Transdisciplinarity and the Future of Engineering
B.R. Moser et al. (Eds.)

doi:10.3233/ATDE220647

Systems Engineering for Innovation Portfolio Management in the Energy Industry

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Abstract. The establishment of development pipelines for innovative technologies is a familiar aspect of digital transformation within the energy industry. One variant relies on innovation teams to rapidly prototype ideas as Proofs-of-Concept (POC) that, when successful, are matured and commercialized as new technical solutions within product lines. However, as the number of ideas grows, diversity of in-scope energy systems broadens, and resources remain constrained, identifying the highest-value ideas aligned with innovation goals and enterprise strategy has become paramount. We outline a prioritization and selection (PAS) approach founded on systems engineering (SE) to manage the work progressed within an innovation team. Specifically, we adapt the tradespace methodology for design selection when stakeholder needs and project constraints create a multi-objective optimization problem. The assessment combines a rigorous stakeholder analysis and surveys to characterize a multi-attribute utility function measuring POC benefit. POC resources are estimated from anticipated duration, development needs, validation requirements, and process change required by the technical solutions. These metrics characterize cost-benefit trade-offs, complemented by innovation measures associated with each POC. The final end-to-end workflow enables innovation idea comparisons with a dashboard to guide POC selection, portfolio shaping, and work prioritization across multiple energy disciplines and industry asset classes.

Keywords. Systems thinking, system engineering, decision support tools and methods, value engineering and practice, portfolio management, innovation

Introduction

Digital transformation in the energy industry has progressed into a broader evolution of organizational structures, project management practices, and innovation governance [1–3]. Integrated, cross-functional platforms focused on the maturation and delivery of digital solutions are replacing traditional paradigms like stand-alone research laboratories, skunkworks teams, and hybrid technical service and innovation roles. Within each platform, product lines develop *minimum viable products* (MVPs) that, upon meeting a level of certainty for business value creation, will be hardened into deployable technologies in alignment with standards around security, scalability, and broader technical dependencies. Product line backlogs contain a collection of prototypes not yet selected for active development as an MVP. These technical solutions address challenges with a proven but potentially non-optimized form, sometimes referred to as a *proof-of-concept* (POC). Even earlier in the process are unproven ideas, which must be

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investigated through rapid prototyping and run a high risk of failure. Figure 1 illustrates these stages as an innovation pipeline, building from idea to deployable capability.

Figure 1. Maturation hierarchy of innovation concepts from idea to minimum viable product. Attributes and owners of the different innovation stages are noted.

Firms can promote a healthy and active innovation pipeline by building the necessary culture, including the formation of fully-dedicated innovation teams tasked with identifying, engineering, and validating POC solutions [4-6]. Under the constraints of limited resources and time, these teams may maintain a backlog of ideas to work on. A fraction of the ideas can be selected for active POC development at any given moment as capacity allows. However, selecting ideas from a backlog can be a challenging task, particularly in the energy industry as the energy transition creates a new innovation landscape to be balanced with mainstream business problems.

The underlying prioritization and selection (PAS) methodologies may vary from ad hoc team choices, to simple heuristics, to the maximization of a well-defined objective function. For some teams, prioritization efforts include multi-year R&D projects requiring deep decision analysis and financial figures of merit [7]. The Scaled Agile Framework relies on a Weighted Shortest Job First metric based on an estimated cost of delay for prioritization, typically calculated from proxies like stakeholder preference, value erosion, and value enabled by new opportunities [8]. The Department of Energy (DOE) recently demonstrated an alternate approach, using a non-financial multi-attribute value optimization for energy R&D funding allocations given the challenges in characterizing eventual monetary benefits of projects with low technical readiness [9].

In this paper, we consider a situation where financial value metrics are similarly difficult to apply due to the immaturity of product ideas being prototyped. Innovations are developed by a small team assigned to a digital product delivery organization for one division of a major energy firm. Members represent a diverse cross-section of subject matter experts (SMEs) covering many branches of science, engineering, and IT capabilities, and, like an innovation "tiger team," the group has the autonomy to fully focus on innovative work [5]. However, instead of long-duration R&D, team members target POC efforts taking 3–12 months to build validated prototypes. We apply a systems engineering (SE) methodology similar to the DOE example to evaluate ideas and rationalize the choice of which ideas should be pursued. The process establishes a multivariate optimization of cost-benefit trade-offs for assessing different opportunities in the innovation backlog. When combined with additional innovation metrics and portfolio visualizations, this SE PAS system empowers the team to simultaneously account for stakeholder feedback, resource constraints, and a strategic balance of the POC portfolio.

1. Methodology

1.1. Stakeholder Analysis

Defining the principal value measures for an innovation backlog begins with understanding the stakeholders. Here, we take a broad view of the term *stakeholder*, considering the spectrum of those who provide resources toward a PAS system for an innovation team and those who benefit from such a system. The output or outcome of the system meets the needs of both *charitable beneficiaries* and *beneficial stakeholders*, but only the latter contribute toward meeting the system's needs. The system provides little to no value for problem stakeholders, but they supply essential contributions to the system [10]. This terminology helps establish a comparative framework for assessing stakeholder significance founded on their importance to the PAS system and its importance to them.

Figure 2 illustrates the workflow used to identify, rationalize, and rank the system stakeholders in this study. First, an initial list was constructed by a small project team, capturing those internal and external to the firm with interests that intersect the activities of our dedicated innovation team. These individuals or entities were labeled by stakeholder type, then ordered from highest to lowest importance by the project team. Rank-ordering allows the team to focus on a manageable subset for needs analysis, targeting approximately 7 $\pm$ 2 stakeholders per the typical limits of human cognitive load [11]. Relevant needs for each shortlisted stakeholder were documented, and the team performed a second ranking exercise to ensure alignment on the stakeholder order.

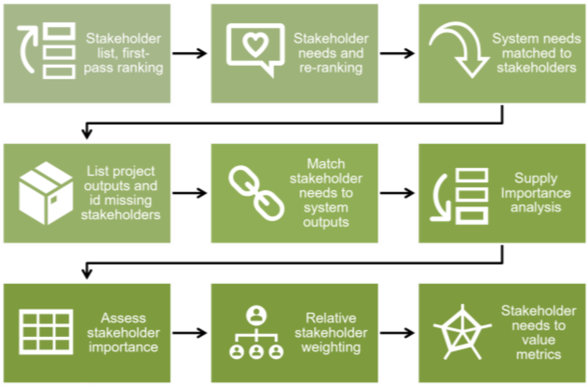

Figure 2. Stakeholder analysis adapted from the needs-to-goals framework illustrated in Figure 11.1 of [10].

Next, the required inputs and resources for the PAS system were itemized and checked for consistency against the identified stakeholders. Project team members ranked the importance of each of the system inputs, and an associated score was defined by calculating the reciprocal of the sum of squared team member rankings. Stakeholder importance to the system was approximated by adding together the scores for all inputs provided by the stakeholder. These importance totals naturally separated into three clusters, from which high, medium, and low labels were mapped to the stakeholders.

Stakeholder needs were subsequently matched to system outputs, and the strength of each connection was tested based on supply availability to differentiate needs uniquely met by the system from those with accessible alternative solutions [10]. Using group consensus, the project team applied high, medium, or low importance labels for the system to the stakeholder following the needs and supply analysis.

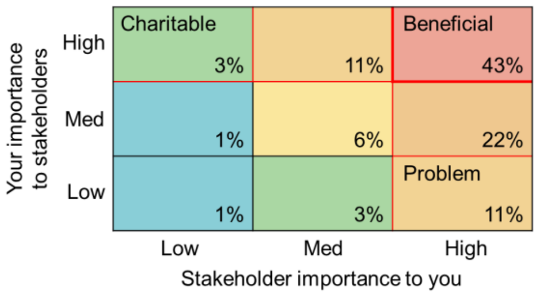

Figure 3. Stakeholder value matrix mapping stakeholder-system and system-stakeholder importance to relative influence (percentages) on value assessments. Matrix adapted from [13].

All stakeholders were then mapped to a 3×3 matrix covering all combinations of stakeholder-system and system-stakeholder importances. Figure 3 depicts the matrix with labels indicating where the three representative stakeholder types would plot. Also included are percentages based on theoretical network modeling for complex stakeholder environments [12]. The percentages specify the relative weight teams should place on the stakeholders, i.e., the degree to which their voices should contribute to system decisions.

Another fundamental output of the stakeholder analysis is a comprehensive list of value metrics that differentiate among the backlogged innovation opportunities and determine if they satisfy stakeholder needs. The simplest process for deriving this list focuses only on the highest-priority stakeholders, while more complex approaches analyze the flow of needs and resources throughout a stakeholder network model [10]. We chose to list the relevant needs of the shortlisted stakeholders and identify matching patterns or clusters among them. Critically, if a need could be expressed neutrally and applied to more than one stakeholder, it was added to the collection of final metrics. Additional considerations for the distillation of needs-based metrics were i) did the final set cover the primary needs of the beneficial stakeholders and ii) were the final metrics suitably independent to describe a meaningful multidimensional space for investigating benefit trade-offs. We also specified a categorical list of options for each value metric, ensuring a wide range of possible metric values for innovative ideas was represented.

1.2. Model Construction

Discriminating among many innovation ideas in a portfolio backlog first requires an assignment of benefit-at-cost to each idea. The collection of value metrics and associated assignment options can be converted into a single characterization of benefit using the concept of a multi-attribute utility function (MAU):

$$MAU = \frac{1}{w_{tot}} \sum_{i=1}^{N} w_i U_i = \frac{w_1 U_1 + w_2 U_2 + w_3 U_3 \ldots + w_N U_N}{w_{tot}}, \tag{1}$$

where N is the number of value metrics, w_i are weights providing a relative scaling to each metric, w_{tot} is the sum of all w_i, and U_i are utility functions that convert a metric choice to a value between 0 and 1, representing low and high utility, respectively [14].

Utility acts as a numerical benefit assessment derived directly from the system stakeholders. The process fundamentally relies on a survey of the stakeholders, first on the relative importance of the value metrics for determining benefit, then on the ranked value of different metric options. The latter forms the basis of the utility functions (U_i) in (1) that map metric options to decimal utility values for categorical variables. To reinforce the terminology: the benefit or value of an innovation idea is characterized by the weighted combination of utility scores across multiple value metrics. The weights and scoring functions come from the stakeholder survey, and they get applied to new innovation ideas based on the option-mapping of those ideas to the value metrics.

Figure 4 depicts the workflow used for collecting stakeholder feedback and building the multi-attribute utility model in this study. First, a survey was constructed for determining metric weights and utility functions. Although beyond the scope of this paper, the design of the survey as short in length and broadly understandable is fundamental to securing a high response rate and reliable results across all stakeholders. An initial pilot among innovation team members was used to validate the survey mechanics and user experience before sending it to over 100 targeted stakeholders.

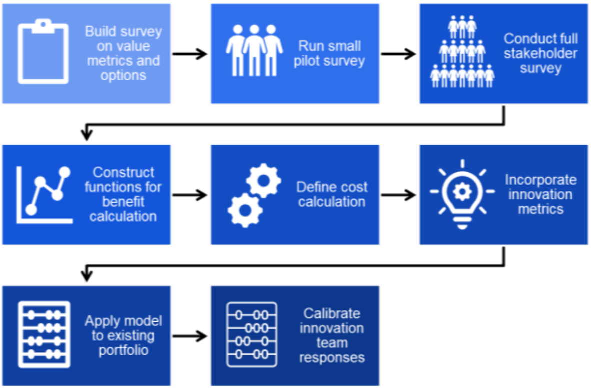

Figure 4. Model-building workflow defining benefit, cost, and innovation metrics for the idea backlog.

Results were compiled for analysis after a suitable time for engaging with potential respondents. We assigned surveyed stakeholders to one or more stakeholder groups depending on their roles and responsibilities. The relative weights for each of the value metrics (w_i) were determined by first averaging within each stakeholder group, then applying a weighted average across groups using the stakeholder percentiles in Figure 3. This method preserves the stakeholder importances determined in Section 1.1. A similar procedure was used to derive value metric utility functions; the ranking of metric options was averaged within stakeholder groups, then combined by weighted-averaging across groups. The final list of metric option utility values was min-max scaled such that the highest-ranked option received a utility value of 1.0, and the lowest-ranked option was assigned a utility of 0.0.

Before directly comparing innovation ideas, we next needed a model for the cost of each idea to balance against its MAU-defined benefit. The cost calculation was standardized by reframing it as resource intensity, consisting of the expected effort (time) and the number of individuals required to complete the POC. These project attributes were combined using internal estimates of fractional time dedicated to innovation projects and the labor rates for contributors from different work functions. Figure 5 illustrates the various inputs and a min-max scaling step needed to build a scaled resource metric. In addition, we defined a

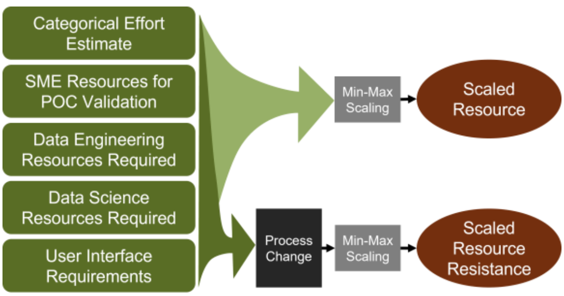

Figure 5. Elements integrated into a resource "cost" calculation for innovation ideas. The model combines categorical values and whole number people requirements (green boxes) with labor rates and fractional time commitments to estimate resource needs. Resource resistance includes a process change multiplier.

scaled resource resistance metric that incorporates a multiplier for the anticipated process change needed to move a particular POC into MVP development (i.e., Process Innovation in Table 1).

Innovation metrics offer another dimension for portfolio shaping and analysis to match the strategy of an innovation team [15]. However, the connection between stakeholder needs and the benefit associated with specific categories of innovation remains ambiguous without focusing on specific technologies or processes that might be implemented. Rather than survey the stakeholders on general innovation level utility functions, we defined three categorical innovation metrics to track as ideas are cataloged in the POC backlog (Table 1). This metadata offers an alternative way to decompose and evaluate the portfolio, extending the SE PAS system beyond simple benefit-at-cost trade-offs to include innovation portfolio balance decisions.

Table 1. Innovation metrics recorded for each idea added to the innovation team POC backlog.

Metric	Description
Innovation Level	Levels that separate existing technology support from quick-win enhancements and emerging transformational solutions not yet seen or implemented in the target domain. Defined along a 4-tier scale based on [15].
Novelty Level	Novelty with respect to intellectual property, e.g., is the idea in published records, and if not, does it meet the threshold for publication or patenting? Measured on a 5-tier scale.
Process Innovation	The required process change and effort needed to align others around MVP development and deployment if POC is successful. Defined along a 4-tier scale.

Having defined a set of value metrics, resource cost measures, and innovation metrics, we implemented a system intake process for assigning values to all backlogged ideas and active POCs for the innovation team. Including active POC work ensured the entirety of the team's portfolio would be represented in the analysis. Team members independently added their assigned work into the SE PAS system using a digital intake form. While the form facilitated consistency by restricting the range of selections for each required intake question, further calibration was required to verify and validate the categorical metric selections chosen by different team members. We used a round-table group share and feedback session to seek initial team alignment and identified a system owner to regularly review system entries for future inconsistencies.

1.3. Portfolio Visualization

The success of a PAS system strongly depends on transparency and communicating data with intuitive and insightful visualizations. Preferences on graphical formats, color palettes, and interesting metric trade-off combinations will vary, so we followed a progressive approach of rapid ideation by plotting in Python, formal dashboard design using Power BI®, and eventual cloud-based Azure® pipeline construction to establish a real-time end-to-end solution.

First, we constructed a scatterplot of the innovation portfolio, placing the MAU benefit metric on the vertical axis and scaled resource on the horizontal axis. This plot defines a tradespace, or "trade-off playspace," illustrating the tension between benefit and (resource) cost for the innovation opportunities (Figure 6). The most optimal innovation activity would have perfect utility at no cost, as noted in the upper left corner of the plot. A curve connecting the lowest scaled resource activity for each benefit level describes the Pareto frontier, with all intersecting solutions considered Pareto-efficient options. Those that plot to the right of the frontier are dominated by other options and hence considered less efficient choices for prioritization and selection.

Next, we prepared an alternative plot illustrating impact versus effort measures (Figure 7). Due to the potential ambiguity of these terms, we strictly defined impact using the scaled sum of utilities for value metrics associated with the projected user community and business value realization timeline (metrics 6, 7, and 9 in Table 2). The scaled resource resistance metric noted in Figure 5 served as a proxy for POC effort, reducing potential redundancy between this and the tradespace plot.

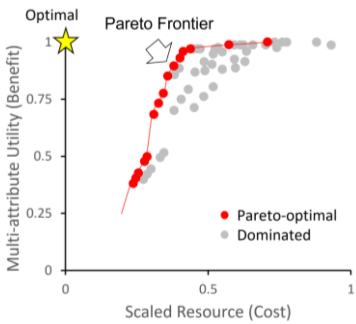

Figure 6. Tradespace plot illustrating benefit-at-cost trade-offs for a dedicated innovation team's active and backlogged portfolio. Red markers define the Pareto-optimal choices.

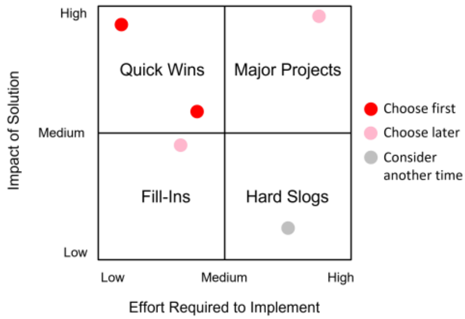

Figure 7. Impact/Effort chart that clusters work activities for rapid prioritization. The legend notes typical guidance based on plot placement. Actual decisions should leverage insights from all plots.

Our final dynamic innovation portfolio dashboard incorporated additional plots, tables, and filter options. Feedback on these displays was critical to addressing the needs of key stakeholders, so this approach required iteration and user engagement to refine appropriately. In a parallel effort, we incorporated a user app for editing existing SE PAS system entries, pipeline triggers to automatically apply MAU and resource cost models on the idea collection, and self-refreshing capabilities for the published dashboard. The final system supports rapid ingestion of new innovation ideas and evergreen communication of the entire portfolio with a consistent model and custom displays.

2. Results

Stakeholder analysis for the PAS system initially considered eighteen stakeholder groups. Early ranking exercises reduced the list to ten, although an eleventh was later added when mapping system deliverables to stakeholders revealed a missing beneficiary. The needs of these stakeholder groups are clustered into nine categories, reframed as value metrics for the stakeholder survey and MAU calculation (Table 2). All metrics were associated with no more than five categorical choices (not listed here) to simplify and standardize the option-mapping of innovation ideas to metrics.

Table 2. Value metrics identified from stakeholder analysis and used for a multi-attribute assessment of utility or benefit based on surveyed feedback. The listed weights are from the results of the stakeholder value survey.

No.	Metric	Definition	Wt.
1	Domain Knowledge	Expertise of the innovation team member who owns the innovative idea/POC, specifically regarding the investigated technical challenge.	0.125
2	Community Awareness	Breadth of community awareness regarding the technical challenge targeted by the innovation idea/POC.	0.102
3	Deployment Pathway	Vision for how a successful POC would be matured as an MVP and deployed (e.g., stand-alone app or as part of a pre-existing platform).	0.116
4	Asset Class Alignment	Level of alignment of innovative idea/POC with focus areas defined by the technology customers within the business (i.e., asset classes).	0.121
5	Strategic Initiative Alignment	Level of alignment of innovative idea/POC with the published strategic initiatives for the parent organization of the innovation team.	0.127
6	Urgency	The expressed stakeholder urgency for the solution provided by the technology being proven as a POC.	0.129
7	Breadth of Use	Best estimate for the size of the end-user community after the technology matures and is deployed.	0.108
8	Innovation Source	Organizational source from which the innovative idea originated.	0.067
9	Value Realization Timeline	Lag time between innovation technology deployment and business value realization if deployed today.	0.105

The value survey was sent out in two waves, with repeated follow-ups from the project team and innovation team manager over a three-week period. The final results tallied 68 unique responses, although the distribution across stakeholder groups was noticeably imbalanced. This highlights why within-group averaging precedes across-group averaging for the metric weights and utility functions; a large response rate for one group can benefit the group’s statistics without artificially boosting that group's perspective in the MAU model. The final weights for each value metric based on the 68 responses are noted in Table 2.

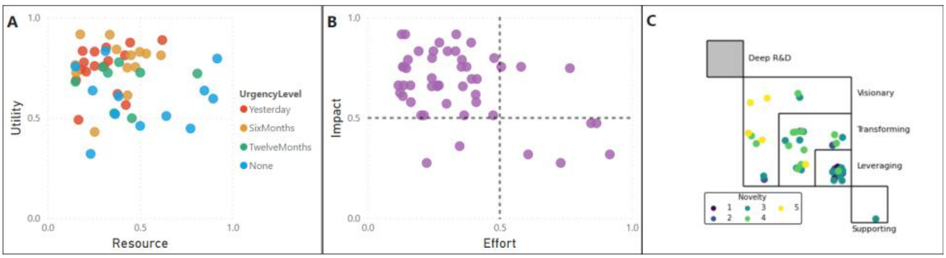

Figure 8. Example dashboard plots illustrating A. the benefit-at-cost tradespace, B. an impact/effort plot, and C. an innovation plot for portfolio analysis adapted from [15].

Figure 8 depicts example dashboard displays generated by running the innovation team's backlog and active project portfolio through the utility model, calculating resource values, and visualizing innovation metrics captured during the SE PAS system intake process. These only cover a subset of many displays in use today, giving a flavor for the kind of portfolio analytics and decision support possible with the system.

3. Discussion

Early feedback from applying the SE PAS methodology to a small innovation team's portfolio highlights its rigor and repeatability as key benefits. The underlying stakeholder-calibrated value model helps reduce the risk of familiarity bias or group-think that can impact assessments made in group meetings or at the innovation team level. Furthermore, the metrics for product and process innovation and intellectual novelty provide alternative levers for tuning the strategic balance of innovations being pursued. Validation testing of the system is still in progress and will rely on direct surveys of stakeholders on the value, resource requirements, impact, and effort for a subset of POCs during upcoming engagement meetings. This mimics the legacy approach of ranking and selection for project prioritization.

Greater process efficiency is an advantageous consequence of applying the SE PAS method. Consider bringing 100 of the surveyed stakeholders together once a quarter to evaluate and rank ideas in the innovation portfolio. Assuming meetings last ≈ 3 hours, 1200 person-hours/year would be dedicated to value and ranking discussions. By contrast, the value survey in Section 1.2 lasts ≈ 10 minutes per respondent, and applying the value model to new ideas and updating the dashboard thereafter is nearly instantaneous. The method represents an overall 94% reduction in stakeholder time committed to valuation.

Instead of lengthy ranking meetings, richer alignment conversations are emerging from the use of the SE PAS system dashboard. Stakeholders and team members can rapidly view portfolio segmentation by completion status, asset class association, energy transition linkage, target product lines, or alignment with Agile epics. Conversations can focus on the connections between POCs, MVP development for technology delivery, and future collaboration opportunities with SMEs and business unit partners. Initial managerial feedback suggests greater transparency of the team's work and portfolio balance helps improve perceptions of the team's performance. Empirical evidence suggests management satisfaction will similarly grow with this formalized approach to measuring, strategically shaping, and reporting innovative efforts [16].

Importantly, the SE PAS methodology cannot rely on a single initial survey in perpetuity. System stakeholders may vary over time due to organizational changes. Additionally, value judgments of all stakeholders will shift as both internal and external forces reshape business objectives, as seen in response to volatility in the oil & gas markets and acceleration of energy transition efforts over the past few years. It is therefore critical to revisit the stakeholder value survey with regularity – we are testing an annual feedback cycle – to ensure the underlying model remains relevant.

Lastly, a well-calibrated utility model paired with verified cost estimates should not supplant the decision authority of the innovation team. Tradespaces fundamentally highlight a subset of options that most efficiently balance two metrics, but decision-makers must also consider factors like delivery timelines, available resources, and innovation goals and strategy when selecting the ideas to pursue. Instead of promising an automated scheduling system, the SE PAS methodology delivers visualizations that facilitate discussions where even Pareto-inefficient ideas in the cost-benefit space could be elevated due to better alignment with an underserved asset class or high-level enterprise goals. Future work will focus on process refinements like simplifying the stakeholder analysis workflow, building tiered or higher-dimensional tradespace views, incorporating uncertainty in the model, and establishing greater integration with popular Lean and Agile project management tools that are widely in use.

4. Conclusions

In this paper, we reviewed the application of systems engineering concepts to provide decision support for managing an innovation portfolio. New ideas and active proof-of-concept work are assigned value metrics tuned to stakeholder feedback, in addition to measures characterizing resource cost and relative innovation levels. A streamlined process supports the intake of new ideas into an innovation backlog, automatic application of the benefit-at-cost model, and visualization of an entire portfolio to support prioritization and selection of work items. This method has successfully been applied for a dedicated multi-disciplinary innovation team within an energy firm, enhancing the decision-making process as the demands of digital transformation and energy transition require more resources than are available. Stakeholder-derived value assessments are the cornerstone of the process, maintaining innovation portfolio decision quality even as the pace of business pushes for ever-increasing efficiency and progress.

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