.0%	77.2%	4.4825	7.6442	0.1797	0.1395	0.1676	0.0216

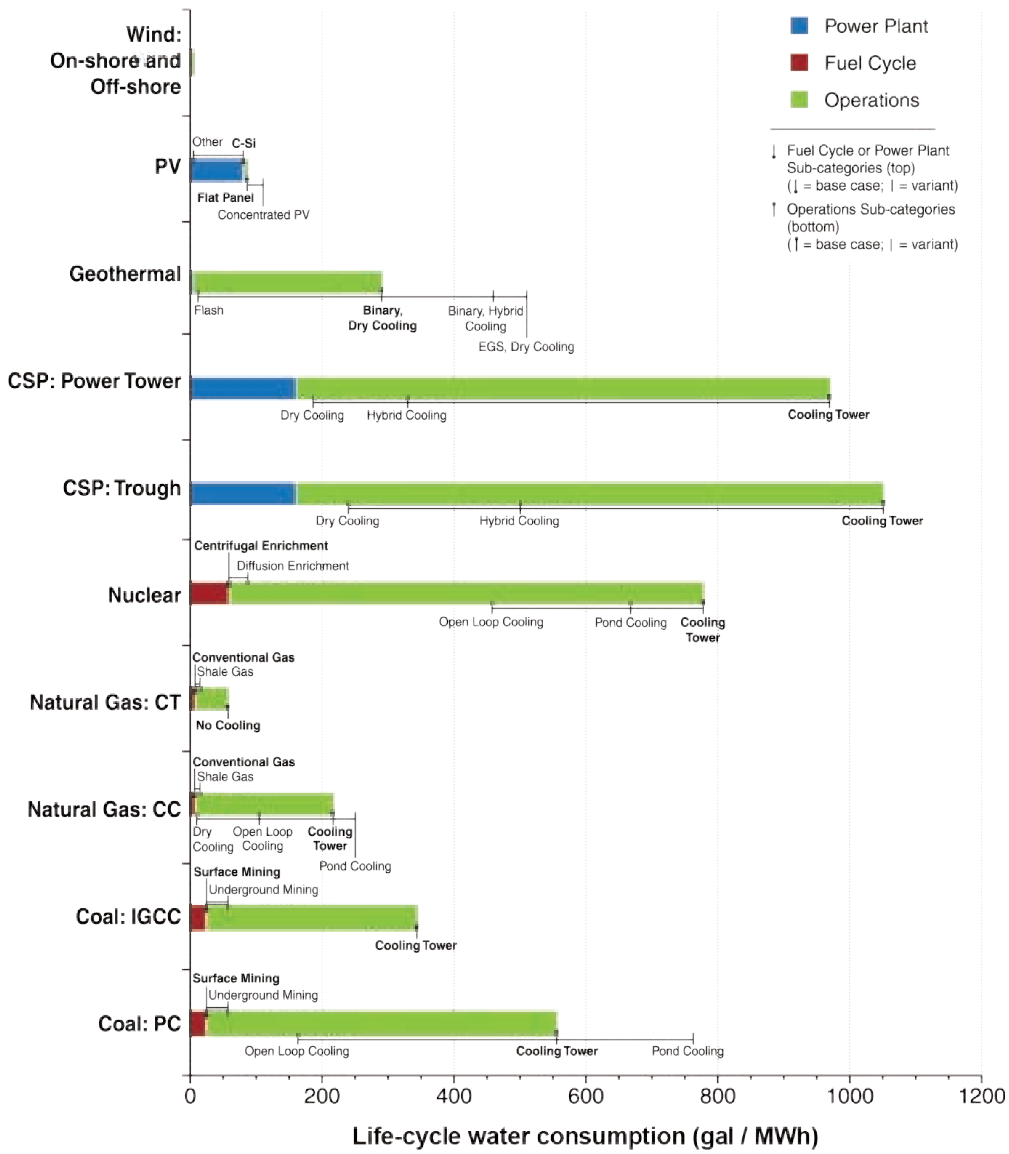
Notes: Plant-level (not life-cycle) emissions. Technology share is the ratio of the amount of electricity generated by each technology to the total electricity generation by fuel type. Key: **NO_x** = nitrogen oxides, **SO_x** = sulfur oxides, **PM_{10}** = 10 µm particulate matter, **$PM_{2.5}$** = 2.5 µm particulate matter, **CO** = carbon monoxide, **VOC** = volatile organic carbon, **ST** = steam turbine, **IGCC** = Integrated Gasification Combined Cycle, **NG** = natural gas, **CC** = combined cycle, **GT** = gas turbine, **ICE** = internal combustion engine.

[a] Adjusted based on averaged 2007 emission factors for coal IGCC, NG ICE or oil ICE as appropriate, and the 2007 to 2010 emission reduction rates of NO_x and SO_x for coal-, NG- or oil-fired power plants, respectively.

Water Use

Water is used in many phases of the energy life cycle from resource extraction and fuels production to electricity generation. With changes in climate, technology, and society, it is increasingly important to understand the withdrawal (or throughput), consumption, and degradation of water.[40,41] While some technologies use very little water (e.g., wind, solar photovoltaic [PV]), others are far larger consumers, with biofuels from irrigated crops being among the highest consumers per unit of useful output energy.[42] Thermal power plants (i.e., those using steam to spin turbines) fall somewhere in the middle, with the amount of water "lost" (to the atmosphere) depending strongly on whether it is used in a once-through (low loss) or recirculated (high loss) cooling fashion, but with a trade-off in higher degradation (via thermal loading[43]) to the water in once-through cooling. Figure 10.3 compares water consumption among electricity generation technologies as an example of the range of values that can be encountered depending on specific system assumptions. However, estimates from other sources may produce quite different results.

Figure 10.3 Life Cycle Water Consumption Estimates for Various Electricity Generation Technologies[44]



Notes: Not all cooling options are shown; for instance, more expensive, dry cooling (with zero water consumption and withdrawal) is an option for most plants. Key: **PV** = solar photovoltaic; **C-Si** = crystalline silicon; **EGS** = enhanced geothermal system; **CSP** = concentrating solar power; **CT** = combustion turbine; **CC** = combined cycle; **IGCC** = integrated gasification combined cycle; and **PC** = pulverized coal, sub-critical.

Land Use

Extracting, producing, and consuming energy all require land in some way. Fossil fuels and biomass require a significant area of land for mines, wells, and fields. Land is required for electric power generation facilities. Some of the more obvious land uses are well-accounted for in the literature, while others, such as embedded land use in transportation, are mostly absent. Comparing the required land areas can inform decision making for development and prioritization of RDD&D efforts to reduce technology or process footprints.

One major challenge to understanding land use in the energy sector is that there is no definitive source for land use energy intensity (LUEI), and as a result, metrics often have different units that are not always easily comparable.[45] The importance of the appropriate unit is key to ensure normalization of LUEI over plant lifetime. Table 10.2 presents one LUEI unit in meters squared per megawatt and values across various energy technologies. It should be stressed that these are examples only, and moreover, for land use, methodological issues remain that make comparisons across certain types of technologies extremely problematic. Most significantly, the metric does not account for intensity, or degree, of impact.[46] Extreme parameter combinations, changes in technology, and definitional ambiguity may also contribute to estimate variations. A further complicating factor is time-to-recovery. These issues are delineated in more detail in Section 10.5.7.

Table 10.2 Representative Land Use Energy Intensity Estimates for a Variety of Electricity Generating Technologies[47] (Note that these estimates are from different studies and are not comparable as they use different assumptions for what is included and how it is included—i.e., they are not harmonized)

Energy technology	m^2/MW	System boundary Power plant site only; does not consider energy resource mining or collection, processing, or transport area, or land used for waste disposal
Biomass: direct-fired	9,000–45,000	Power plant site only
Coal	270–8,000	Power plant site only
Coal: CCS	12,000	Power plant site only
Nuclear	6,700–13,800	Low estimate is site only. High estimate includes transmission lines, water supply, and rail lines, but does not include land used to mine, process, or dispose of wastes.
Energy technology	**m^2/MW**	**System boundary Energy resource extraction area plus power plant site**
Biomass: gasification	3,000,000	Site and crop area. Area used primarily driven by biomass productivity and power plant efficiency.
Coal (site and upstream)	40,000	Site and strip mining included
Geothermal: hydrothermal	1,200–150,000	Low estimate is for the site only. Upper estimate includes well-field and plant.
Geothermal: hot dry rock	4,600–17,000	Includes well-field and plant
Hydropower: reservoir	20,000–10,000,000	Site of generators and reservoir
Solar: PV	10,000–60,000	Site of PV system, which includes the area for solar energy collection. PV systems on pre-existing structures have essentially no net increase in land use.
Solar: thermal	12,000–50,000	Site of concentrating solar thermal system, which includes the area for solar energy collection
Wind	2,600–1,000,000	Low-end value is for the site only, which includes the physical footprint of the turbines and access roads. The high-end value includes the land area between turbines, which is typically available for farming or ranching (see Section 10.5.7).

Materials and Criticality

All energy technologies require materials, but the types and amounts of materials consumed vary widely. Some technologies require only common, plentiful materials such as steel, glass, and concrete, but many require varying amounts of rare materials such as noble metals. Moreover, the degree of material recycling varies widely from technology to technology and material to material, and design, as well as consumer behavior and social attitudes can have a big impact on how easily recyclable certain materials will be. Identifying materials and understanding their flows including reuse, remanufacture, recycling, and disposal are key to the inventory step in LCA. Examples of material inventories for selected vehicle types and electric power plants are presented in Table 10.3 and Table 10.4. Key materials by mass per vehicle or energy lifetime include steel, concrete, cement, glass, and aluminum.[48]

Table 10.3 Range of Material Requirements for Select Passenger Car Technologies[51]

Materials (pounds per vehicle lifetime unless otherwise noted)	Passenger car (160,000-mile lifetime)		
	ICEV	EV	FCV
Vehicle weight	2,900	3,700	3,500
Steel	1,900	2,600	2,200
Cast iron	310	74	55
Wrought aluminum	63	39	170
Cast aluminum	130	200	110
Copper/brass	53	180	160
Glass	82	130	100
Average plastic	320	450	370
Rubber	300	310	300
Carbon fiber-reinforced plastic for general use	0	0	140
Carbon fiber-reinforced plastic for high-pressure vessels	0	0	140
Nickel	0	0	3
PFSA (Nafion117 sheet)	0	0	12
Carbon paper	0	0	12
PTFE	0	0	3
Carbon and PFSA suspension (Nafion dry polymer)	0	0	1
Magnesium (g, per-vehicle lifetime)	230	360	280
Platinum (g, per-vehicle lifetime)	7	0	92
Others	54	110	84

Note: Assumes conventional materials for passenger cars. Key: **ICEV**=internal combustion engine vehicle; **EV**=electric vehicle; **FCV**=fuel cell vehicle; **PFSA** = perfluorosulfonic acid; **PTFE** = polytetrafluoroethylene.

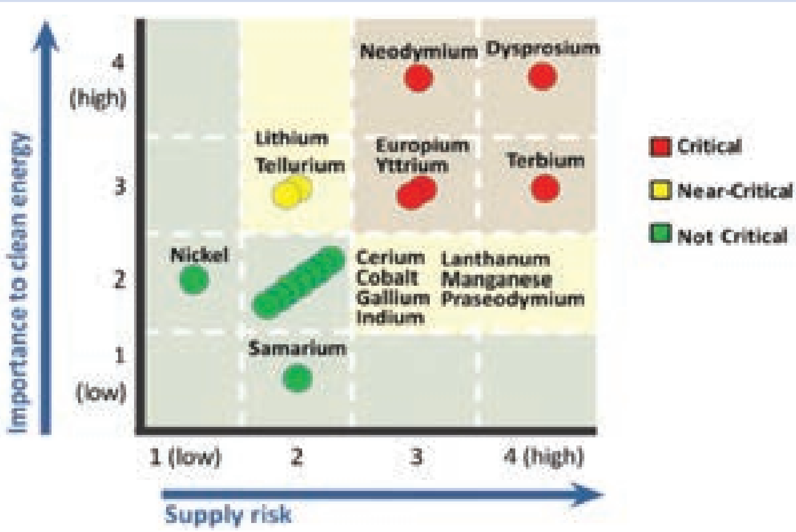
Table 10.4 Range of materials requirements (fuel excluded) for various electricity generation technologies[52]

Materials (ton/TWh)	Generator only				Upstream energy collection plus generator			
	Coal	NGCC	Nuclear PWR	Biomass	Hydro	Wind	Solar PV (silicon)	Geothermal HT binary
Aluminum	3	1	0	6	0	35	680	100
Cement	0	0	0	0	0	0	3,700	750
Concrete	870	400	760	760	14,000	8,000	350	1,100
Copper	1	0	3	0	1	23	850	2
Glass	0	0	0	0	0	92	2,700	0
Iron	1	1	5	4	0	120	0	9
Lead	0	0	2	0	0	0	0	0
Plastic	0	0	0	0	0	190	210	0
Silicon	0	0	0	0	0	0	57	0
Steel	310	170	160	310	67	1,800	7,900	3,300

Key: **NGCC** = natural gas combined cycle; **PWR** = pressurized water reactor; **PV** = photovoltaic; **HT** = high temperature

An important recent concept in the area of materials use is "criticality," which is classified in terms of importance to the clean energy economy, risk of supply disruption, and time horizon.[49] Critical materials have important magnetic, catalytic, and luminescent properties, with applications in solar PV, wind turbines, electric vehicles and efficient lighting. Five rare earth metals (dysprosium, neodymium, terbium, europium, and yttrium), as well as indium, were assessed as most critical between 2010 and 2015. Four other rare earth elements, as well as gallium, tellurium, cobalt, and lithium, were also considered. Important factors include high demand, limited substitutes, political or regulatory risks in countries where critical materials are produced, lack of diversity in producers, and competing technology demand (e.g., consumer electronics such as mobile phones, computers, and TVs all use materials that are also essential to clean energy technologies).[50] See Figure 10.4 for an illustration of a variety of these materials in terms of their importance to clean energy technologies versus risk to supply.

Figure 10.4 Critical Materials in the Medium Term (2015–2025)[56]



While many so-called rare earths are in fact more plentiful than gold and highly dispersed around the world, they are expensive to separate from ore owing in part to how similar their chemical properties are to each other. Recycling, reuse, and more efficient use of critical materials could significantly lower demand for new materials; currently, only 1% of critical materials are recycled at end of life. Other priorities include diversification of global supplies, environmentally sound extraction and processing, and development of substitutes[53, 54] (see Chapter 9, Section 9.2.2 for DOE RDD&D efforts in critical materials through the Critical Materials Institute). As some technologies could significantly increase or decrease the criticality of certain materials, it is important to include a criticality metric in assessments.

Reliability and Resilience

The reliability and resilience of the energy system is affected by factors spanning human error, malicious acts, equipment breakdowns, interdependencies with other parts of the energy system, extreme weather and other natural disasters, and more.[54, 55] Many of the technology opportunities discussed in Chapter 3 are geared toward improving the reliability and resilience of the power grid. However, some of the technology opportunities discussed in other chapters can also affect the reliability and resilience of the energy system as a whole. Thus, the potential impact of different RDD&D activities on reliability and resilience across the energy system should be considered.

The most common indicators for electric grid reliability include System Average Interruption Duration Index, System Average Interruption Frequency Index, Customer Average Interruption Duration Index, and Average Service Availability Index.[57] However, these metrics are retrospective in nature and are generally calculated based on data from the previous five years. Furthermore, the calculations will usually not include "major" events that are beyond the control of the electric utility. Finally, the data for different electric utilities and systems are often not comparable due to differences in reporting requirements by different state utility commissions.[58] Other potential metrics are based on probabilistic estimations of system failures such as Loss of Load Probability (LOLP) or Expected Unserved Energy (EUE); however, these metrics relate primarily to the delivery of energy and may not be useful in evaluating the impacts of end-use technology RDD&D activities.

Resilience is more difficult to define, but a framework for developing resilience metrics is laid out by Watson et al. (2014).[59] See Section 10.5.8.

Other Metrics

While the preceding sections list important metrics for assessing energy technologies, it is not exhaustive. Other significant metrics that might need to be considered include the following:

- Social cost of carbon
- Human health impacts
- Supply security and other diversity-related metrics
- Energy imports

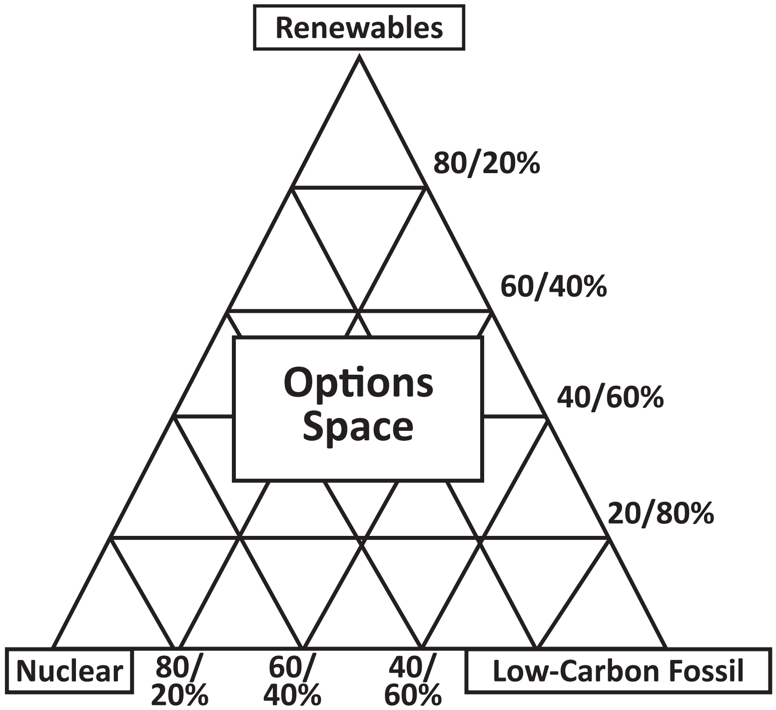
10.2.4 Evaluation Tools

Options Space Analysis

The future is highly uncertain. For this reason, it is important to invest in a broad range of technologies. An "options space" is the set of technologies that can contribute to a particular desired service (e.g., power, transportation, thermal comfort) and the characteristics needed of the technologies that will supply this service.

Figure 10.5 presents the electricity sector as an example, which identifies the major technology types for achieving near-zero GHG emissions. For this sector, there are renewables, nuclear power, and "low-carbon" fossil power, e.g., with carbon capture and sequestration (CCS), each of which has several different resources and technologies

Figure 10.5 Example of Options Space Visualization for the Electricity Sector



that can contribute. Each technology could supply a large share of electricity but probably not all of it; each also carries a different set of advantages and risks. Similar options spaces diagrams have been developed for other sectors.

Wedge Analysis

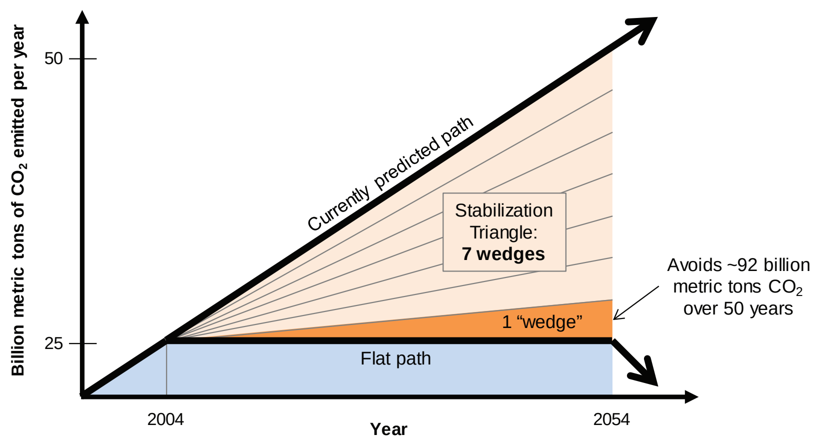
Pacala and Socolow (2004)[60] proposed a conceptual framework for assessing climate change mitigation activities that facilitates comparison of different sectors and mitigation options. The framework describes an approach to demonstrate the current technical feasibility of reducing global CO_2 emissions to the degree necessary to stabilize atmospheric concentrations, by dividing the triangular space between the business-as-usual emissions projection and the desired emissions pathway into "wedges," each of which represents the phased-in implementation of a significant CO_2 reduction activity over time. A wedge is defined as reducing global CO_2 emissions by one gigaton (that is, one billion metric tons) of carbon (GtC), which is approximately equal to 3.7 gigatons of CO_2 ($GtCO_2$) per year after fifty years, or ~92 $GtCO_2$ in total over that time period.[61, 62] This is shown in Figure 10.6. Pacala and Socolow identified fifteen available technologies, based solely on technical feasibility, which could each deliver one or more wedges. The pathway toward stable atmospheric CO_2 concentrations implies continued emission reductions beyond fifty years.

Since its publication, the wedge concept has entered the scientific vernacular, with researchers downscaling the framework to apply to national or state emissions, emissions within a specific sector, or extending it to other impacts (e.g., human health).[63, 64, 65, 66, 67, 68] The use of wedges to analyze energy portfolios is limited, however, because in most cases multiple technologies cannot be "stacked up" simultaneously in the same system without affecting one another. Moreover, assuming linear penetration of technologies over time is unrealistic and inconsistent with deployment strategies as well as economics. However, wedges provide a convenient way to visualize and approximately rank-order solutions that otherwise differ significantly in technology, impacted sector, or other parameters.

Integrated Assessment Models

The research community has extensive capabilities in multisystem, multiscale modeling, analysis, advanced computation, and data management. These include internationally recognized strengths in integrated research, modeling, analysis, and assessment of human and physical Earth systems; methods of crosscutting modeling and analysis of system interactions; and observations, data, computation, software, and user interfaces. Government and private science programs have evolved to explore important and complex scientific questions at the interface of energy, environment, and the economy that benefit from advanced computational and software capabilities. These programs have pushed the scientific frontiers in both disciplinary and interdisciplinary science. They have also created methods, models, and data tools that can be employed broadly. For example, the capabilities associated with an integrated assessment model (IAM) provide important science-based information used for scientific research. They also are used by government programs for assessing the potential impacts of science and technology advances that benefit the United States and its economy.

Figure 10.6 Stabilization Wedges Concept[62]



IAMs provide a more comprehensive description of the relationship between an energy technology, its competitors and complementary technologies, the larger energy system, and its interactions with the economy, land use, land cover, water, atmospheric composition, and climate. IAMs have been used in the assessment process to provide information about human systems[69, 70] and also to assess interactions between human and physical (Earth) systems. IAMs have decade-to-century time horizons and global spatial coverage. Typically, they employ five- to ten-year time steps, and varying regional disaggregation, but many IAMs identify the United States separately, and some models report sub-national information. For example, the Global Change Assessment Model (GCAM) includes a model branch that disaggregates the United States. into fifty states plus the District of Columbia; this same model is moving toward one-year time steps. Longer-term efforts might result in seasonal time steps, a potentially significant advancement for this class of IAM recognizing that many key systems, such as energy, water, and land, exhibit strong seasonal variations. IAMs also vary in the degree of technology detail they include. None include engineering process models, but some include a range of different technology options that distinguish between different types of solar power systems, for example, and the grade of solar resource to which the technology is deployed and whose performance evolves over time.

Two IAM teams have models with global coverage, century time horizons, and significant technology detail: GCAM, developed at the Joint Global Change Research Institute[71, 72, 73, 74] and the Integrated Global Systems Model (IGSM), developed at the Massachusetts Institute of Technology.[75, 76, 77, 78] Because IAMs are comprehensive in scope, they avoid the problem of double counting, and they do not assume that the rest of the global energy system remains unchanged as a new energy technology evolves and deploys. IAMs pick up secondary effects, such as indirect land-use change emissions for some bioenergy technologies; international trade effects, which occur, for example, when the technology for producing natural gas is enhanced; and water and land-use consequences of alternative technology deployment, e.g. expanded use of cooling towers for thermal power plants. A major limitation of global-scale IAMs is their lack of insight into local or near-term phenomena.

A new class of model called the regional integrated assessment model (RIAM) is beginning to emerge.[79] RIAMs differ from global IAMs in that they focus on local and regional phenomena over shorter timescales than IAMs. RIAMs are useful for studying economic circumstances and energy technology, characterized to reflect local circumstances, in the context of infrastructure, local topography, land-use restrictions, local ecology, climate, water, and other natural resources such as wind fields. RIAMs such as PRIMA hold the potential to shed light on local and regional energy technology deployment opportunities and limitations.[80]

While IAMs and RIAMs are powerful tools for assessing the role of technology in the context of larger regional and global contexts, they are best used in combination with information derived from complementary technology assessment tools.

Modeling, analysis, and data management capabilities should evolve with scientific and technological advancements. Five capability development areas that could benefit from further scientific and technological advancements are as follows:

- Robust projections, analyses, and scenarios at decision-relevant scales
- Characterization of uncertainty and risks
- Modeling and analysis of extreme events
- Interoperable modeling, data, and analysis platforms
- Confronting models with observations and using observations to improve projections

Each of these is discussed in more detail below.

Robust projections, analyses, and scenarios at decision-relevant scales: Decision makers need robust projections, analysis, and scenarios at decision-relevant scales. This means expanding the scope of models of human systems to include energy, water, land, the economy, and interactions with physical Earth systems that capture weather, climate, and extreme events. All of these systems interact with the others. Land is critical to successful deployment of bioenergy. Water is critical to cooling thermal power plants, producing hydroelectric power, and supporting bioenergy crops. To understand the complex interactions among these systems and provide the variety of information needed to support decisions that range from national and global scales to regional and local scales requires a suite of models. For example, improved Earth system models (ESMs) with finer spatial and temporal resolutions, and added complexity, are enabled by the progress of scientific knowledge and the availability of advanced computing capabilities and software. RIAMs provide high-resolution information about physical and human systems, including the landscape, climate, hydrology, infrastructure, and energy systems. Improved capabilities to assess impacts, adaptation, and vulnerability of energy and other human systems are needed as well as improved information transfer across disciplinary communities. Modular systems with interoperable component capabilities will help facilitate examination of a wider range of science and decision problems. The scope of the next generation of models will be broader, explicitly representing energy systems in greater technical detail, but they will also capture the interaction of the energy system with hydrologic systems, the landscape, carbon cycle, ecosystems, critical infrastructure, urban systems, atmospheric chemistry, weather, climate, and extreme events. Advancements in software and hardware technologies such as next generation supercomputers and software tools should enable more capable models with better representation of complex human-Earth systems.

Characterization of uncertainty and risks: Effectively characterizing uncertainty requires a suite of models that include state-of-the-art representation of key processes such as ESMs, RIAMs, reduced-form Earth system emulators, and long-term, global IAMs with energy, economy, water, land, and climate interactions. Models will need to be exercised in coordinated programs that transfer information between them and utilize each modeling system to highlight different aspects of uncertainty. Because human systems both shape physical Earth systems in which they are placed, and are shaped by those same physical Earth system processes, uncertainty characterizations should include socio-economic drivers of change. Analytical tools employed by researchers are unlikely to communicate well to a broader community. Additional work is needed to transform research into usable knowledge. Research is needed on the problem of communicating risk and uncertainty findings beyond the narrow communities in which they were derived. The resulting techniques for developing and communicating risk and uncertainty will provide insights that can help inform and guide investments in energy technology, leading to more robust RDD&D strategies.

Modeling and analysis of extreme events: Extreme events occur on short timescales, but can have long-term consequences. Storms and other disruptions can directly affect energy and other infrastructure. Modeling and data management tools have not generally been available to address problems that require high-fidelity representation of extreme events. Research could focus on developing higher resolution ESMs, global and regional IAM capabilities, and associated data management capabilities. Detailed examination of explicit hypothetical events can help identify system vulnerabilities and thresholds. Retrospective analysis to test new model capabilities against observations can help guide capability development.

Interoperable modeling, data, and analysis platforms: Scientific and applied questions have evolved to require increasingly sophisticated models, analysis, and data management tools capable of operating across highly-varied scales in time, space, and technical detail. Since it is the problem that determines the appropriate data, tools, and approach, an increasingly varied problem set is best addressed with a tool set that is designed from the beginning to be interoperable. Platforms are needed that can operate at relatively coarser resolution when large ensembles are needed to explore risk and uncertainty, yet which can be reconfigured with different modules to explore fine spatial, temporal, and technical issues. New community-based platforms could facilitate cross-discipline, cross-agency, and cross-model collaborations to address specific science and applied problems. New platforms should be able to employ specialized modeling tools for one problem, but lower-resolution emulators for other problems. For example, the Hector model,[81] a newly developed carbon-cycle and climate emulator, was designed as a modular, open-source, community modeling platform, to facilitate use with a wide range of alternative component modules to address a wider range of applications.

Advanced, high-performance computing enables the development of models that push the frontiers of science. This capability benefits next-generation ESMs and facilitates large ensemble calculations that provide heretofore unavailable opportunities to explore risk and uncertainty. To complement this "leadership class" computing, new visualization tools and analysis software could accelerate data analysis and model diagnostics. New software and tools could take full advantage of leadership class computing, including flexible architectures, advanced adaptive mesh gridding for scale-aware simulations—which offer the ability to deliver very high resolution for local scales—coupled hydrology, subsurface transport, and land-use and land-cover modeling.

Confronting models with observations and using observations to improve projections: Models are conditional descriptions of the major features governing phenomena. Their usefulness is contingent on the accuracy with which the relationships in the model are described, the particular phenomena of interest, and the range over which external factors have varied in the past and could vary in the future. Models need to be both anchored to observations and tested against data and observations. Models and tests can be used to describe the limits of model application and point to additional model and data needs. Open model documentation, standards, and applications can accelerate the rate of improvement of models and point to new data requirements.

Science of Human Decision Making

To accelerate adoption of clean energy technologies, RDD&D should address not only the technologies themselves, but also their design, adoption, and use. These additional requirements point to the intersection of technology, behavior, and decision science. In other words, decisions along the supply chain deserve as much attention and research as those of final energy consumers. Estimates of the energy-saving potential from human decision making in the residential building and personal transportation sectors range from five to nine quads.[82, 83, 84] Estimates of impacts in other sectors do not yet exist.

Previous researchers have used evidence-based social science to develop principles that impact the design, selection, and use of new clean energy technologies. These principles go beyond providing information to customers and focus on directly engaging energy users, understanding the context of decisions, leveraging technology for greater user control, understanding and navigating social networks, using strategic rewards to increase participation, and raising the profile of energy. Moreover, in addition to evaluation, social science research can play a key role prior to technology deployment by identifying solutions that will be more acceptable to affected groups.

Social science research has traditionally focused on consumers and less on suppliers and providers. The widespread adoption of clean energy technologies could be facilitated by RDD&D employing social and decision science insights in ways that address the problems of siting new sources of generation, transmission, and use of energy across the diverse sectors of transportation, buildings, and industry (including agriculture, construction, manufacturing, and mining). Examples range from understanding public concerns about siting of energy facilities to corporate decisions regarding the design, manufacture, and sale of efficient products.

Flexible Decision Making: Real Options Valuation

An extension of more traditional decision tree analysis, "real options" valuation is a strategic investment analysis method that parts ways with conventional financial modeling, which often undervalues investments that may lead to large but uncertain future payoff.[85, 86] Real options valuation considers the full uncertainty in future value and focuses on potential value if projects or technologies are successful. A strategy for using real options valuation is to make iterative follow-on investment decisions that do not require large outlays of funding at early stages, providing time to reduce the uncertainty in future value and hopefully improve prospects for success. Options are contingent decisions to invest depending on how events unfold.[87] Options are not free and must be created early to preserve flexibility; once it is clear that they will not be beneficial, however, they can be dropped.

10.3. Application of Metrics and Tools for Technology Analysis

As stated earlier in this chapter, multiple metrics must be considered when making prioritization decisions for investing in energy RDD&D. This can be seen clearly in discussion of LCOE. While useful to compare relative economics for technologies delivering a similar service, it can be misleading when comparing technologies that have different operating characteristics or are at different points along a deployment curve. Thus, even within the economic dimension, multiple metrics are needed to fully characterize the trade-offs among competing technologies or technology portfolios, and many of these metrics have not yet been identified. And beyond economics, numerous metrics expressing aspects of national security and the environment are also necessary to assess impacts along these dimensions. Other challenges include the need to consider how the values of metrics will change over time as technologies and the systems in which they are embedded evolve.

When one looks across sectors, the challenge of finding appropriate metrics becomes greater. One cannot, for instance, use the same metric to compare energy generation and vehicle technologies, because energy generation technologies are often expressed by LCOE (in $/kWh), while vehicle technologies are typically characterized by the levelized cost of driving (LCOD, in $/km). Similar incompatibilities exist for the other sectors under consideration. At the system level, however, it may be possible to choose simpler metrics; for instance, one could look at the full per capita cost of providing a suite of energy services across all end uses (food, shelter, mobility, health, entertainment, etc.) to a given level of quality for different energy portfolios. Similarly, per capita GHG emissions, water consumption, land use, etc., could be and have been developed (for instance, ecological footprint or per capita societal energy consumption). Nonetheless, assumptions and value judgments are still unavoidable for such high-level metrics.

Identifying the right portfolio involves four interlinked steps:

- Estimating technological improvements (in terms of cost or performance) for a given RDD&D activity, both on a stand-alone basis and as part of a broader technology portfolio
- Estimating the future system-based impacts of an RDD&D portfolio across multiple metrics, relative to a baseline without investment
- Repeating the process for multiple portfolios and comparing the impacts across multiple metrics
- Selecting the portfolio with the largest positive impact

The above-mentioned metrics must then be expressed in a ratio to dollars of RDD&D spending, in order to assess the relative benefit of different investments. Much work remains to identify, characterize, test, and refine these metrics.

Such estimates must account for the inherent uncertainty in current knowledge as well as forecasted change. As noted earlier, evaluation must also be done within an evolving context of economic, political, institutional, and social forces that contain much uncertainty themselves. It is critical that a wide range of possible outcomes be considered, in order to evaluate the robustness of technologies and portfolios.

This section ends with four examples of portfolio decision-making processes in use in different organizational contexts, spanning corporate (General Electric Research), nonprofit (Electric Power Research Institute), academic (Massachusetts Institute of Technology), and government (DOE Building Technologies Office) organizations. While each type of organization may prioritize investments based on different factors, they all share a similar challenge in having to allocate limited funds across a range of opportunities of varying levels of risk. While not comprehensive, they serve to illustrate the types of approaches currently being pursued.

General Electric Research

General Electric (GE) Research is a branch of GE that invests in research and development. GE is a large company, with consolidated revenues of $146 billion in 2013. GE-funded RDD&D expenditures totaled $4.75 billion, with an additional $711 million coming from customers (principally the U.S. government). GE has spent $43 billion on RDD&D over the past ten years.[88]

About 60% of funding comes directly from GE businesses, where they together determine the long-range RDD&D needed to support new product introduction strategies. Products are based on marketing analysis and customer feedback. Of note, businesses seldom receive any type of formal proposal from a researcher, but rather they start down an uncertain path based on prior work and the trust that has been developed through earlier collaborative work. These programs will often change direction several times as knowledge accumulates, but the majority is ultimately successful, with associated product launches.[89]

Roughly 25% of research is funded through GE corporate headquarters, and portfolio selection is different, focusing on very long-range and high-risk but potentially disruptive technologies. Often, there is no GE business to provide a commercial perspective, but GE's internal marketing team and GE Ventures provide guidance, as well as considerable judgment used in making selections. There are lower but realistic expectations for these projects, with the understanding that far fewer will ultimately become products. Solid oxide fuel cells are one example of a ten-year effort that is just now becoming commercial. A small fraction of this funding is also spent on fundamental science in GE's research areas.[90]

The remaining ~15% of research funding comes from government and customer sources, and GE generally works on projects only when there is good strategic alignment with GE's existing portfolio. This allows pursuit of additional, higher-risk options, or to retire risk more rapidly. This type of funding is also commonly used in technical demonstration projects.[91]

Electric Power Research Institute

The Electric Power Research Institute (EPRI) conducts research, development, and demonstration relating to the generation, delivery, and use of electricity for the benefit of the public. An independent, nonprofit organization, it brings together scientists and engineers as well as experts from academia and the industry to help address challenges in electricity. The fundamental research process is collaborative, and is informed by technical experience and advice from a wide array of organizations.

As an input to project identification and selection, EPRI engages in RDD&D planning at several levels.

- EPRI evaluates long-term RDD&D strategy through a combination of roadmapping and other strategic planning exercises. The horizon of these activities is usually three to ten years, and EPRI typically engages several different organizations in these processes. Consequently, at any given time, EPRI maintains an internal set of roadmaps and other strategic planning documents, typically organized around key long-term issues, which capture the results of its ongoing strategic planning activities.
- There is an annual process of evaluating past and ongoing RDD&D, and identifying and prioritizing new RDD&D projects for the upcoming year. Each research sector (Nuclear, Generation, Power Delivery and Utilization, and Environment) conducts this process in their area. Each RDD&D program has an advisory committee formed of external technical experts from funders, other research organizations, and so on. This annual process is informed by the strategic planning processes described above, and is outlined in greater detail below.
- Each research sector also runs a large number of technical workshops, conferences, and standing technical meetings that are an important source of insights related to key RDD&D priorities.
- EPRI also allocates 10%–12% of all funding to its Technology Innovation (TI) program, which operates independently to identify and pursue emergent research ideas. EPRI staff work with EPRI management to identify and propose potential projects. Typically, TI projects are envisioned to lead to inclusion of new RDD&D content in existing or new RDD&D programs. EPRI senior management reviews and approves TI projects.

The EPRI technical staff (RDD&D management, program managers, etc.) is responsible for final selection of projects and deliverables, based upon their integration of input from the planning activities described above. This integration is a highly collaborative process and involves substantial communication and iteration with advisors on an ongoing basis. The underlying philosophy is to maintain a flexible RDD&D portfolio that can be modified in response to changing priorities relatively quickly.[92]

Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT) is a premier U.S. research institution located in Cambridge, Massachusetts. The MIT Energy Initiative (MITEI) Seed Fund is an annual research grant competition open to all MIT faculty and research staff with principal investigator status (approximately 3,000 people in total). Typically, sixty to seventy proposals are submitted each year for $150,000 grants of up to two years in duration. Approximately twelve projects are funded each year, with an emphasis on high-risk/high-reward ideas. Projects are voted on by a committee composed of senior MIT faculty, and high-ranking representatives (Chief Technology Officer, or equivalent) of MITEI Founding and Sustaining Member companies. The MITEI website has a full description of the MITEI member program.[93] These companies fund the competition on an equal basis ($100,000 per member) and have an equal voice in the consensus-driven selection process. MIT typically supplements the fund modestly with philanthropic contributions, and participating faculty also weigh in. Selection is therefore inherently strongly influenced by both industrial and academic perspectives and experience. Importantly, because members have no right to the intellectual property that may be produced, selection is free of parochial interest and is much more directed by broad societal benefit.

While the size and number of Seed Fund awards are comparatively small, generally amounting to a small fraction of total member-supported research at MIT, the prestige attached to the awards, along with their influence, is high. This is, in-part, an outcome of the highly visible and competitive nature of the program, but it is also a reflection of the rare opportunity the awards provide for researchers to pursue speculative ideas, often outside their established fields. Unsurprisingly, the creation of the Seed Fund has been accompanied by a rapid increase in the scale and variety of energy-related research at MIT, with many researchers participating from outside disciplines that are traditionally energy-related. Approximately $16 million has been awarded to 129 early-stage research projects since 2006.[94]

10.4 Cross-sector Synthesis for Portfolio Analysis

The goal of portfolio analysis is to provide key data and analysis for leaders as they make decisions about the RDD&D portfolio on a spectrum of different scales, from allocating individual project funding to U.S.-wide energy considerations, and along different time horizons ranging from near-term (less than five years) to long-term (more than fifteen years). Such decisions offer alternative pathways to improve specific technologies or technology components, as well as develop promising new technologies that currently exist only as research concepts.

Portfolio analysis happens at varying levels of thoroughness, analytic rigor, and transparency. Many institutions engage in portfolio analysis and decision making, using a variety of approaches. The central question that portfolio analysis needs to address is how best to prioritize funding allocations for its RDD&D portfolio. As stated earlier, this chapter does not provide answers to this question, but it indicates approaches that could improve the evaluation of RDD&D investments.

Among the many challenges in making prioritization decisions are data and tool limitations, some of which could be inherent and thus, not easily mitigated. The data needed to calculate multiple relevant metrics are not always available or easily obtainable. Forward-looking projections, for example, often involve estimating data that is highly uncertain, making it a dynamic problem that values flexibility to make investment decisions as conditions change.

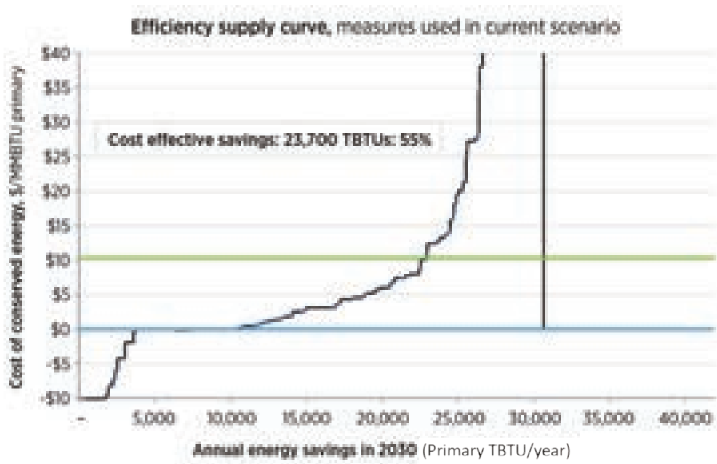
DOE Building Technologies Office

The Building Technologies Office (BTO) within DOE developed a prioritization tool (P-Tool) that calculates multiple output metrics to set RDD&D priorities for a range of energy efficient technologies. One metric is the cost of conserved energy (CCE), expressed in dollars per million British thermal units ($/MMBtu). The CCE is defined as the ratio of the net present value of incremental capital cost (including installation) of the new, more efficient equipment, divided by the primary energy savings over the equipment lifetime. Both the numerator and denominator of this calculation are relative to baseline technology cost and energy consumption, and therefore, CCE can be sensitive to the choice of baseline. Figure 10.7 shows example CCE model estimates for all building technologies, represented as a supply curve for 2030.[95] The CCE may be used to determine the cost effectiveness of a measure by comparing its value with the cost of the energy the measure saves; accordingly, the energy cost is not included in the CCE calculation itself.

Aside from CCE, the other calculated metrics are 1) technical potential primary energy savings (i.e., the maximum possible energy savings if all units were immediately replaced with the more efficient technology), and 2) the maximum adoption potential primary energy savings (i.e., the energy savings realized if units were replaced with the more efficient technology as they reach the end of their normal lifetimes, as well as all new units). The P-Tool is used by BTO to help make RDD&D investment decisions across the programs they administer. For example, analysis by the P-Tool suggested that energy savings realizable from solar water heating systems are generally not cost-competitive with energy savings that can be obtained from electric heat pump water heaters, and thus, R&D in solar water heating has been de-emphasized.

Possible future improvements to the P-Tool include: 1) addition of uncertainty to key variables (capital cost, performance enhancement, equipment life, and discount rate); 2) addition of new metrics including GHG emissions (converted to dollars via the social cost of carbon [SCC] metric), health, comfort, productivity, benefit to infrastructure, etc.; 3) regional performance estimates based on detailed building simulations in different climates; and 4) more realistic estimates of measure improvements in the context of interactions with other building systems (e.g., lighting and heating, ventilation, and air conditioning) or in bundled measures commonly implemented together (e.g., high-efficiency windows and efficient heat pump).

Figure 10.7 Efficiency Supply Curve for Baseline Assumptions in 2030 for Selected Building Technologies[96]



Key: **TBTU** = trillion British thermal units.

To perform more relevant and transparent portfolio analysis, one must move more towards an "opportunity" analysis of research pathways and couple these results with a stochastic, integrated energy-economic model of the economy that includes an acknowledgment of the social, economic, institutional, and political context that is also inherently uncertain. Portfolio comparisons need to be based on an "apples to apples" approach using the same methodologies, metrics, and assumptions. It must also make its many assumptions transparent, and perhaps make the models it uses available for public use and scrutiny.

This process begins with technology planning and projection tools (e.g., technology roadmaps, expert elicitation, etc.) to assess the likely improvement in technology cost and performance with a certain level of RDD&D investment. The next step is using quantitative assessment tools to estimate impacts across several relevant metrics.

From here, evaluation tools such as IAMs, options space analysis, wedge analysis, and real options valuation are applied, set in a probabilistic context where many options must be considered. Such information will provide decision makers with what they consider most relevant: relationships between choices and outcomes, weighted by risk. Complicating the picture is the fact that technologies do not exist in a vacuum, but they often interact with each other. For instance, an IAM study[97] systematically examined the contribution of performance improvements in a range of technologies—individually and in combination—for reducing the cost of limiting climate change to 2°C. They found that a portfolio of technologies was most effective as it provided mechanisms for reducing emissions across a spectrum of energy uses. Thus, entire portfolios, and not simply individual technologies, must be considered when evaluating impacts.

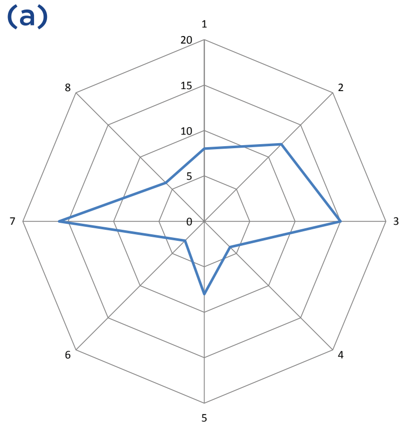
The final set of RDD&D investment decisions should be made by a diverse set of decision makers to ensure there are no personal stakes in particular outcomes. It is tempting to weight metrics in order to combine them together into a single composite metric that can be rank-ordered. Often people use cost as a weighting factor, "monetizing" other metrics using established relationships such as the social cost of carbon or the value of a statistical human life. However, such approaches are fraught with difficulties, because different people will value such weightings differently, so no such decision can ever be "optimized" in an absolute sense. The use of multiple metrics precludes a true optimization, as it is impossible to maximize multiple objective functions simultaneously, unless they are all linearly related to one another and governed by a single underlying function. Moreover, many assumptions such as time horizon, discount rate, future fuel prices, future capital cost trajectories, climate sensitivities, etc., can strongly affect the values of metrics.

In practice, the volume of data produced from such an undertaking will be too large to readily digest, and may overwhelm and paralyze decision making; instead, a balance must be found between too little and too much information. Examples include "radar plots" and "stop light" matrices,[98] which are useful to compare the multiple impacts that different RDD&D portfolios may have in a single, compact format. Figure 10.8 shows both a radar plot and a stop light matrix approach for the impacts of displaying multiple metrics associated with generic (unspecified) RDD&D opportunities. They are for illustrative purposes only.

Beyond these examples, "data browsers" or "dashboards" can be used to quickly call up data and plot it in different ways according to the desires of the decision maker. It should include the ability to combine metrics together using user-adjustable weightings. It should also include the ability to "dive deeper" into particular metrics or RDD&D investment combinations—provided the data is present in the database—through a successive disaggregation of data. Providing decision makers with choices of what to focus on may be ideal, but this will require developing a large database of portfolio combinations, input assumptions, contextual scenarios, potential metrics, and weightings, all of which may overwhelm even the most ambitious data management efforts. The ability to quickly rerun model(s) in near-real time in an iterative process to explore the change in impacts if, for instance, the portfolio is rebalanced, may be preferable, but invokes a different set of challenges.

Figure 10.8 Examples of techniques for displaying multiple metrics simultaneously include (a) radar plot and (b) color-coded stop light matrix.

(a)



(b)

RDD&D OPPORTUNITY	METRICS FOR COMPARISON				
	Metric 1	*Metric 2*	*Metric 3*	*Metric 4*	*Metric 5*
Opportunity 1	2	1	1	3	3
Opportunity 2	2	1	1	3	3
Opportunity 3	1	1	1	3	3
Opportunity 4	1	2	2	3	3
Opportunity 5	1	2	2	4	2
Opportunity 6	1	2	3	2	3
Opportunity 7	1	3	3	4	2
Opportunity 8	1	3	3	1	1
Opportunity 9	1	4	4	4	2
Opportunity 10	2	1	1	2	2

Both sets of capabilities may in fact be required and will become key enabling tools to develop. Making RDD&D investment decisions is ultimately a "soft science," but it can be made more objective and transparent through the use of approaches such as those discussed here.

10.5 Summary of RDD&D Decision Support Needs

RDD&D decisions must consider a variety of factors in an environment that is inherently uncertain, is highly dynamic, and has substantial risks. This section will first discuss the process of decision making, including the key questions decision makers must face, the issues they must address, and the metrics they must use in weighing their decisions. This is followed by descriptions of work remaining to help improve the tools and understandings that constitute the tool set of the decision makers.

10.5.1 Compendium of Issues and Metrics Considered in Energy Decisions

Any organization developing an overall RDD&D portfolio should consider questions such as those in Table 10.5. At the individual system and technology level, questions such as those in Table 10.6 should be considered. Technology RDD&D inevitably faces a variety of dynamic factors, however, as sketched in Table 10.7. This requires frequent re-evaluation of how best to guide RDD&D programs, particularly considering where technologies and markets will potentially be in twenty or more years when technologies in early stage RDD&D today may have progressed to large scale markets. The potential impacts of new technologies and systems can vary significantly across different metrics, including measures of security, economic, and environmental impacts, and also materials use, water use, land use, and others, as indicated in Table 10.8. Finally, the time frame for when a technology can be commercialized (e.g., by 2030) and provide a significant market impact (e.g., by 2050) needs to be considered. The years 2030 and 2050 may seem far away, but they can be challenging for energy technologies due to the long periods required for conducting RDD&D and achieving market impact. Notional time frames for RDD&D are indicated in Table 10.9. These can vary from relatively short periods (e.g., four years) for a commercial technology such as photovoltaics, to longer periods (e.g., ten or more years) for a technology that is large-scale, slow, and expensive to demonstrate and commercialize, and requires significant oversight for public health and safety.

For all the considerations in Tables 10.5 to 10.9, how decision makers weigh these factors varies according to their perspective of the relative importance of different challenges and national goals. These are policy decisions and are not addressed here; the focus here is on identifying approaches to provide decision makers with analytical inputs for their consideration.

Table 10.5 Portfolio-Level Questions

Issue	Questions	Considerations
Public role	Is the portfolio/system/technology appropriate for and worthy of public investment? Does it potentially provide significant public benefit? What are private sector trajectories and scenarios with and without public support?	Technology RDD&D may be too long term, too high risk, too easily appropriable, or too large an investment. Or it may face a lack of infrastructure or have unpriced externality or other public benefits, etc., that deter private investment.
Investment choice	Where should the next dollar of RDD&D investment go across the portfolio?	RDD&D investment decisions depend on the best public return as well as the overall portfolio balance.
Portfolio balance	How should the RDD&D portfolio be balanced over risk, return, time, technologies, and markets?	Any investment portfolio needs to be balanced across dimensions such as those listed here to improve return and manage risk over a time frame that matters.
Portfolio pathways	What are the best RDD&D pathways to pursue to achieve program/portfolio goals? How much benefit is provided by having multiple pathways and how many pathways are sufficient? How do RDD&D efforts connect to other public supports, such as financial incentives or mandates?	Energy RDD&D may need to pursue multiple pathways to solve a particular technology challenge, such as RDD&D on different chemistries to successfully develop CCS. The challenge is determining how many options are useful and at what point there are substantially diminishing returns.
Investment levels	What is the "right" level of investment in a technology and system?	Insufficient RDD&D investment can drop below a critical mass of researchers for there to be adequate progress; too much investment can lead to diminishing returns.
Robust portfolios	How does one ensure that the portfolio is robust? Is this picking winners?	A robust portfolio requires careful development and sufficient resources. They are formed from competing RDD&D options to improve the likelihood of success within a balanced portfolio, avoiding putting "all the eggs in one basket" of so-called winners. Portfolios are the antithesis of picking winners.

Table 10.6 Representative Criteria and Decision Questions for Systems/Technologies

Factor	Issues and questions
Security impacts	Will the system/technology reduce vulnerability to energy shocks towards zero? Will the system/technology raise reliability and resiliency to high levels?
Economic impacts	Is there a pathway for the system/technology to supply/save energy at market prices? How big is the market the system/technology could potentially address?
Environmental impacts	Will the system/technology significantly reduce criteria pollutants or air toxics? Will the system/technology reduce direct GHG emissions to near zero? Is there a transition path?
Performance requirements	Will the system/technology have additional requirements, such as for grid integration, energy storage, or others, for the system to function appropriately?
Risk	Will the system/technology face risks—technical, managerial, financial, scale-up, regulatory, institutional, business model, political—that may delay or end its large-scale use?
Time frame	Will the system/technology RDD&D impact its markets in a time frame that matters? What is the full value that the technology or system provides, including security, economic, environmental, and other factors?
Public role	Are there appropriate public roles in RDD&D for this system/technology?

Table 10.7 Representative Dynamic Factors Impacting Technology RDD&D and Questions

Factor	Issues and questions
Time frame for impact	■ A technology early to market can get costs down the learning curve, build a supporting infrastructure, and potentially lock in market advantage. A technology slow to market will have more difficulty overcoming incumbents, and will take longer to offset installation of old technology, thus increasing inertia in old systems. What is the time frame to penetrate the market for the technology versus its competitors? ■ A technology may provide near-term advantages, but then lock in factors, such as imported fuel use or environmental impacts, that are undesirable in the long term. How should near-, mid-, and long-term costs and impacts be balanced with long-term requirements?
RDD&D transitions	■ The progress of technologies can be very uneven, with long periods of slow development, followed by breakthroughs that allow rapid advance. How should these factors be taken into account in stage-gate decisions on terminating RDD&D, or exploring alternative pathways?
Transition costs	■ To demonstrate a new technology at scale and then drive costs down the learning curve to competitive levels can require an extended period (years) of cost buydown and cost billions of dollars. There may be very limited high-value market niches to initiate these cost reductions. How can advanced RDD&D accelerate this process and reduce costs? (Policies may be important but are not considered by the QTR.)
Low demand	■ Demand forecasts for energy indicate slow growth in the United States. How can innovative clean energy technologies advance when there are limited market opportunities? What market niches could the technology fill? Are they large enough to drive scale-up and learning curve cost reductions?
Global markets	■ Global clean energy markets are large and growing rapidly. Can U.S. companies remain viable without a significant presence in these markets to capture sufficient scale in production, develop specialized equipment, and earn sufficient returns for supporting high levels of RDD&D? What RDD&D would be appropriate to provide broad foundational support of U.S. companies?
Risk and uncertainty	■ Energy markets are highly volatile, yet generally require long-term, large capital investments. This raises significant challenges for long term RDD&D. How might this be addressed, including by small innovative clean energy companies? ■ How should low-risk, high-impact events be addressed? ■ Regulatory processes can be long and involved. How can the risks and uncertainties of these processes best be managed while protecting public health and safety?
Energy portfolio	■ The volatility of energy markets, risk and uncertainty of supply, and other challenges for the critical services that energy provides to our economy suggest the importance of diversification in our supply, yet this is a period when there is a pronounced emphasis on low-cost natural gas. How might the value of a diversified energy technology portfolio be evaluated and used to guide RDD&D investments?
Public-private roles	■ What are appropriate public and private roles in RDD&D on a particular system and technology? Where can public investment have the most leverage for public benefit?

Table 10.8 Representative Metrics for Evaluating Energy Technology RDD&D

Issue	Metric, per unit energy (UE) or capacity (UC), and issues
Security	■ **Reliability:** For electricity, reliability measures include the System Average Interruption Duration Index, the System Average Interruption Frequency Index, and the Consumer Average Interruption Duration Index. ■ **Resiliency:** Resiliency is more difficult to define. See Section 10.5.8.
Economy	■ **Market sales for the technology:** \$/year; this can indicate the long-term market opportunity for the technology. The large uncertainties (Table 10.3) suggest wide ranges for estimates. ■ **Cost of energy supplied or saved:** \$/UE; levelized cost of energy (LCOE) is often used, but it ignores the type of service provided and should be considered with great caution, as detailed in Section 10.2.3. Production scale and learning curve (Table 10.3) effects should be considered; security and environmental externalities could be considered as shadow costs, per environmental issue described in next row. ■ **Cost of capacity:** \$/UC; capital costs are highly sensitive to financing structure, which is influenced by market experience with the technology and changes over time. All of these effects need to be considered. ■ **Energy imports offset:** \$ total; this considers the potential of the technology to reduce energy (or technology) imports by using domestic production or efficiency gains. Macroeconomic factors due to import costs can also be considered.
Environment	■ **Criteria air pollutant emissions:** kg/UE; this includes sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), and others, that have regulatory controls limiting emissions, but the remaining emissions still have significant health and other environmental impacts. ■ **Air toxics emissions:** kg/UE; this includes neurotoxins such as mercury and lead, as well as others. ■ **GHG emissions:** tCO_2e/UE; a social cost of carbon value has been developed and can be considered as a shadow cost.[99] ■ **Water:** Pollution of water, reduction in oxygen levels, thermal heating of water, disruptions of waterways and others can be included, with corresponding metrics for each. ■ **Land:** Pollution of land, disruption of land, impacts of induced seismicity, and others can be included with the corresponding metrics for each. ■ **Health:** Air pollution mortality, such as deaths/year, and morbidity, such as days of labor lost/year or hospital visits/year, can be estimated for criteria air pollutants and air toxics emissions, but they require detailed analyses of air pollution transport and fate, and human exposure and dose response data. These data which are too complex for regular application to energy RDD&D portfolio analyses; therefore, direct emissions can be used as proxies, with parameterizations developed for estimating corresponding impacts and costs.
Water	■ **Gallons** withdrawn gal/UE—per unit energy supplied (or saved); for withdrawals, since most of the water is returned to the environment, the quality of the water returned is also important. ■ **Gallons** consumed gal/UE—per unit energy supplied (or saved); it is important to distinguish withdrawals from consumption. Since consumption is returned to the environment as evaporated water, the quality of this evaporation is not considered; any pollutants with it need to be separately accounted for above.
Land	■ **Area involved** per unit energy supplied, m^2/UE; technologies such as wind energy have widely spaced wind turbines and thus a wind "shadow" over large areas, but most of this area is still available for farming, ranching, or other uses. The area involved should not be confused with disrupted land. ■ **Area disrupted** per unit energy supplied, m^2/UE; disrupted land is not available for other uses. For wind, this includes the wind turbine pad and dedicated access roads. For fossil and nuclear energy, it includes the mined area, transport corridors, refining or power plant areas, and public safety exclusion zones. For solar, this includes areas dedicated to solar plants but does not include rooftop system areas. For biomass, this includes dedicated crop area but not crop areas where the biomass is a waste product; it also includes refinery or power plant areas, etc. Details are discussed in Section 10.5.7.
Materials	■ **Materials used:** kg/UE; this includes materials such as cement, steel, and copper. ■ **Critical materials used:** kg/UE; this includes critical materials such as neodymium, tellurium, etc.

Table 10.9 Notional Times Required for Stages of RDD&D

RDD&D activity	Notional time
Technology R&D	4*–10+ years
Regulatory/siting/other	1–10+
Technology demonstrations (one or more)^	1–10+
Financing (to mobilize capital for a full scale commercial demonstration)	1–5+
Commercial pilot	1–5+
Commercial build-out (Growth at xx%/year, depending on capital stock turnover, etc.)	

* Publicly supported R&D is generally for earlier stage technology than for private firms, thus having longer times.
^ For large energy systems, multiple demonstrations may be required to sequentially scale up to commercial size.

10.5.2 Expert Elicitation

Much additional work is needed to improve and, in particular, reduce the cost of expert elicitation. The science needs greater development (including investment in social science), better understanding of the impact of public RDD&D on private RDD&D, and different forms of RDD&D spending and cooperative agreements on technology outcomes. Also, there is a need for better modeling of technology spillover at the global level, where investment or advancement in one technology has beneficial impacts in others.

10.5.3 Experience Curve Analysis

Research could improve our understanding of the predictive drivers behind technological progress (that is, "learning" or "experience") at a more granular level, and in particular, how RDD&D investments can affect learning rates.

10.5.4 Life-Cycle Assessment

Finkbeiner et al. (2014) identified 34 gaps and challenges associated with LCA.[100] Gaps that are particularly relevant to the energy sector include double-counting of renewable energy, modeling the production or consumption mix of the grid, using a consistent approach to account for biogenic carbon flows, and including impacts of improbable events (both positive and negative), particularly when evaluating toxicity. Wender et al. (2014) discuss challenges related specifically to prospective LCA.[101]

10.5.5 Complementary Metrics to Levelized Cost of Energy

While the methods of calculating LCOE are well established, complementary metrics could more fully (and fairly) characterize energy technologies, particularly for electricity generation where many characteristics besides cost must be considered when making procurement and dispatch decisions. Research could thoughtfully consider a minimum set of metrics that would adequately describe the pros and cons of each energy technology from a performance perspective.

10.5.6 Water Use

There are numerous knowledge research gaps for water use in energy technologies. Unlike GHG emissions, which have global impacts, water impacts are local; therefore, the impacts of water consumption and withdrawal should be assessed at a local or regional level.[102] Although there are established approaches for assessing eutrophication, ecotoxicity, or ecosystem health,[103, 104] these require inventory flows at the regional or local level, and without this data, it is difficult in practice to implement established impact methodologies. Efforts to address this gap in the near term have been developed through allocation assumptions,[105] but regionalized water inventories are needed in the long term. Although the U.S. Geological Survey (USGS) tracks water withdrawals at the state and county level every five years, it does not currently track water consumption.[106] A specific data gap for electric power includes limited data availability for new or small-scale technologies, as the U.S. Energy Information Administration's *Annual Electric Generator Survey* only requires water use reporting for power plants that are larger than 100 MW.[107] Addressing this could be an initial step in developing regionalized water inventories.

10.5.7 Land Use

The studies reviewed in Table 10.2 are binary in that they only count land as used or not used. In many cases, land can be occupied but not used exclusively by its occupier. For example, farming and grazing can still occur around wind turbines. Several studies attempted to limit this effect by only counting the land area actually occupied by the facilities and equipment (rather than the full area bounded by the site).[108, 109] Similarly, nuclear power plants are surrounded by safety exclusion zones beyond the site boundary that are not directly necessary for the production of energy. The land within this zone is useful for wildlife and recreational activities, but its use is limited because no development can occur there due to safety restrictions. A binary metric is ill-equipped to handle such a case. Nor is it helpful with dual-use situations, such as the reservoir behind a hydroelectric facility, which can be heavily utilized for irrigation, recreation, and flood control along with electricity generation.[110]

There are also technology-specific factors to be considered. Extreme parameter combinations, changes in technology, and definitional ambiguity may all contribute to variations in land use estimates. For example, it is not always clear whether "land use" or "land requirements" account for roads, occupied by undeveloped land surrounding generating units, in addition to facilities and other physical infrastructure.

A further complicating factor is time-to-recovery.[111] Use that impacts land so little that it can recover to its previous state in a matter of months or a few years after use ends should not be counted the same as use that delays full recovery for decades or centuries. However, this information cannot be preserved in the binary study metric. Additionally, land used to supply renewable energy, can continue to produce energy in perpetuity whereas land used to produce energy from coal, gas, oil, or nuclear fuels will depend upon resources that are depleted over time, requiring new lands to be opened for resource extraction. Further work is critically needed to determine appropriate land-use metrics for meaningful cross-comparisons.

10.5.8 Reliability and Resilience

Watson et al. (2014) lay out a framework for developing resilience metrics and designing a Resilience Analysis Process (RAP).[112] While the report focused on the generation, transmission, and distribution of energy (electricity, oil, and natural gas), the framework could be extended to include end-use sectors. A significant effort will be required to implement a robust RAP process. This includes improvements to analytical models to be able to measure the impact of different events with respect to geographical and temporal impacts. Methods also need to be developed to model human interactions with the energy system from both operator and consumer standpoints. Analysis will also be required to translate the model output into economic and social costs.

10.5.9 Science of Human Decision Making

Among the challenges for improving decision science research are the following:[113]

- Integration of behavioral, institutional, and technological aspects of decision making
- Rigorous analysis and social science expertise to identify what works in different contexts
- Use of established theory and research design to implement projects including rigorous baselining to allow comparison of results

- Use of standard, robust, and well-defined methods for research, evaluation, validation, and dissemination
- Promotion of an enduring institutional transformation by evaluating outcomes to determine what strategies work best, which should be revised, and which are not effective
- Sponsorship of social science research to build the evidence base for successful decision-making strategies

10.5.10 Portfolio Analysis and Prioritization

From the wide variety of potential metrics, organizations need to decide upon a set that will best serve their prioritization objectives and allow for comparisons across technologies, sectors, and portfolios. A sufficiently-detailed model of integrated economy-environment-security systems to represent technology changes arising from RDD&D investments improve evaluation of these metrics, including the ability to rapidly rerun analysis in near-real time with different RDD&D investment distributions, metric weightings, or other inputs. Such evaluations should be done within a robust uncertainty/risk framework to capture a realistic range of outcomes. Finally, visualization tools aid decision makers by allowing them to explore and manipulate the resulting multidimensional metrics.

Many tools, while they exist, have not yet been combined and tested in the manner suggested here, and an overall candidate approach has yet to be developed. The following process could be considered to aid in this development:

- Evaluation of the effectiveness of different approaches, with follow-up discussions among experts to better understand strengths and weaknesses
- Small-scale experiments with promising approaches and tracking key performance factors ranging from effectiveness to overhead costs
- Development of a research plan going forward to resolve methodological issues and implement an objective portfolio analysis process that can systematically and rigorously develop RDD&D investment options and articulate trade-offs

Supplemental Information

Additional Information on Concepts in Integrated Analysis

[See online version.]

Endnotes

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