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Application of systems readiness level methods in advanced fossil energy applications

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Abstract

The Department of Energy's Fossil Energy Program (FE), through the National Energy Technology Laboratory (NETL), has been tasked with developing fossil energy technologies to meet U.S. greenhouse gas emissions reduction goals for over a decade. NETL has adopted Technology Readiness Levels (TRL) for the last five years to estimate progress in technology development under its research portfolio. Advanced fossil energy systems need to be tested at full-scale in an integrated facility before they can be considered ready for commercial deployment. Commercial-scale demonstrations of energy technology present numerous challenges associated with first-of-a-kind facilities, one in particular being the need to integrate multiple emerging technologies that were previously demonstrated in pilot-scale applications into a design that can be constructed and operated under commercial plant operating conditions.

Systems Readiness Level (SRL) methodology is an analysis approach developed by the Department of Defense (DoD) as a metric for assessing progress in developing major military systems. SRL methodology builds on Technology Readiness Levels (TRL) widely used in government agencies to assess the maturity of emerging technologies under development. To estimate the level of readiness of a system comprising multiple emerging technologies in their current state, SRL methodology unites the TRL for each technology with Integration Readiness Levels that express the need

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for each of these technologies to be integrated with other technologies in the system. A matrix algebra approach is then used to estimate an overall level of systems readiness for the intended system.

NETL tested SRL methodology in a pilot application with the objective of developing better analysis tools to support major decisions regarding advanced fossil energy technologies. NETL applied SRL methodology to estimate the readiness of two advanced fossil energy technology projects using data that was available at the time they were initiated. This paper describes the successful pilot application, the lessons learned and the potential for SRL methodology to support technology development.

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Keywords: Systems Readiness Level (SRL); Technology Readiness Level (TRL); Integrated Gasification Combined Cycle power plant

1. Introduction

Commercial-scale demonstrations of advanced energy technologies help industry understand and overcome early technology adoption and scaling issues. The opportunity for private financing and investment for subsequent plants is greatly improved by reducing the risk profile associated with new and often first-of-a-kind technologies. Since 1985, DOE/NETL has been successfully funding large-scale demonstrations of advanced fossil energy technologies to hasten their adoption into the commercial marketplace. These major demonstrations form a key part of the integrated research, development, and demonstration (RD&D) program conducted by NETL.

NETL is addressing key challenges affecting the wide-scale industrial deployment of carbon management technologies by sponsoring large-scale demonstrations of key technologies integrated into power-generation and industrial facilities. The integration of emerging technologies in prototype systems functioning at commercial scale in field performance environments will always introduce some level of risk and create a continuing need to balance opportunities for breakthrough performance while limiting technology risk to an acceptable level. While the risk of implementing first-of-a-kind commercial-scale demonstration projects cannot be reduced to zero, the risk associated with introducing new and emerging technologies into such systems can be better understood, communicated, and minimized. Over the last five years, NETL has adopted Technology Readiness Levels (TRL) to estimate progress in research and development of key fossil energy technologies. NETL has found TRL metrics to be suitable for estimating the level of technological maturity for emerging technologies under development. However, the integration of emerging technologies into advanced energy system projects introduces an additional level of complexity such that it has been difficult to assess RD&D progress with TRL metrics alone.

SRL methodology was developed by the Department of Defense (DoD) as an outgrowth of a decade-long effort to develop improved methods and data to assess the readiness of military hardware/software systems under development, particularly if the technologies in question were still in the process of maturing and/or had not been required to function in an integrated manner. SRL methods were first proposed by researchers at the Stevens Institute of Technology (Systems Development and Maturity Laboratory)[1] under contract to the Office of the Secretary of Defense Acquisition Research Program–Naval Postgraduate School, as a means of addressing weaknesses in a strictly TRL-based approach to managing the development of complex weapons systems. In the original work, TRLs were used to estimate the level of technological maturity of the emerging technologies, Integrated Readiness Levels (IRL) to characterize the maturity of technology interfaces, and a calculated System Readiness Level (SRL) to characterize the overall state of readiness of the system for the intended application. Similar to descriptions of various levels of technology readiness, nine levels of integration readiness were defined for technology interfaces that could be estimated using the best (historical or experimental) evidence available.

SRL methodology was applied in a prototype evaluation by the U.S. Navy to estimate systems readiness of technologies being developed in its Littoral Ships Program[2]. The SRL process has undergone further review and testing by DoD organizations, and at least one early review was negative[3]. However, since its inception, the methodology has been applied to a number of applications[4], particularly for monitoring development of integrated technologies and systems of systems. SRL methodology has been suggested as one of the key and evolving methodologies with significant potential to support a broad range of systems acquisition programs in the future[5]; the National Security Administration has recently prepared a handbook for Systems Readiness Assessments to be used to support its complex technology development and integration activities[6].

2. Conduct of the Pilot Study (What Was Done)

NETL's interest in SRL methodology was as a means of incorporating TRL metrics, already accepted for use in assessing progress of the R&D portfolio, into a more comprehensive approach that could be used to assess the readiness of complex systems of individual technology elements to perform in an integrated fashion as part of a total system. If SRL methodology could be successfully demonstrated for the complex projects being managed through NETL, it could provide a ready tool for managing complex RD&D activities.

Adapting the DoD SRL methodology for use in fossil energy technology demonstrations involved development of IRLs and a basis for interpreting quantitative SRL values. It was important in the pilot study to develop definitions of IRLs that were consistent with the definitions developed previously for military systems and applications, but also suitable for assessing the level of demonstrated integration of technologies in energy related projects. Equally important were the defined ranges of values that would be used to interpret calculated SRLc scores for fossil energy projects. Since the pilot application did not afford an opportunity for developing a broad user consensus, the SRL pilot team adapted DoD defined ranges of SRLc values to fit DOE energy projects. Tables 1 and 2 provide definitions of TRLs and IRLs that were developed for the DOE pilot project.

Table 1. Technology readiness level definitions

	Technology Readiness
9	Actual system operated over the full range of expected conditions
8	Actual system completed and qualified through test and demonstration in a plant environment
7	System prototype demonstrated in a plant environment
6	Engineering / pilot scale, similar system demonstrated in a relevant environment
5	Laboratory scale, similar system validation in relevant environment
4	Component and/or system validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof of concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

Table 2. Integration readiness level definitions

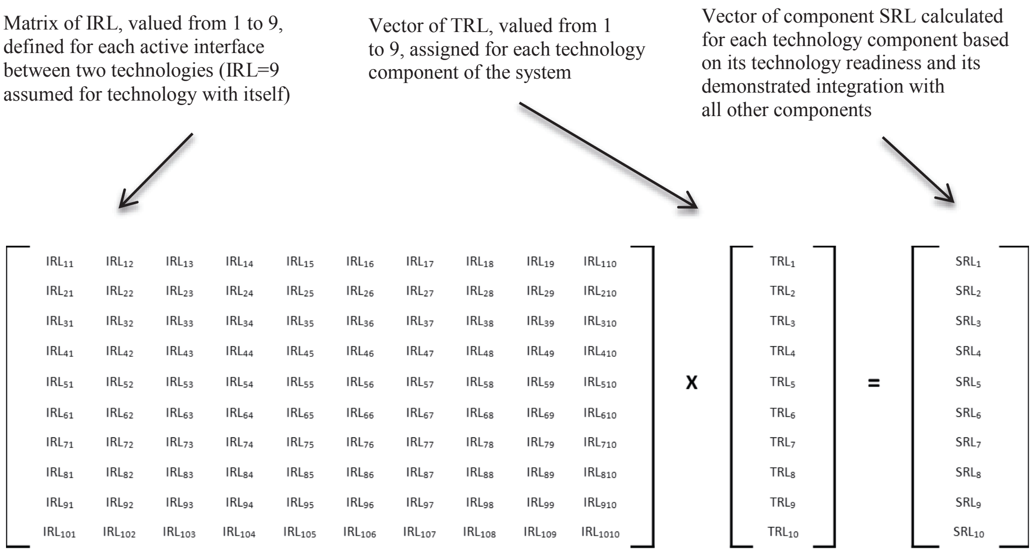
	Integration Readiness
9	Integrated functionality among technologies successfully demonstrated in Nth-of-a-kind application with planned system configuration & design
8	Integrated functionality among technologies successfully demonstrated in Nth-of-a-kind application in relevant environment
7	Integrated functionality among technologies successfully demonstrated in 2nd application in relevant environment.
6	Integrated functionality among technologies first successfully demonstrated at commercial scale
5	Most elements of integrated functionality among technologies in the application successfully demonstrated
4	Some level of integrated functionality between technologies in application successfully demonstrated
3	Compatibility of technologies and requirements for technology integration in application established
2	Requirements for technology integration in application are characterized with some specificity
1	Need for integration of technologies in application identified or speculated

Table 3 provides ranges of consensus SRL values and their interpretation in terms fossil energy technologies.

Table 3. SRL ranges and definitions for advanced fossil energy demonstration projects

SRL	Name	Definitions
0.90 -1.00	Operations and Support	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-efficient manner over its total lifecycle.
0.80 - 0.89	Production and Deployment	Achieve operational capability that satisfies mission needs.
0.60 - 0.79	System Development & Demonstration	Develop system capability (or increments thereof); reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility.
0.40- 0.59	Technology Development	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
0.10 - 0.39	Concept Refinement	Refine initial concept; develop system/technology strategy.

Finally, Figure 1 shows the calculational basis for evaluating a consensus SRL for a project (SRLc)



Composite SRL for System = $\sum SRL_{1,10}/10$

Figure 1. Calculational basis for evaluating a consensus SRL for a project (SRLc)

For the SRL pilot study, the team chose two past projects involving commercial scale technologies. These past and now completed projects were chosen because (a) they were typical of projects (historically) that have been funded as major fossil energy demonstrations, and (b) both projects had been implemented to completion, providing an opportunity to test the SRL methodology against known outcomes. In this way, its usefulness for identifying potentially significant technology issues early in projects could be demonstrated.

The SRL pilot team followed the same process for both pilot applications:

- Project documentation was assembled that included project descriptions, technology experience, and conceptual design studies available at the time the decision to fund the project was made†.
- A working process model was developed based on the project system configuration (Figure 2), and used to identify the role of each technology and the working interfaces between technologies.
- TRLs for critical technology components were estimated‡. Uncertainties in technology readiness for each technology were captured concurrently using an upper and lower bound on the TRL for each technology.

† Technologies were considered critical for SRL purposes if the system assembled for the project could not function otherwise, and if the technology had working interfaces with other technologies other than supplying water or power to the working process.

‡ TRL definitions and descriptions currently used for tracking progress on technology development projects comprising NETL's R&D portfolio were used (Reference FE TRL Guidelines published in 2012).

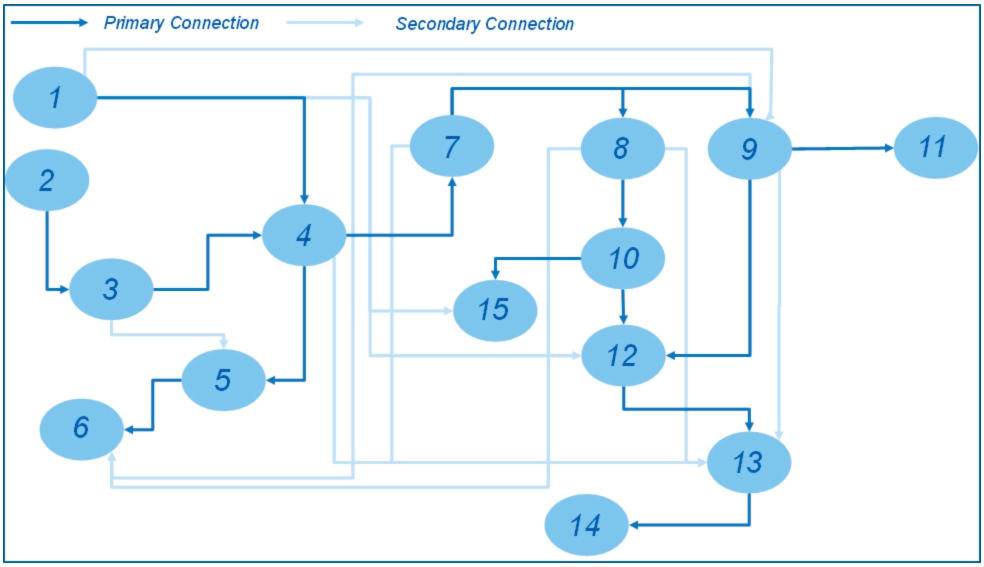


Figure 2. Directed digraph, plant B project proposal

- IRLs to capture the demonstrated maturity of each interface were estimated. As with the TRLs, a sense of the uncertainty of the demonstrated maturity of each interface was captured using upper and lower bound estimates of the IRL for each technology interface.
- A calculational matrix[§] (Figure 3) was developed and used to estimate a set of contributed SRLs for each technology and a consensus SRL score (SRLc) for the project. Three evaluations of SRLc provided the SRL team with a perspective on the bounds of system readiness that could be produced with existing data. The consensus SRL score was then compared with the range definitions of SRL values to arrive at a rated systems readiness based on the calculated information.
- A Monte Carlo simulation was performed to estimate the sensitivity of the set of contributed SRLs and the composite SRL for the system to uncertainties in the input information.

On one project (Plant A), a critical design change was made during the final design phase. This offered the SRL pilot team an opportunity to test the sensitivity of the consensus SRL scores to changes in design and other refinements of technologies and interfaces as the project advanced toward implementation.

§ For a system with N component technologies, this is an NxN matrix with values reflecting the IRL for identified significant interfaces.

	IRLk,1	IRLk,2	IRLk,3	IRLk,4	IRLk,5	IRLk,6	IRLk,7	IRLk,8	IRLk,9	IRLk,10	IRLk,11	IRLk,12	IRLk,13	IRLk,14	IRLk,15	TRLk
IRL1,k	9	0	0	7	0	0	0	0	2	0	0	4	0	0	8	9
IRL2,k	0	9	8	0	0	0	0	0	0	0	0	0	0	0	0	9
IRL3,k	0	8	9	7	7	0	0	0	0	0	0	0	0	0	0	8
IRL4,k	7	0	7	9	6	0	6	0	0	0	0	0	6	0	0	8
IRL5,k	0	0	7	6	9	7	0	0	0	0	0	0	0	0	0	8
IRL6,k	0	0	0	0	7	9	0	7	2	0	0	0	0	0	0	8
IRL7,k	0	0	0	6	0	0	9	6	4	0	0	0	6	0	0	8
IRL8,k	0	0	0	0	0	7	6	9	0	7	0	0	6	0	7	8
IRL9,k	2	0	0	0	0	2	4	0	9	0	2	2	2	0	0	4
IRL10,k	0	0	0	0	0	0	0	7	0	9	0	6	0	0	7	8
IRL11,k	0	0	0	0	0	0	0	0	2	0	9	0	0	0	0	9
IRL12,k	4	0	0	0	0	0	0	0	2	6	0	9	7	0	0	7
IRL13,k	0	0	0	6	0	0	6	6	2	0	0	7	9	8	0	9
IRL14,k	0	0	0	0	0	0	0	0	0	0	0	0	8	9	0	9
IRL15,k	8	0	0	0	0	0	0	7	0	7	0	0	0	0	9	9

Figure 3. SRL model for plant A project proposal stage

3. Results of the Pilot Study (What Was Learned)

Results of the SRL evaluation of one project at the time the project was initiated are shown in Table 4.

Table 4. Composite SRL calculation for project proposal stage

Subsystem		Subsystem SRL Contribution1	Best Estimate	Lower Bound	Upper Bound	Simulation2
1	Technology 1	SRL1/n1	0.60	0.56	0.67	
2	Technology 2	SRL2/n2	0.90	0.85	0.94	
3	Technology 3	SRL3/n3	0.79	0.74	0.87	
4	Technology 4	SRL4/n4	0.70	0.65	0.79	
5	Technology 5	SRL5/n5	0.72	0.67	0.79	
6	Technology 6	SRL6/n6	0.59	0.58	0.65	
7	Technology 7	SRL7/n7	0.59	0.54	0.67	
8	Technology 8	SRL8/n8	0.72	0.65	0.80	
9	Technology 9	SRL9/n9	0.27	0.21	0.37	
10	Technology 10	SRL10/n10	0.72	0.65	0.79	
11	Technology 11	SRL11/n11	0.55	0.52	0.57	
12	Technology 12	SRL12/n12	0.54	0.46	0.61	
13	Technology 13	SRL13/n13	0.62	0.55	0.70	
14	Technology 14	SRL14/n14	0.94	0.89	1.00	
15	Technology 15	SRL15/n15	0.82	0.74	0.90	
		SRLc	0.67	0.62	0.74	0.67

<u>**Notes**</u>

1 - Contribution of subsystem technological and integration readiness (normalized) to composite system readiness

2 - Only composite SRL is simulated, and mean is provided for comparison

The best estimate, lower bound, and upper bound estimates all verified that the system as originally proposed could be considered for a demonstration project. In addition, the SRL estimates indicated that most of the technologies had evolved to a sufficient level of technology maturity, and a sufficient level of experience existed to integrate the technologies into the proposed system application. Table 4 shows that the readiness of the plant system was significantly reduced by inclusion of a technology with a low level of demonstrated technology maturity. The SRL for Plant A was re-evaluated with this system bypassed (consistent with the final engineering design) and the simulation SRL calculation indicated that the impact of this design change on overall system readiness was substantial (Figure 4).

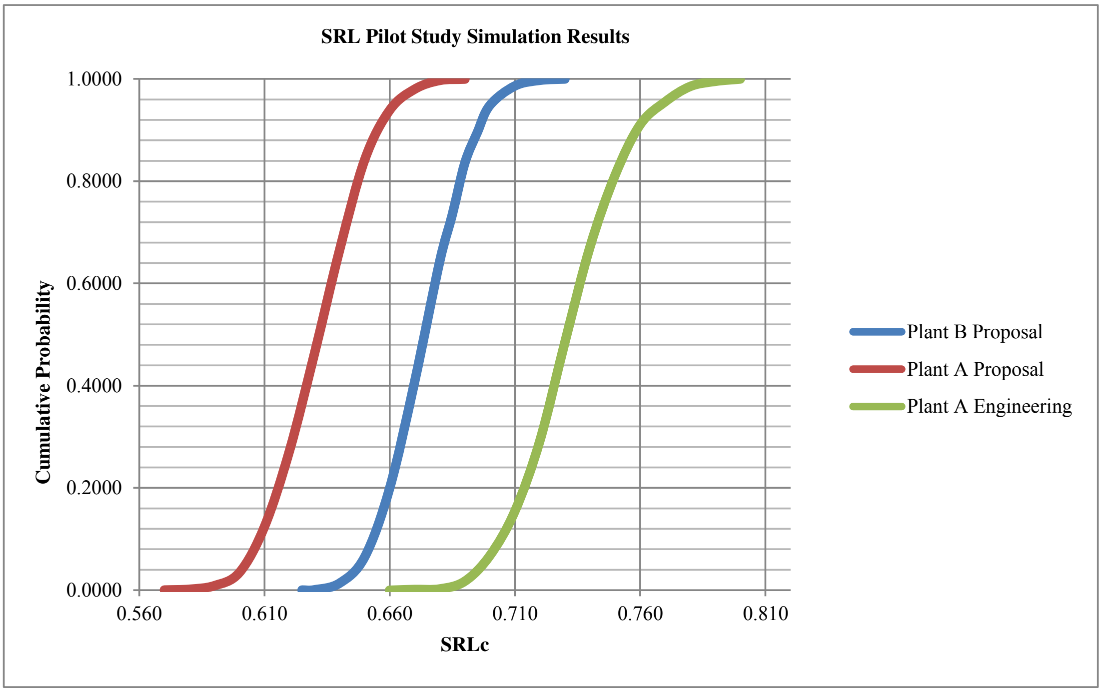


Figure 4. Comparison of simulated SRLc for two projects

The results of the pilot study for the two projects indicate that SRL methodology, with further refinement, can provide an effective basis for supporting technical planning and decision-making on major energy projects.

- The SRL pilot team developed a consistent basis for translating DoD readiness level definitions and descriptions of IRLs for use in describing energy projects. The team was also able to agree on a draft set of ranges and descriptions for interpreting consensus SRL estimates.
- The SRL pilot team was able to arrive at an informed consensus on the TRL for each technology (subsystem), the IRL for each significant technology interface, and the ranges of uncertainty surrounding various inputs to the SRL evaluation.
- The SRL pilot team was able to consistently estimate the system level readiness (SRLc) of projects based on the information provided. The team was also able to reach consensus on the fact that SRLc values captured the state

of the integrated system technology development at the time proposals were submitted, and in light of the project histories that ensued.

- The team was able to effectively estimate the impact of uncertainties in input data using Monte Carlo algorithms.
- The SRL pilot team was able to demonstrate the capability of the SRL methodology to track progress in refining project designs based on differences in the SRLc calculated for one project between the proposal and final design stages.

4. Building on the DOE Pilot Study (Where Can We Go From Here)

The methodology developed and tested in this pilot study was based on DoD SRL methodology used for assessing the readiness of new military technology systems. Several government organizations and contractors have conducted prototype applications of SRL methods. One, the National Security Agency, has published a handbook for use in applying the methodology to the acquisition and deployment of new technology.

SRL methodology is of value for applications because it unites the concepts of TRLs that are currently used to assess progress in technology development, with IRLs that address the extent to which the contributing technologies are ready to be integrated into a system that can meet objectives and program goals. Use of SRLs to define the demonstrated level of technology integration supplements the use of TRLs where a single project unites multiple technologies in various phases of development, or where technologies from multiple RD&D processes must be coordinated to perform as a system of systems. The results of the pilot study suggest that SRL methodology can be applied within an R&D portfolio to improve understanding, evaluation, and communication of risks associated with first-of-a-kind commercial-scale demonstration projects.

SRL methodology may be an effective tool to support several aspects of major project planning, selection, and execution, including

- Support for planning procurement objectives and technology maturity requirements
- Down selection of proposed projects for award
- Identification of additional information requirements to reduce mission risk prior to award
- Evaluation of project progress as a basis for management actions and decisions

For government agencies performing RD&D activities, SRL methods can supplement technology readiness assessments to provide an overall state of readiness for complex projects integrating emerging and legacy technologies. Also, for evaluating contributors to emerging technology readiness, several DoD applications have demonstrated that SRL evaluations can be performed in a nested hierarchy**. As such, subsystems or component technologies that limit the overall readiness of a system can be treated as systems with readiness evaluated at a further level. In this way, SRL evaluations of systems composed of promising but immature technologies can be used to support planning of technology developments and selection of competing projects with the best prospects for success. SRL methodology can thus help balance opportunities for breakthrough performance (through successful introduction of new technology) with the need to limit technology risk to an acceptable level in the execution of program activities.

Based on the pilot study, NETL is encouraged to continue development of SRL methodology as a tool to support program management activities at the Laboratory. NETL is aware that several refinements are needed for reliable and comprehensive application of the methodology:

** In a nested hierarchy, a subsystem is defined to embrace all functions associated with its performance, and its boundaries are defined to include all interfaces with other systems (process, control, information) that are needed for required inputs and outputs. Translating SRLc into a set of readiness levels, the system readiness of the evaluated subsystem becomes the technology readiness level for a component of a larger system.

- Current definitions of Integration Readiness Levels and the means of scoring the maturity of technology interfaces need to be refined and broadened to consider technology systems radically different from the advanced gasification systems considered in the pilot study.
- The concept of using a nested analysis approach to demonstrate the impact of complex subsystem interfaces on system readiness needs to be demonstrated and evaluated as a tool for staged application of SRL methods to assess RD&D needs.
- A literature review is needed to identify other methods for identifying and evaluating systems technology integration issues associated with prototype and first-of-a-kind system applications.
- It is understood that for specific technologies, as the technology readiness increases, the level of technology risk decreases; however, the cost and complexity of further reducing technology risk can (in some cases dramatically) increase. The current SRL methodology does not consider increasing back-end resistance as an impact on the allocation of RD&D investment and a means of evaluating and capturing this effect on system readiness should be developed.
- The application of SRL methodology may need to be refined to adequately identify the difference between technology risk (that is associated with integrating emerging technologies into a system) and project management risk inherent in any commercial scale prototype that is mainly a function of project complexity and management processes.

Given the successful implementation of NETL's methodology refinement efforts, SRL methodology can be introduced into project management operations as a means of applying TRL-style metrics to the planning and execution of a range of integration activities associated with optimized management of the RD&D portfolio.

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