SCHOOL OF PUBLIC POLICY
CENTER FOR GLOBAL SUSTAINABILITY

GLOBAL SUSTAINABILITY INITIATIVE

WORKSHOP REPORT: ACCELERATING CLIMATE-MITIGATING TECHNOLOGY DEVELOPMENT AND DEPLOYMENT

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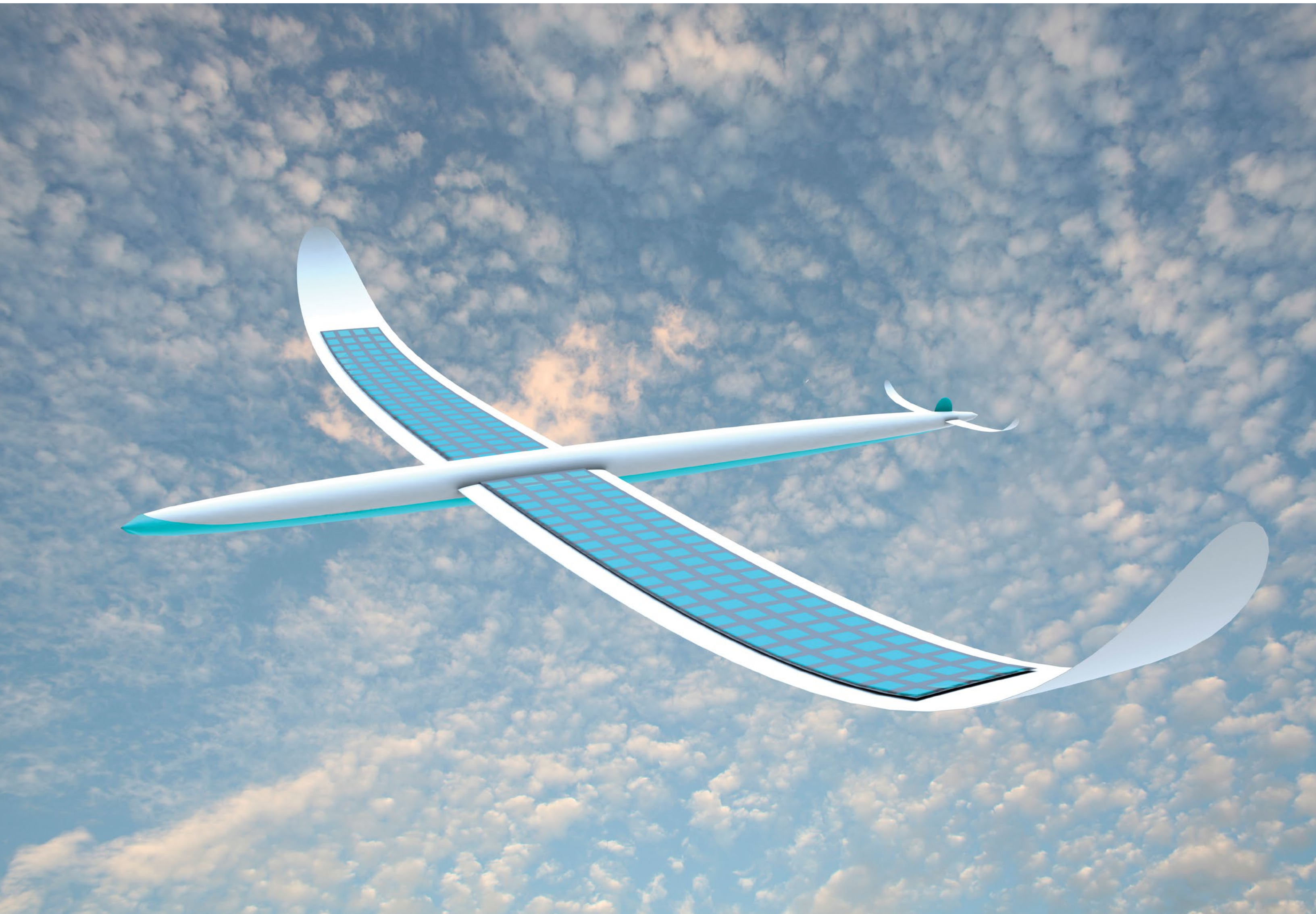

WORKSHOP PURPOSE

POLICYMAKERS AND INVESTORS ALIKE COVET BETTER INFORMATION ABOUT THE RISKS AND POTENTIAL OF EARLY-STAGE TECHNOLOGIES. THE MOTIVATION FOR THE WORKSHOP ON ACCELERATING CLIMATE-MITIGATING TECHNOLOGY DEVELOPMENT AND DEPLOYMENT[1] WAS TO EXPLORE HOW DIFFERENT PERSPECTIVES FROM THE POLICY, ANALYSIS, AND INVESTOR COMMUNITIES INVOLVED IN CLEAN ENERGY INNOVATION MAY BE COMBINED FOR MORE EFFECTIVE DECISION MAKING.

1 Sponsored by the University of Maryland Global Sustainability Initiative. Held in College Park, Maryland, in June of 2018.

WORKSHOP SUMMARY

The urgent needs of climate mitigation are still outpacing the changes needed in the world's energy system. Despite stunning technical advances in renewable energy and energy efficiency, accelerated deployment of demonstrated clean energy technologies as well as new innovation and investment are essential to meet climate goals. The Paris Agreement marked a major shift toward climate mitigation that engages diverse national concerns in policy development. Such attention to granular local conditions and constraints can expand opportunities to develop and deploy innovative early-stage technologies to accelerate climate mitigation.

The workshop participants included 39 academic researchers, modelers, investors, and policymakers involved in energy innovation and climate change mitigation (see Appendix). The participants engaged in a day and a half of structured presentation and discussion to explore different viewpoints and develop specific examples of how policy impacts technology, how early-stage innovations develop, what factors drive success in commercial deployment, and how modeling and analysis can support the feedback between technological change and climate policy.

The workshop discussions explored how, at each stage of energy innovation, investment decisions balance risks of regional and national policies, regulations and tax structures, as well as technical potential, market demand, competing products, and supply chains. Next steps proposed to guide development of policy that effectively supports and leverages this process are:

- **Granular data tracking.** Establish a database of investments in early-stage energy technologies that can provide contextual granularity on technical approaches used and on how technical approaches and investments vary by region.
- **Technology indicators.** Develop and assess context-dependent indicators for technology costs and performance trends by linking energy innovation data to process engineering and energy market models.
- **Impact assessment.** Incorporate new technology indicators in climate and economic models to evaluate the potential diffusion of early-stage technologies and associated climate mitigation potential.

In the body of the report, we summarize the background, lines of evidence, discussion, and expand on the recommended next steps from the workshop. Unless otherwise noted via footnotes to external work, the content is based on the workshop presentations and discussion.

INTRODUCTION

In contrast to the primarily top-down perspective of the Kyoto Protocol two decades ago, experience with incentivizing low-carbon power generation, improving energy efficiency, and reducing emissions from the transportation sector has led to the more granular geographical and technological perspectives in the Paris Agreement. The role of bottom-up economic and social drivers and technology investments in this emerging paradigm is illustrated through the knowledge flows and action flows in Figure 1.

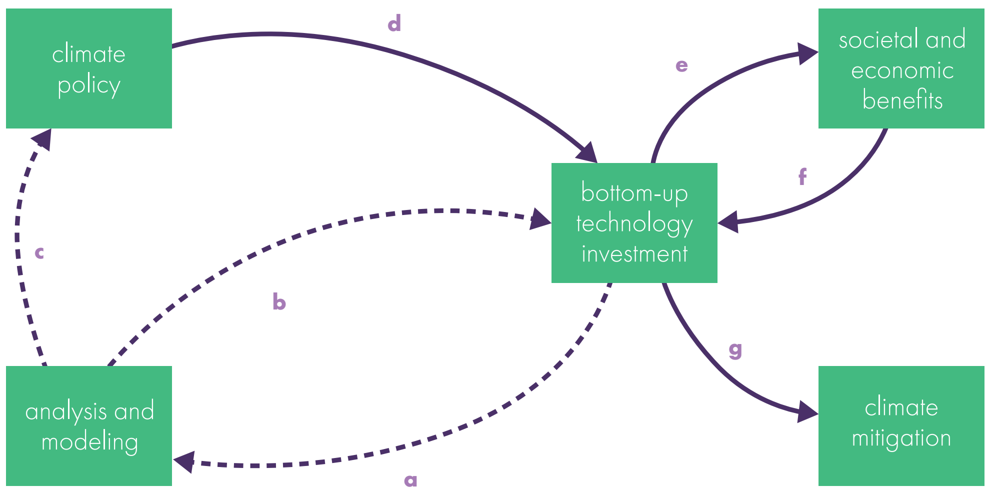

FIGURE 1: Knowledge flows (dotted lines) and action flows (solid lines) to accelerate climate-mitigating technology development and deployment under the Paris paradigm, emphasizing regional and technological granularity. Information from technology investors (a) can improve targeted analysis and modeling efforts (b) and assessments of the overall economic and climate impacts of investments (c), taking into account the regional and technological variability inherent in these bottom-up decisions. Analytical results on the positive impacts of action (c) can motivate more effective and ambitious policy action (d), which enables technology investment for enhanced societal and economic benefits (e)—which in turn leads to further investment (f)—and climate mitigation (g).

An approach where countries define their own mitigation contributions can enable actors to fulfill existing climate pledges and catalyze more ambitious pledges over time. This is because a bottom-up approach (1) embraces the need for policies that align mitigation goals with regional aspirations for sustainability and economic development and (2) recognizes the potential for new technologies to respond to local economic opportunities. Stakeholders who understand the specifics of low-carbon technology development and deployment in their regional contexts thus have a critical role to play in climate policy.

The perspectives of the development and investment communities are shaped by the challenges that an early-stage technology faces before generating impact for climate mitigation, as illustrated in Figure 2. At each stage of development shown, policy decisions shape the potential for success:

- **Research with Innovation Output:** The earliest development of innovative ideas is strongly influenced by government support for research and development (R&D).
- **Proof of Concept and Prototype:** 'Technology-push' policies supporting early proof of concept (translational) research can help prepare early-stage technologies to move into commercial development.
- **Pre-Commercial Demonstration:** Subsequent private sector decisions are shaped by policy decisions that impact the potential market for new clean energy technologies ('market-pull'). These include regulations as well as a variety of economic incentives.

The early technologies that survive the first three stages of commercial development (the 'first valley of death') then face major financing challenges in scaling up production to commercial operations and market growth. Here again, government policies and practices can be a determining factor in whether a new technology achieves its potential:

- **First Commercial Operations:** Innovative technologies require new manufacturing approaches, which, in their 'first of a kind' deployment, are often too risky and expensive for private sector financing. Policy factors can include government-backed loans or other finance support.
- **Market Growth:** Growth in markets with strong incumbents often needs interim policy support, such as incentives and sales guarantees, until the new technology becomes competitive, as well as policies such as carbon pricing that recognize market failures.

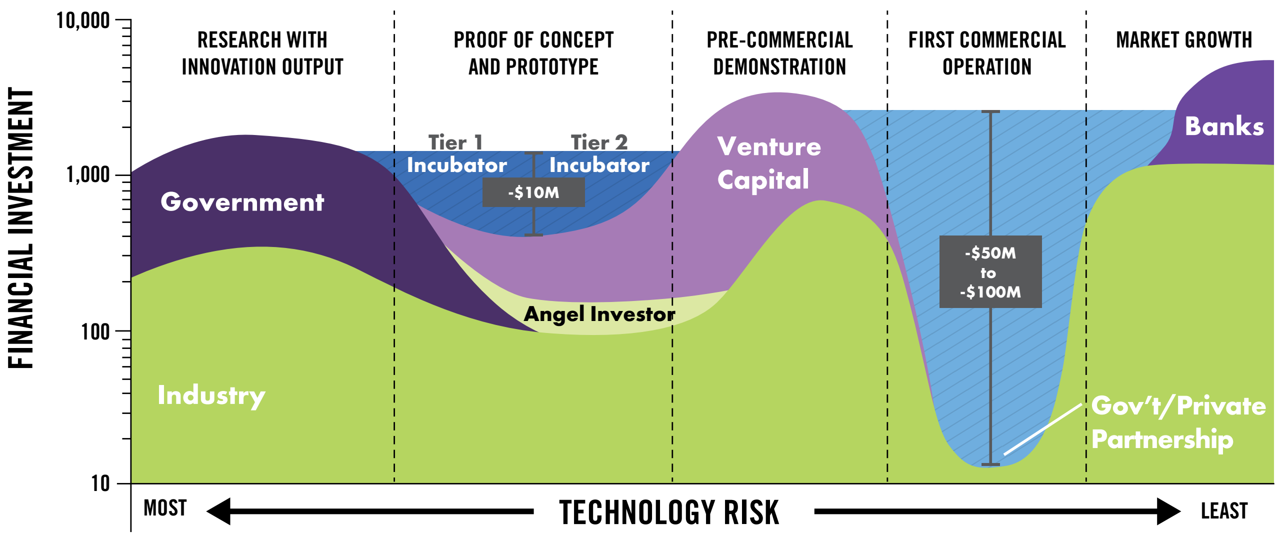

FIGURE 2: Typical stages of investment as clean-energy innovations move from research to market deployment. Achieving a proof of concept, prototype, and pre-commercial demonstration involves a transition from primarily government funding to private sector funding. The subsequent scale up to full commercial operation is often considered too risky to attract purely private investment. The proof of concept stage and the first commercial stage, where there are deficits in available investment, are often called the first and second 'valleys of death.' Figure adapted from D. Miller presentation with permission.

As suggested by Figure 2, technology developers and investors must approach the introduction of a new technology into the energy system as a situation-specific and risky process. At each stage of development, investment decisions are made that depend on regional and federal policies, regulations and tax structures, as well as technical potential, market demand, competing products, and supply chains. In identifying these factors, and making decisions based on them, stakeholders are carrying out the bottom-up process of capturing economic opportunity while also delivering climate mitigation benefits (arrows 'f' and 'g' in Fig. 1).

In the following 'Viewpoints' section we build on the linkages between policy and innovation – and relate them to applications of analysis and modeling to reduce risk and improve decision making.

VIEWPOINTS

The policy, investment, and modeling communities have developed a wealth of expertise on effective approaches to promoting clean-energy research and development (Textbox 1). These approaches target both technology-push (e.g., R&D for new technologies, improving performance, etc.) and market-pull (e.g., creating incentives for new technologies) and have demonstrated success. But even well-designed policies can have large variation in implementation and outcomes, especially if top-down policy goals do not align with regional priorities or the realities of commercial deployment.

TEXTBOX 1
KEY ELEMENTS OF EFFECTIVE TECHNOLOGY DEVELOPMENT POLICY

- Clear goals and prioritization
- Stability and predictability in policies and funding
- Balance of development incentives (push) with market incentives (pull)
- Conditions for risk-taking, experimentation, and entrepreneurship
- Cost- and risk-sharing with industry

Successfully moving an energy innovation through commercial development and growth in market share is essential to successful outcomes for climate mitigation. That process is fragile because identifying and supporting early-stage technologies is a high-risk endeavor. The risks described in the previous section are amplified because lack of stability in regulation or economic incentives can derail deployment and destroy the value of the investment. The needs for different policy approaches, and the balance of costs and risks borne by government and industry, vary depending on the stage in the innovation process.

To effectively balance costs and risks borne by the government and private sector, policymakers and investors alike need better information about the risks and potential of early-stage technologies. National and global policymakers have derived useful insights about technology growth and emissions reduction from integrated assessment and energy market models. While these models typically use coarser-grained inputs than the level of detail required for early-stage investment decisions or local policy development, they provide key baseline information about the (scenario specific) evolving energy systems in which an emerging technology must compete and grow.[2]

Analysis that bridges the different types of models shown in Textbox 2 can be used to link bottom-up decision-making to economy-wide impacts.[3] Converting outputs from one level into inputs for the next requires disciplined definition of the questions and objectives to be addressed. Such an analysis can incorporate the location-specific technical and economic risk factors used by investors as inputs to process engineering and energy market models. The desired outputs include directional information about rates of growth and market shares for different technologies in different regions. Aggregating those outputs to form useful inputs for integrated modeling is challenging, but with care can illuminate the geographic and temporal diffusion of technologies.

2 For example: Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy, https://www.energy.gov/sites/prod/files/2017/01/f34/Energy%20CO2%20Emissions%20Impacts%20of%20Clean%20Energy%20Technology%20Innovation%20and%20Policy.pdf.

3 For example: NREL Electrification Futures Study, https://www.nrel.gov/analysis/electrification-futures.html.

TEXTBOX 2

TYPES OF ENERGY/ENVIRONMETAL MODELS

Model Type	Technology Granularity	Energy Market Feedback	Economy-Wide Feedback
Process Engineering Models	**Strong** Individual technologies represented	Moderate	Potential feed-in to higher level models
Energy Market Models	Potential for model bridging	**Strong**	Potential for model bridging
General Equilibrium (Human-Earth System) Models	Relatively low technology resolution with technologies typically part of a larger aggregate	Moderate	**Strong** Aggregated economic growth and climate outcomes

In the following two sections, 'Leaping the First Valley of Death' and 'Getting to Deployment,' we outline how best practices and policy support for commercialization of energy innovations have been evolving. In the penultimate section, 'State of the Art in Analysis and Modeling,' we discuss issues and approaches in assessing the more granular variables of energy innovation to support improved decision making.

LEAPING THE FIRST VALLEY OF DEATH

Early-stage technologies face the 'first valley of death' as they move into the earliest stages of developing a technology proof-of-concept and prototype as well as pre-commercial demonstration (see Figures 2 and 3). The gaps in traditional funding at this stage lead many technologies to fail. However, practical experience in applying technology policy (see Textbox 1) has led to new understanding about effective approaches to support early innovations.

	PROOF OF CONCEPT	PRE-COMMERCIAL DEMONSTRATION	1ST OF KIND COMMERCIAL	COMMERCIAL ROLL-OUT
FOCUS	Technical de-risking	Technical and commercial de-risking	Financing	
TIMELINE	2–5 years	3–6 years	Multiple years	
INVESTMENT	10x proof-of-concept $10–60M	5–10x pre-commercial demonstration	>1st of kind	

FIGURE 3: Time and investment scales for the stages of commercial deployment of a clean energy innovation. Adapted from Z. Rahme workshop presentation with permission.

Clean energy technology developers and investors, both public and private, have used a spectrum of approaches to increase success in early-stage innovation. Many such investors were represented at the workshop, including Japan's New Energy and Industrial Technology Development Organization (NEDO), Sustainable Development Technology Canada (SDTC), the U.S. Department of Energy's Advanced Research Projects Agency—Energy (ARPA-E), Clean Energy Venture Group/Fund (CEVG/F), Cyclotron Road, PRIME Coalition, Breakthrough Energy Ventures, and X. Each of these investor organizations differs in its strategic direction and level of funding. Their investment decisions and activities all involve their own mix of market, policy, and technical considerations.

A common failure mode for innovators is a lack of balance in development strategy. They may focus work primarily on optimizing technical performance, i.e. a technology-push approach, assuming that a novel technology will be able to find a market. Experience has shown that mentoring young teams in skills needed to scale-up their production, deliver products at competitive costs, and assess market pull is a differentiating factor in their ability to attract continuing funding and investment. Different approaches to mentoring include structured partnering of young companies with established industrial partners (e.g., SDTC), coaching for mandatory commercialization milestones (e.g., ARPA-E), active guidance by experienced mentors (e.g., CEVG/F), and incubation with both technical and business development support (e.g., Cyclotron Road).

For investors, the decision-making process for supporting an early-stage technology involves (1) identifying commercial potential (market-pull) for the product, (2) supporting technical performance improvement for projects in their portfolio (technology-push), and (3) for mission-oriented investors, assessing potential climate impact. Portfolios of innovative energy technologies are designed to simultaneously meet these requirements. This goal-oriented, bottom-up planning approach yields early portfolios with a diversity of topic areas across investor organizations, illustrated in Figure 4. The diversity represents the flexibility of each investor's selection criteria, and it suggests how top-down policy might limit exploration of different types of innovations.

TECHNOLOGY DISTRIBUTION OF CLEAN ENERGY INVESTMENTS

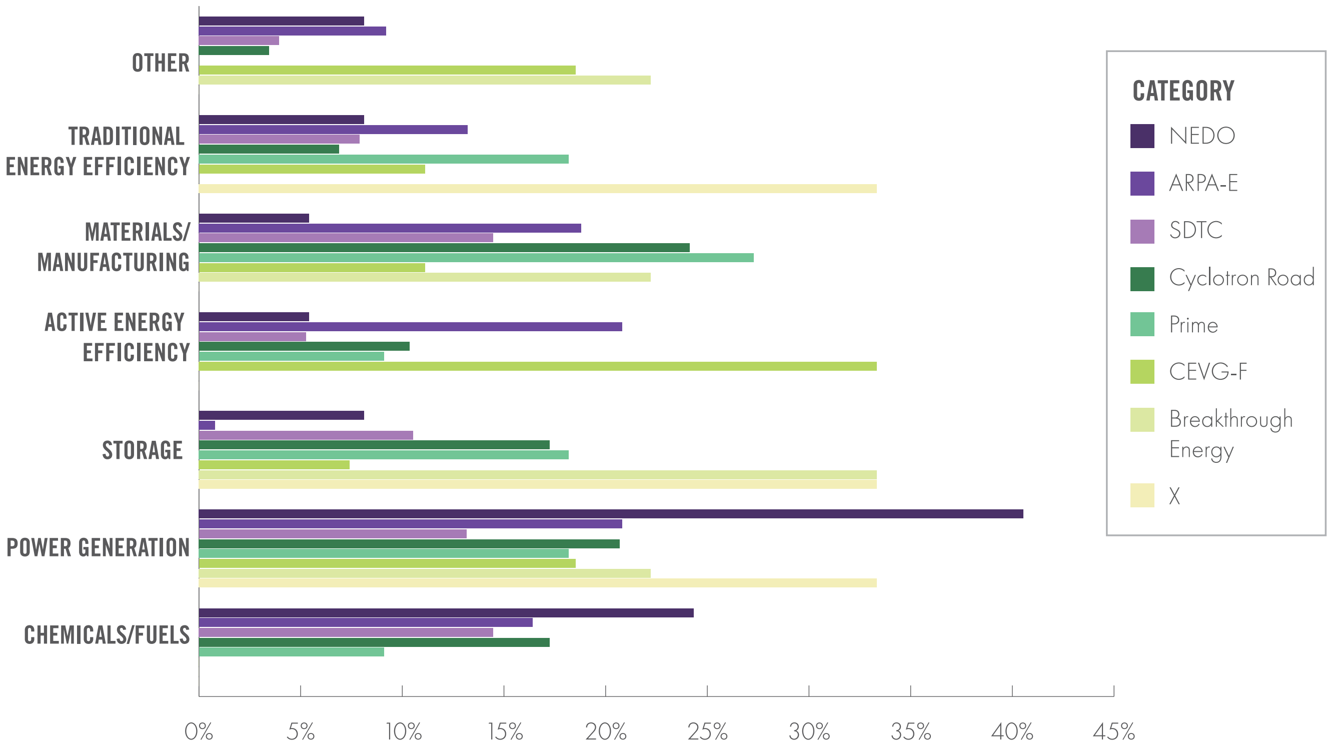

FIGURE 4: Summary of the breakdown of technology areas supported by the different funders or investors indicated. 'Active Energy Efficiency' refers to technology that uses digital controls for feedback and optimization. Data was assembled from each entity's public records[4] and represents the percentage of presently active projects in each technology area.

Diversity in portfolios reflects each investor's assessments of the factors in translating a project's potential for climate impact[5] into desired outcomes. For instance, some early-stage energy projects may find their first markets by considering regional needs and economic drivers that might not have been addressed in traditional top-down planning. These projects may be more responsive to—or be deeply affected by—regional infrastructure and supply chains, local tax and regulatory regimes, understanding of first markets, and the existence and stability of policy incentives.[6] All of these types of factors also influence the 'economic impact' arrows 'e' and 'f' in Figure 1 and thus the bottom-up policy approaches it represents.

4 Authors' compilation from:
CEVG/F, http://cevg.com/portfolio.
PRIME, https://primecoalition.org/prior-investments.
SDTC, https://www.sdtc.ca/en/projects.
Google X, https://x.company/projects.
NEDO, https://www.nedo.go.jp/search/?type=jigyo.
Cyclotron Road, http://www.cyclotronroad.org/projects-all.
Breakthrough Energy, http://www.b-t.energy/ventures/our-investment-portfolio.
ARPA-E, https://arpa-e.energy.gov/?q=arpa-e-site-page/projects.

5 Climate Impact Assessment for Early-Stage Ventures, NYSERDA and PRIME report, 2018, https://primecoalition.org/learn.

6 For example, the different portfolios of manufacturers engaged in the DOE SuperTruck program: https://www.energy.gov/eere/vehicles/downloads/report-adoption-new-fuel-efficient-technologies-supertruck.

TEXTBOX 3

INDICATORS OF SUCCESS IN ENERGY INNOVATION

- Knowledge development: Publications, patents, licenses
- Leveraging government investment: Private sector matching or follow-on investment
  - ARPA-E Early Indicators: https://arpa-e.energy.gov/?q=site-page/arpa-e-impact
  - Cyclotron Road Impact: http://impact.cyclotronroad.org
- Success stories: Concrete examples of early-stage companies delivering products of value
  - NEDO Project Success Stories: https://www.nedo.go.jp/library/pamphlets/ZZ_pamphlets_00002.html and https://www.nedo.go.jp/hyoukabu/index.html
  - ARPA-E Project Outcome: https://arpa-e.energy.gov/?q=site-page/arpa-e-impact
- Return on investment: Concrete outcomes of early private-sector investment
  - Clean Energy Ventures Actively Managed Portfolio: https://www.cleanenergyventures.com/portfolio
  - Clean Tech 3.0: https://www.ceres.org/resources/reports/clean-tech-30-venture-capital-investing-early-stage-clean-energy
- Jobs and regional economic benefits: Longer-term impacts of both product and production, including through direct and indirect employment generation
  - SDTC Economic and Environmental Benefits: https://www.sdtc.ca/en/results/our-impact
- Climate mitigation: Early-stage demonstration of greenhouse gas reduction potential and later-stage demonstration of actual impacts
  - PRIME Emissions Reduction Analysis: https://primecoalition.org/prior-investments
  - SDTC Economic and Environmental Benefits: https://www.sdtc.ca/en/results/our-impact

The success of early-stage energy innovation portfolios is measured by the development of high-value products with demonstrable potential for commercial growth[7] that delivers climate-mitigating benefits at scale. Outcomes occur over timescales of many years, requiring patient investing. Thoughtful support of early innovation using the approaches discussed above now has documented successes with follow-on funding that greatly exceeds the development funding provided (see Textbox 3). The first several indicators listed in Textbox 3 are most relevant for early-stage development. Success for technologies that have passed the first valley of death and moved to deployment is measured by the later indicators, including technical and commercial de-risking, scale-up to production of commercial products, and first product sales.

7 Clean Tech 3.0: Venture Capital Investing in Early-Stage Clean Energy, A Changing Investment Climate, 2017, https://www.ceres.org/resources/reports/clean-tech-30-venture-capital-investing-early-stage-clean-energy.

GETTING TO DEPLOYMENT

As new technologies move on from the first valley of death, they face the challenge of growing to scale. In the context of remaking the world's energy system to address climate change, the issue of scale is massive. The capital required can create serious barriers to deployment efforts, the 'second valley of death.' One common misconception – that growth to commercial scale can occur solely using private, market-driven finance after the early-stages of demonstration are complete – is decreasingly likely to be correct as the scale of the first commercial deployment increases, and with it the upfront capital costs. This problem is illustrated in Figures 2 and 3 as the 'first (or first of a kind) commercial operation.' Government programs and policy can make or break the transition of a technology through the second valley of death and into market growth. Regional or federal tax breaks, carbon-trading initiatives, and other incentives play a deciding role in whether an investor moves forward in early deployment of a new technology. Similarly, government-driven efficiency standards or environmental regulations can create market pull for a product that might otherwise have difficulty achieving market share. Risks that policies or regulations may change is a major deterrent in private-sector decisions about whether to invest in innovative energy technologies.

There are several approaches to reducing the risk of the second valley of death, summarized in Textbox 4.

One involves the scale of the technology itself. Large technologies, such as renewable power generation, generally have many components which can individually be improved, resulting in steady improvements in cost and performance in the overall system. Because these component technologies are smaller scale, their development costs and subsequent capitalization may be accessible to industrial sponsors or large private investors. One example of such a component-scale innovation is the development of 'kerfless' silicon wafers for solar power.[8] Ultimately, many small innovations in concert can create the 'learning curve' decreases in costs that play an important role in meeting climate goals.

Another risk reduction approach involves identifying a high-value first market for an early-stage technology. Young technologies generally have higher costs that will be brought down with experience in production and continuing technical improvement. When a high-value product can be identified, possibly outside the energy sector, this can provide a first market. Examples for this include the original development of CO_2-capture technology for natural gas production, which is now being developed into carbon capture for power plants,[9] or chemical pathways[10] for low-carbon production of high-value pharmaceutical or cosmetic chemicals, which have potential future applications for low-carbon fuels.

8 This is an area of active competitive energy innovation, see for instance: https://www.energy.gov/eere/solar/project-profile-leading-edge-crystal-technologies-t2m3, https://www.nexwafe.com/, http://1366tech.com/technology-2.

9 For instance, the Petra Nova plant: https://www.nrg.com/case-studies/petra-nova.html.

10 For instance, the Opus 12 start-up company: https://www.opus-12.com.

TEXTBOX 4

TECHNICAL APPROACHES TO MITIGATING RISK FOR DEPLOYMENT

Type of approach	Description	Pros	Cons
Component Scale Products	Improve individual components to improve the overall cost and performance of the larger energy product	Smaller-scale technology may be advanced with lower levels of investment	Many components must be considered in combination to understand impacts at the scale of the energy system
High Value First Market	Develop an innovative technology with potential energy applications for a different first market with larger profit margins	Allows market demand to support development and generate the cost reductions of scale up	No guarantee that the potential energy applications of the technology will be realized
Public-Private Partnerships	Drive down technology costs via a consortium of industrial participants under a government-structured program	Supports industrial development and early deployment of capital-intensive low-carbon energy technologies	Need to balance sharing of consortium intellectual property (IP) with proprietary developments of individual members; must have concrete, time-limited goals

In addition, when a technology is intrinsically large and capital intensive, government intervention can be used to reduce financial risk, as outlined in the third row of Textbox 4. The use of public-private partnerships has proven effective as a mechanism to drive down costs for large-scale technologies, such as off-shore wind.[11] Often, pre-competitive consortia of manufacturers participate in these programs, with the intellectual property developed available to all the participants. Such programs have traditionally supported both component-level and systems-level improvements. Another important factor in financial risk is the design of the manufacturing facility itself. As an example, nuclear power generation plants can have significant variability in successive installations, creating recurring costs for design. Private-public collaboration on standardized designs, or even modular construction, could significantly reduce financial risk of such large projects.

The risk factors and mitigation options discussed above, and the decisions that investors make based on them, represent a series of variables that can be influenced by policy decisions. These variables determine the rate and scale of deployment for any developing energy technology. Predicting and modeling cumulative progress is a constant challenge, as demonstrated for instance in failures to anticipate the remarkable decreases in costs for both wind and solar power generation over the past decade.[12,13,14] Just as investors monitor and assess policy developments to guide their investment decisions, analysts can monitor investor choices as indicators of future outcomes, potentially enabling policy makers to adapt their planning to optimize outcomes accordingly.

11 For instance, the US Department of Energy's National Offshore Wind R&D Consortium.
12 Creutzig et al. "The underestimated potential of solar energy to mitigate climate change," *Nature Energy*, 2017.
13 U.S. Energy Information Administration. "Wind and Solar Data and Projections from the U.S. Energy Information Administration: Past Performance and Ongoing Enhancements," 2016. https://www.eia.gov/outlooks/aeo/supplement/renewable/pdf/projections.pdf.
14 Gilbert et al. "Looking the wrong way: Bias, renewable electricity, and energy modelling in the United States," *Energy*, 2016.

STATE OF THE ART IN ANALYSIS AND MODELING

A regionally granular, bottom-up structure of climate action and technology development presents new challenges for analysis and modeling. While a substantial literature has investigated technology innovation and investment, previous energy-system modeling has traditionally focused on abstract, strategic problems or taken the perspective of a top-down decision-maker.[15] Such models have provided important insights on topics ranging from the climate impacts of the natural gas revolution to the potential for electrification of transport to reduce mitigation costs.[16] Now, transformations in mobility, and energy business models drawing on distributed data and integrated systems are introducing more challenges. Technology developers, early-stage investors, and subnational policymakers will need even more from analyses to assess mitigation options with more heterogeneity and granularity across five key dimensions (see Textbox 5).

Information for this broadened analysis can be derived from the knowledge and decisions of the technology developer and investor communities. Just as present well-developed connections between modeling and top-down policy-making demonstrate the value of communication between researcher and decision-maker communities, connections with the developer/investor communities can be expanded to better incorporate information on bottom-up mitigation efforts. For instance, models may not include cutting-edge technologies,[17] a symptom of the difficulty of predicting success, poor communication between technology developer and modeler communities, and the market-sensitive nature of investor decision-making. For the latter issue, transparency in other fields could serve as a model for fostering openness and data-sharing without compromising industry secrets. Developers and investors are also more likely to share information if they can expect modeling outputs to provide them useful insights.

TEXTBOX 5

KEY AREAS OF GRANULARITY TO INCORPORATE IN ANALYSIS AND MODELING

Innovation Processes. Cutting-edge technologies, technological change, investment decisions, and financial institutions

Technology Diffusion. Heterogeneity in technology choices and diffusion across locations and over time

Industrial Structure. Role of industry in mitigation, including industry structures and shifts in key players over time

Policy and Institutions. Strategic behavior and cooperation, policy leakage and risk, and imperfect implementation

Human Behavior. Consumer preferences, public acceptance, technology adoption, and energy end use

15 Weber et al. "Mitigation scenarios must cater to new users," *Nature Climate Change*, 2018.
16 McJeon et al. "Limited impact on decadal-scale climate change from increased use of natural gas," *Nature*, 2014.
17 Or include them in an abstract way, for instance representing generic innovation by changing a learning curve factor.

The technology developer and investment communities can provide inputs for analysis and modeling in a variety of ways. Modelers can compile anonymized data[18] on investment decisions and trends or conduct sophisticated expert elicitations to identify promising technological breakthroughs and develop corresponding probability distributions.[19] This information can shape inputs to the various modeling levels of Textbox 2, ultimately supporting scenarios of technology diffusion and economy-wide emissions reductions. Such data can also provide a check on the outputs of formal modeling.

Technology developers and investors—and modelers, themselves—must be realistic about what models can do. For example, models are not designed to evaluate individual investments, a task for which investors are better equipped, but they can examine systemic behavior and point to technology areas where return on investment may be highest. They can also quantify the benefits of technology improvements and explore how these benefits vary with the sources of granularity in Textbox 5. Technology developers and investors can in turn identify specific actions to support these improvements. Additionally, information on local co-benefits of mitigation—drawing on a large literature on air quality[20] and emerging work on economic opportunity and well-being[21]—can build support for increased technology development and deployment policies.

Model developments should be targeted to specific decision contexts and distinguish carefully between useful and unnecessary complexity. Hybrid models, linking the different analysis levels shown in Textbox 2, present a promising avenue for future research by combining integrated analysis, process engineering models, and/or energy market models with behavioral experiments, analytical derivations, stochastic decision models, and other methods.[22] Early proofs of concept (for example[23, 24]) can provide a foundation for future analysis and modeling. By coupling these analytical approaches with information about technology development and investment, models can better include granular regional factors, which in turn will provide evidence for policy decisions to accelerate technology development and deployment.

18 For example, the use of anonymized data in: A.C. Goodrich et al, "Assessing the drivers of regional trends in solar photovoltaic manufacturing," *Energy and Environmental Science*, 2013.
19 G. Morgan. "Use (and abuse) of expert elicitation in support of decision making for public policy," *PNAS*, 2014.
20 For example: West et al., "Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health," *Nature Climate Change*, 2014.
21 For example: Bain et al., "Co-benefits of addressing climate change can motivate action around the world," *Nature Climate Change*, 2015.
22 Leibowicz, "Growth and competition in renewable energy industries: Insights from an integrated assessment model with strategic firms," *Energy Economics*, 2015.
23 G. C. Iyer et al. "Improved representation of investment decisions in assessments of CO_2 mitigation," *Nature Climate Change*, 2015.
24 D. L. McCollum et al. "Interaction of consumer preferences and climate policies in the transition to low-carbon vehicles," *Nature Energy*, 2018.

INSIGHTS AND RECOMMENDATIONS

There is room for optimism concerning the potential to accelerate the deployment of energy innovation for climate mitigation. Technology developers and policy makers have built on decades of experience and demonstrated successful approaches to support commercial deployment of new energy technologies. These approaches all acknowledge the risks that investors face due to the inherently regional, bottom-up factors that influence success. Two general issues must be addressed to increase the speed and scale at which energy innovation can deliver climate mitigating benefits:

1. The risks that technology developers and private sector investors face in commercializing energy innovations must be reduced.
2. Public-sector decision makers must be convinced that increased investment in energy innovation, commercialization, and deployment will yield both economic and climate mitigation benefits.

As outlined in Figure 1, modeling and analysis can play a key role in meeting these objectives through information links to the development/investment community (link b) and to the policy community (link c) and potential optimization of policy (link d). The workshop discussions lead to a recommendation of three interconnected collaborative research approaches to create the information and tools for improved decision making:

1. **Granular Data Tracking:** Joint action of developers, investors, and analysts to establish a data base of investments in emerging technologies, and:
   - **a.** Develop analytical methods to relate investment patterns to the underlying variables in regional policies, knowledge and industrial infrastructure, environmental factors, etc.
   - **b.** Assess climate impact potential of innovative technologies based on investment patterns in the context of realistic economic and policy expectations.
   - **c.** Follow temporal evolution of investment patterns and use them to ground-truth analysis and modeling outcomes.
2. **Hybrid Model Development:** Joint action of technology developers and analysts/modelers to create tools to incorporate the granular energy innovation data into process engineering and energy market models, and create outputs such as regionally-dependent technology learning curves, that can be used:
   - **a.** as inputs into integrated assessment models and
   - **b.** as inputs to investor/policy-maker decision making.
3. **Climate and Economic Modeling:** Joint action to develop constructive use of the outputs of the hybrid models in integrated models for impact assessment:
   - **a.** For investors and policy makers: Project economic/climate outcomes of energy innovations in different baseline scenarios of the future energy system.
   - **b.** Informing public sector policy decisions: Project economic/climate outcomes based on diffusion of innovative technologies that have nucleated and grown at different rates in different regions.

APPENDIX: WORKSHOP PARTICIPANTS

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