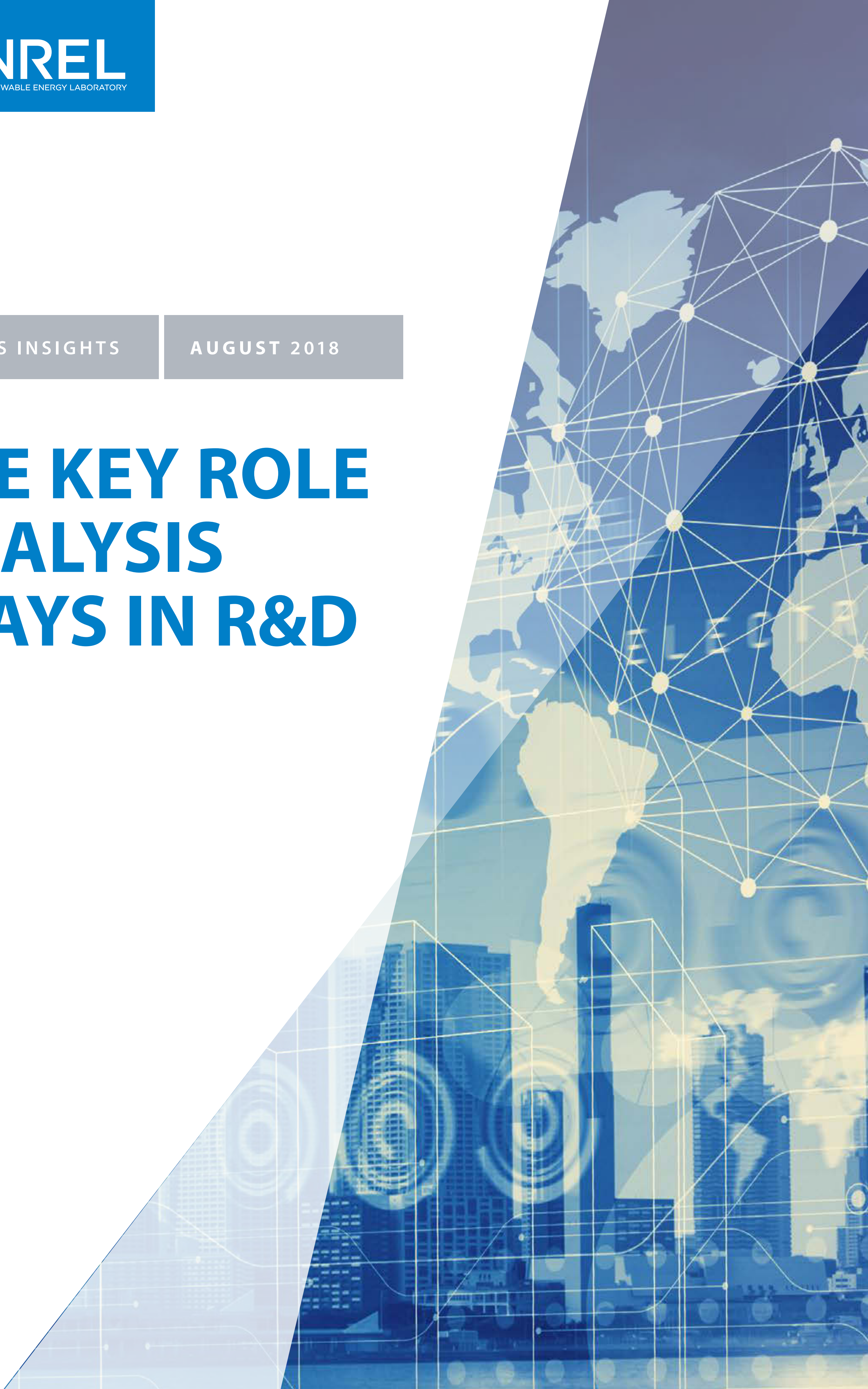
NATIONAL RENEWABLE ENERGY LABORATORY

ANALYSIS INSIGHTS | AUGUST 2018

THE KEY ROLE ANALYSIS PLAYS IN R&D



LAYING THE FOUNDATION FOR OBJECTIVE DECISION MAKING

Over the last two decades, the National Renewable Energy Laboratory (NREL) has been applying its analytical expertise to help guide and advance renewable energy technology research and development (R&D). Working shoulder-to-shoulder with world-class researchers—at NREL, other national laboratories, and universities—and industry partners, NREL analysts continue to search for answers to emerging energy challenges every day.

Our objective methodologies and tools are now helping stakeholders assess and prioritize R&D efforts as fast as new innovative technologies transition from concept to commercial application. Throughout that journey, NREL's analyses highlight key technical barriers, compare tradeoffs among proposed technology development pathways, track progress toward performance and cost targets, and illuminate the impacts of proposed innovations.

This edition of NREL's Analysis Insights takes a deeper look at the role analysis has played in guiding renewable energy innovation at our laboratory, and beyond. In doing so, the report substantiates what we have known for 20 years—that informed analyses must remain at the leading edge of future R&D efforts.

Role of Analysis in Technology Development and Innovation

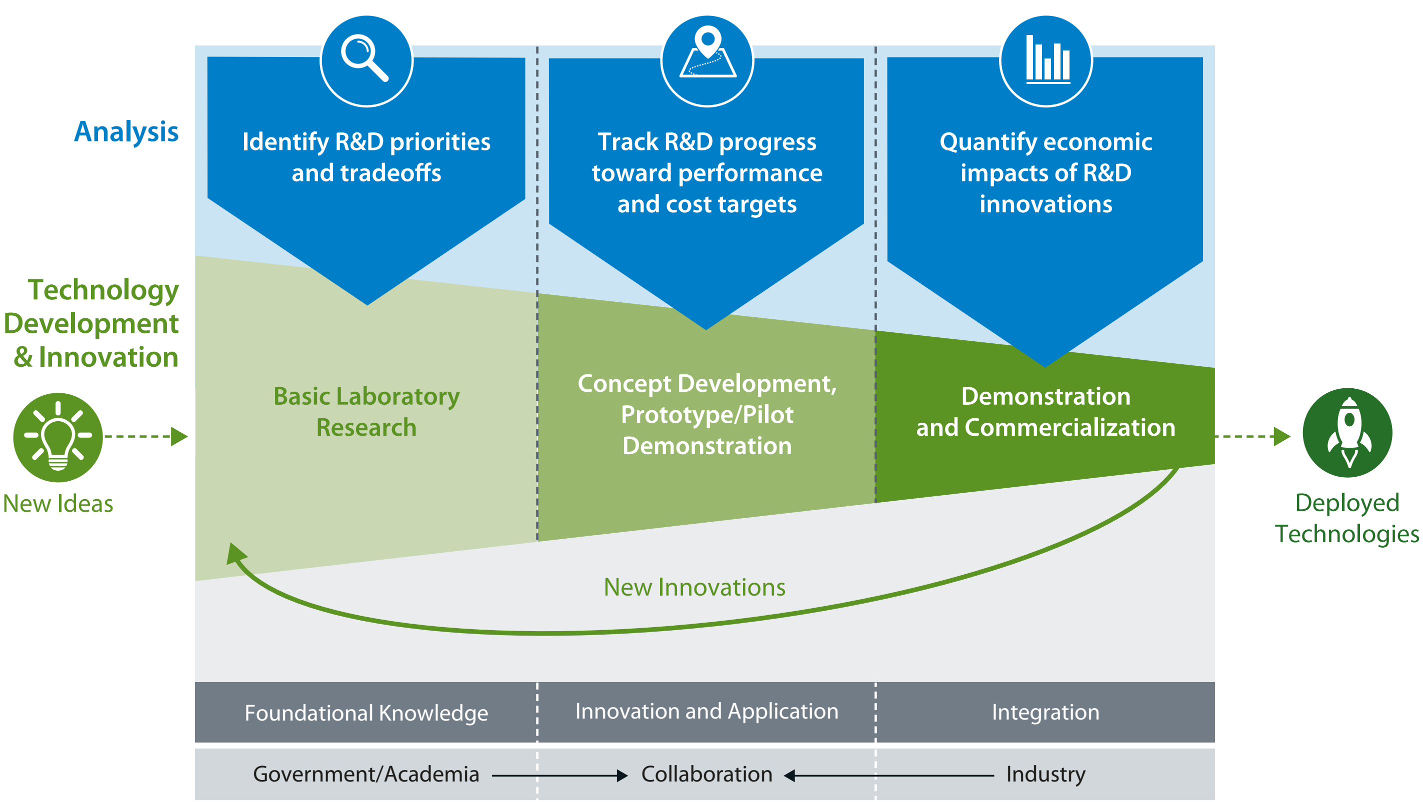


Figure 1. The role of analysis from concept to commercialization

The Role of Analysis in Technology Development and Innovation

NREL employs a wide range of analysis methodologies[1] to inform decisions that support research, development, and deployment (RD&D) of renewable technologies. One approach—the techno-economic analysis (TEA)—has emerged as a leading method for guiding R&D strategy. By providing insight into the technical and economic viability of R&D pathways under consideration, TEA helps identify key technical barriers to focus R&D on the critical challenges throughout the technology development timeline.

Even in the earliest nascent stages, simple spreadsheet analyses can help direct limited R&D dollars to the ideas that offer the most significant impact or best probability for success. As technologies advance from the lab to pilot demonstration to commercial application, analyses are conducted at increasing levels of fidelity or detail.

NREL's TEA models and methodologies have set the standard for energy analysts, investors, and government and industry stakeholders, facilitating objective examination of RD&D areas in terms of costs, benefits, risks, uncertainties, and timeframes.

To demonstrate this impact, we have compiled specific examples of how analysis has informed R&D priorities at NREL across multiple renewable energy technologies and various stages of development, including:

- Conducting sensitivity analyses to identify R&D priorities for solar photovoltaics (PV)
- Setting goals and tracking progress toward achieving performance and cost targets for biofuels
- Quantifying the economic impacts of R&D advances for wind energy.

Conducting Sensitivity Analyses to Identify R&D Priorities for Solar PV

Over the years, NREL's R&D in PV technologies has evolved through material substitutions, solar cell design changes, system improvements, and increases in manufacturing throughput. These advances have driven cost reductions as well as performance and reliability improvements. Along the way, NREL has used sensitivity analyses to help identify and compare the relative impacts of critical parameters that drive cost reductions and performance innovations.

For example, to help meet the U.S. Department of Energy (DOE) SunShot Initiative levelized cost of energy (LCOE) goals, NREL performed sensitivity analyses to illuminate the tradeoffs among key metrics like module price, efficiency, and degradation rate as well as system price and lifetime.[2] Figure 2 models NREL's finding that increased efficiencies are important, but reliability improvements are equally important for meeting SunShot LCOE targets.

Based on these findings, DOE has boosted efforts aimed at meeting reliability targets. For example, scientists are now working to develop new technologies that directly enable longer lifetimes and slow module degradation, such as higher-resistivity encapsulant materials.

SYSTEM ADVISOR MODEL

Launched in 2005, NREL developed the System Advisor Model (SAM) to compare the performance and economics of different PV technologies on a consistent and objective basis. Since then, SAM has evolved from an internal tool used by DOE's Solar Energy Technologies Program to a publicly available tool that helps stakeholders across the renewable energy industry—including project managers and engineers, policy analysts, technology developers, and researchers—assess solar technology improvement opportunities and make informed R&D investment decisions regarding wind, geothermal, and biomass in addition to solar technologies. Most recently, SAM was required for SunShot applicants as they attempted to show how their research would drive down the LCOE significantly in the future. SAM facilitated technical conversations and proved critical for DOE to establish the value of each proposal and the relative impact of the research.

1. Techno-economic analysis is just one type of analysis conducted at NREL. For more information visit https://www.nrel.gov/analysis/research.html.
2. The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs

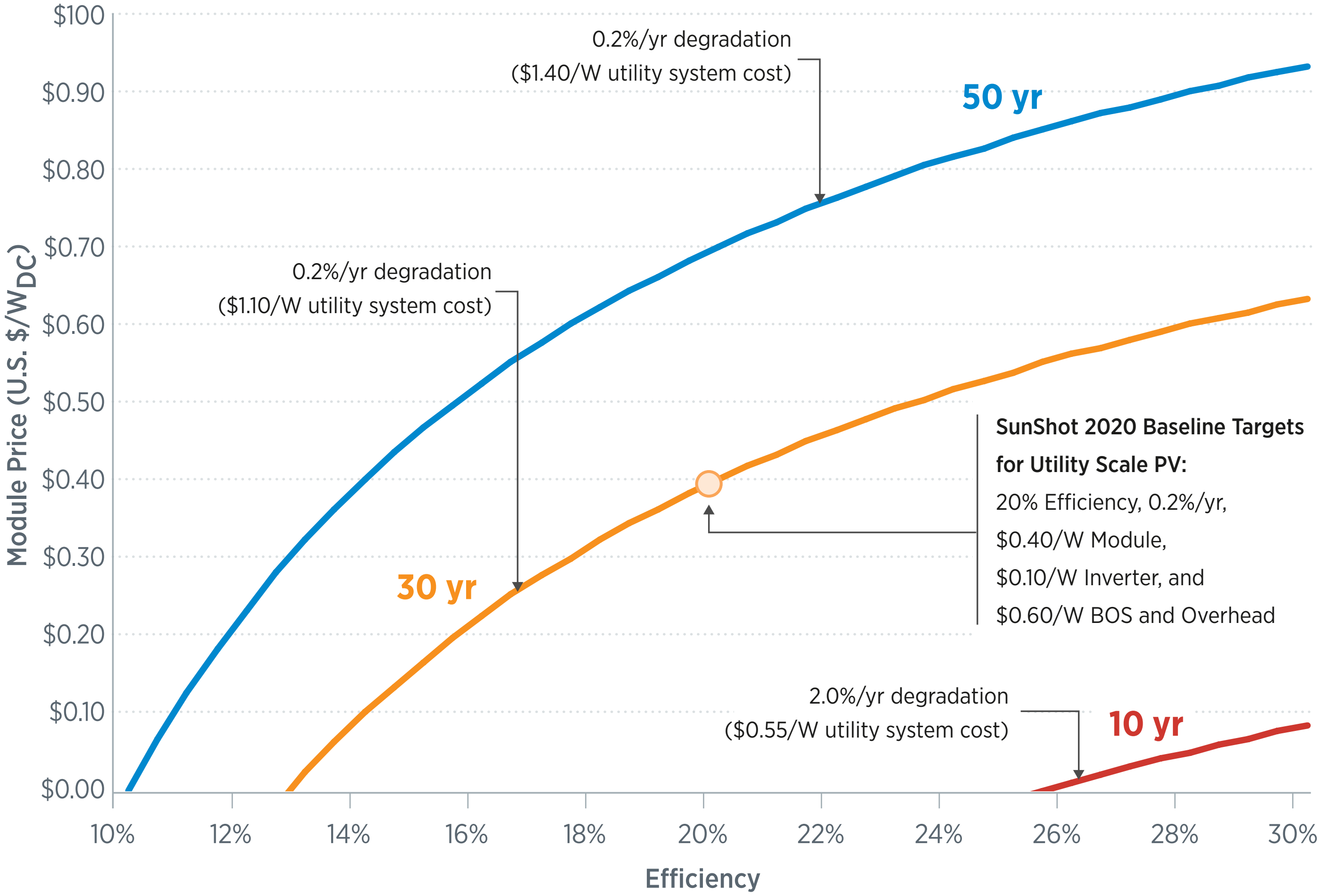


Figure 2. Economic impact of tradeoffs among key metrics—efficiency, degradation rate, and system lifetime—to meet Sunshot targets. Source: http://www.nrel.gov/docs/fy16osti/65872.pdf

NREL uses sensitivity analysis to understand the cost drivers for a wide range of advanced technologies and manufacturing processes. An example of this is analysis on the potential of increasing the area of copper indium gallium diselenide (CIGS) solar modules, which could drive down costs via economies of scale but involves research and engineering challenges.

NREL's bottom-up TEA methodology for assessing module manufacturing costs and minimum sustainable pricing (MSP), showed that larger area CIGS may hold the potential for savings of up to $0.136/W in manufacturing cost and $0.147/W in MSP. Sensitivity analysis, shown in Figure 3, illustrates the how different process and design variables influence these potential savings.

Specifically, the tornado chart shows the sensitivity to varying select parameters by +/- 20% of the baseline model assumptions, highlighting areas where research and development should be focused.[3]

Takeaway

As scientists further improve the efficiency and performance of current (silicon- and cadmium-telluride-based) and emerging (perovskites and organic-based) solar cell materials and technologies, TEA will continue to provide an objective framework to assess and compare the cost competitiveness of innovations and develop potential pathways to guide R&D toward commercially viable options.

3. Note: This not reflective of the magnitude of changes that might be technically possible but rather an indication of impacts on price given uncertainty.

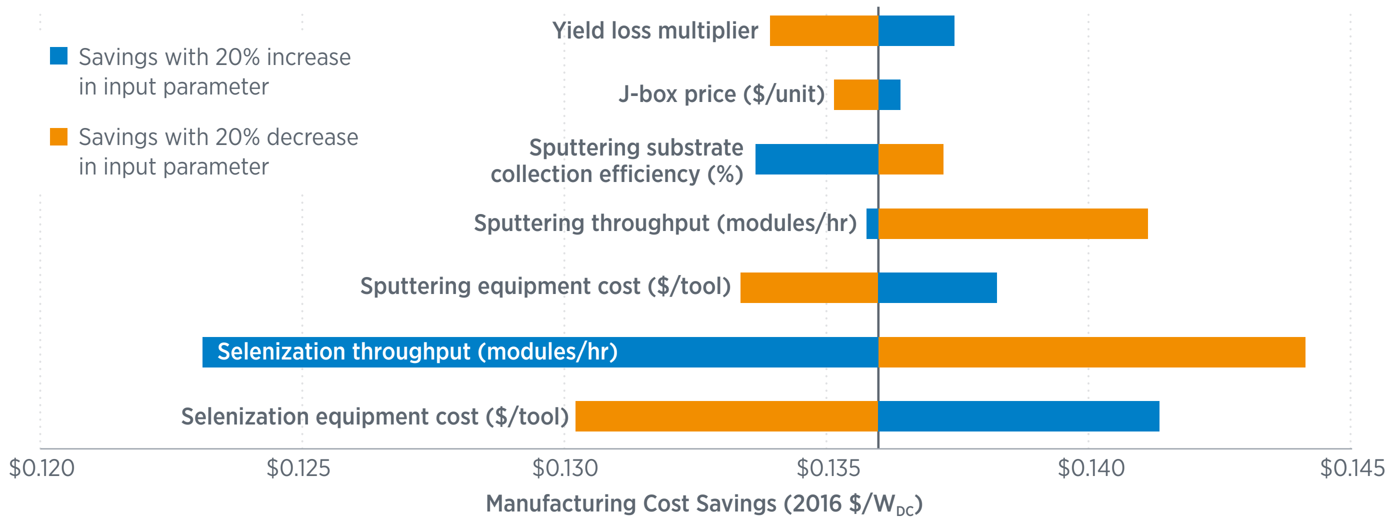


Figure 3. Sensitivity of copper indium gallium diselenide (CIGS) module manufacturing cost savings to ±20% changes in key input assumptions. Source: https://www.nrel.gov/docs/fy17osti/67006.pdf

Setting Goals and Tracking Progress Toward Achieving Performance and Cost Targets for Biofuels

NREL has relied on analysis to guide the laboratory's R&D of novel biofuel and bioproduct production processes for over three decades. Through periodic state-of-technology (SOT) updates, NREL uses TEA to establish a baseline design case for specific biorefinery process concept using the best technology and data available at a defined point in time.

Periodic SOT updates assess progress, relative to technical targets and cost goals from design cases, based on our researchers' latest experimental results. These updates ensure that the process design and its cost benchmarks incorporate the most current data from equipment vendors, NREL, and other DOE-funded research. Annual SOT updates also serve as "on ramps" and "off ramps" for continuing funding of specific conversion pathways or technologies.[4]

Between 2007 and 2012, NREL analysts applied the TEA approach to cellulosic ethanol production.[5] The lab worked in support of DOE's Bioenergy Technologies Office (BETO), helping to set, track progress toward, and validate achieving process and cost targets for ethanol production from cellulosic feedstocks, specifically working to achieve "pilot-scale demonstration by 2012 of biochemical and thermochemical ethanol production at a price competitive with petroleum gasoline based on modeled assumptions for an nth plant biorefinery." [Bioenergy Technologies Office Multi-Year Program Plan, 2016] NREL researchers successfully met this goal, providing a benchmark for industry to leverage as it commercializes the technology.

This important milestone also catalyzed the transition toward a new BETO focus on "drop-in biofuels.". BETO's goals now focus on cost competitiveness for these biomass to hydrocarbon biofuel conversion processes by 2022.

NREL analysts developed design cases for terrestrial biomass conversion (via both biochemical and thermochemical processes) that could meet that goal. In one case, NREL identified a baseline design scenario for converting cellulosic biomass to refinery-ready intermediates via catalytic fast pyrolysis (i.e., in-situ pyrolysis). Cost reduction targets, estimated from projected product yields and quality improvements via catalyst development and process integration, are shown in Figure 4.

NREL's development of design cases for additional pyrolysis pathways, including conventional pyrolysis and ex-situ catalytic fast pyrolysis, helps reduce risk and provide a more complete picture of potential routes to commercialization. BETO uses these annual SOT updates to track progress and make funding decisions for continued R&D work.

4. Bioenergy Technologies Office Multi-Year Program Plan: March 2016
5. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons

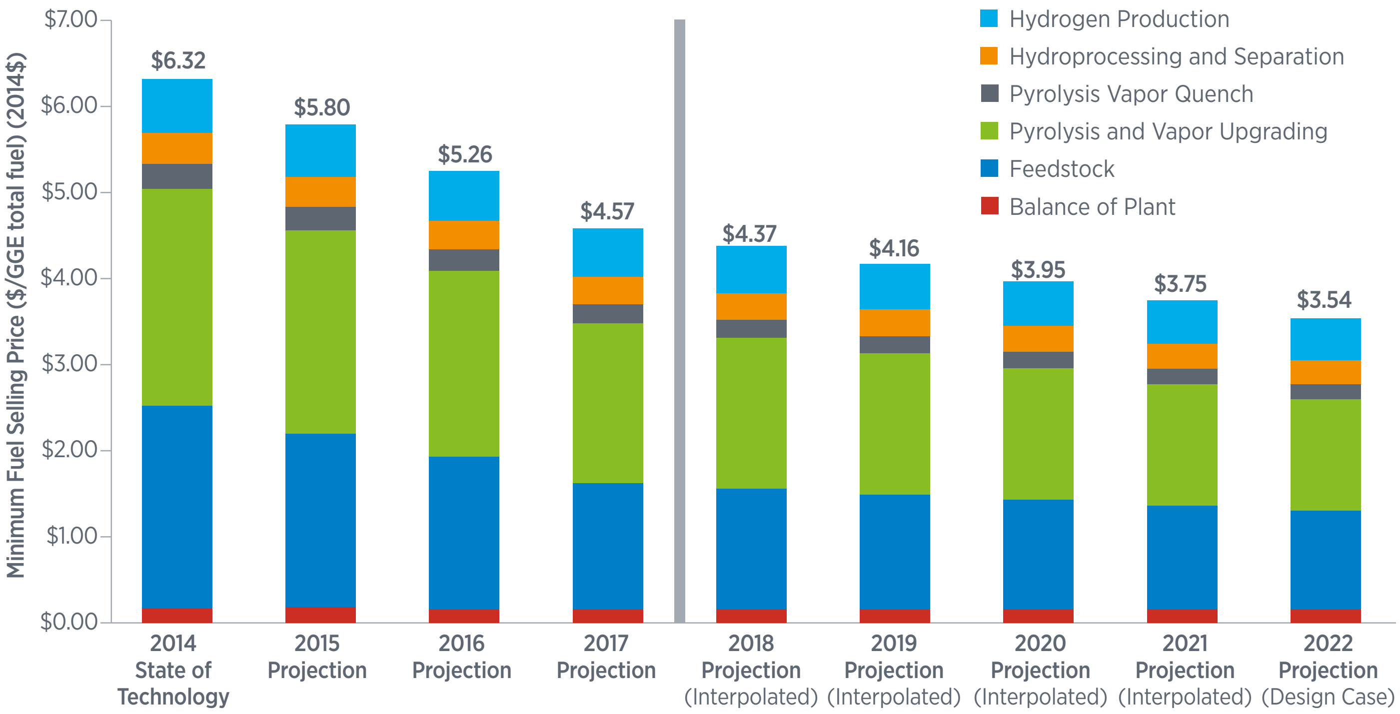


Figure 4. Cost Targets for Thermochemical Production of Hydrocarbons (via Catalytic Fast Pyrolysis) Design Case.
Source: https://www.energy.gov/sites/prod/files/2016/07/f33/mypp_march2016.pdf

Takeaway

Because many of the advanced fuels and processes are at early stages of development, techno-economic analysis will continue to play a vital role in identifying the key technical barriers and providing focus to the myriad of possibilities that exist. NREL's analytical expertise helps BETO set a path toward commercialization for the most promising options that can progressively enable deployment of increasing amounts of biofuels, bioproducts, and biopower from a widening array of feedstocks.

Quantifying the Economic Impacts of R&D Advances for Wind

NREL analysts work closely with their national laboratory colleagues and industry partners to set the course for wind energy research, technology R&D, and innovation. Since 2000, NREL analysts have helped DOE identify the critical parameters that drive cost and performance, inform R&D prioritization decisions and effectively focus R&D resources on key areas, and improve the economics of wind turbine technology.

NREL launched the Wind Partnerships for Advanced Component Technologies (WindPACT) program in 2000 to examine opportunities for reducing the cost of wind energy by 30%, making it cost-competitive with conventional generation. Specifically, WindPACT studied the effect of scale, alternative design approaches, and technology advances on capital cost, annual energy production, reliability, operations and maintenance, and balance of the station for each of the major wind turbine subsystems.

NREL analysts helped develop TEA and engineering models to estimate the potential range of impact for each system in terms of annual energy production and capital cost. The results from this study, as summarized in Figure 5,[6] have guided wind technology R&D for almost two decades, allowing DOE to prioritize R&D funding in the most impactful areas, namely advanced towers and larger rotors.

6. Figure 5 also includes the manufacturing learning-curve effect generated by several doublings of turbine manufacturing output over the coming years.

Guided by WindPACT results, NREL scientists and engineers, in partnership with industry leaders have developed, demonstrated, and deployed an array of innovations—flexible rotors, longer blades, advanced tower technologies, state-of-the-art control systems that effectively capture the energy from the wind more effectively, and improved manufacturing, transportation, and installation methods. These innovations have lowered the cost of wind energy, improved performance, increased production and reliability, and enabled broader geographic deployment of wind power.

However, continued innovation in turbine technology is needed to further drive down costs. For example, NREL scientists are developing state-of-the-art feedforward control systems that sense changes in wind conditions and adjust accordingly. This approach has the potential to capture the maximum amount of energy with minimal structural loading at the lowest cost.[7]

NREL researchers are also looking at tall wind turbine and tower configurations, such as lattice towers that use less material, field cast concrete towers, and large diameter steel towers, to enable continued plant performance improvements.[8] For each of these component systems, NREL relies on analysis to help quantify the economic value of specific improvements under investigation.

Future wind technology advancements will take a systems approach, focusing on the design and development of optimized, integrated wind plants rather than individual wind turbines. Through a combination of incremental technology improvements and advanced technology innovations, NREL's TEA shows that a 50% reduction in LCOE (to $23/MWh) could be realized by 2030.

Takeaway

Although wind turbines are considered a mature commercial technology, R&D investments—in advanced materials, manufacturing, and operations—are still critical to achieving continued cost reductions and performance and reliability improvements. Analysis quantifies the economic impacts of successful R&D pathways and serves to guide the wind industry to the most cost-effective approaches.

Technical Area	Potential Advances	Impact	Annual Energy Production	Turbine Capital Cost
Advanced Tower Concepts	Taller towers; new materials and/or processes; advanced structures/foundations; self-erecting	Least	11	20
		Expected	11	12
		Best	11	8
Advanced (Enlarged) Rotors	Advanced materials; improved structural-aero design; active and passive controls; higher tip speed/lower acoustics	Least	10	3
		Expected	25	3
		Best	35	-6
Reduced Energy Losses and Improved Availability	Reduced blade soiling losses; robust sensors and control systems; prognostic maintenance	Least	0	0
		Expected	5	0
		Best	7	0
Drivetrain (Gearboxes, Generators and Power Electronics)	Fewer gear stages or direct drive; advanced generators and gearboxes; medium voltage equipment; new circuit topologies; new materials (GaAs, SiC) and semiconductor devices	Least	0	1
		Expected	4	-6
		Best	8	-11
Manufacturing and Learning Curves	Sustained, incremental design and process improvements; large-scale manufacturing; reduced design loads	Least	0	-3
		Expected	0	-13
		Best	0	-27
Total	All Advances Combined	Least	21	21
		Expected	45	-10
		Best	61	-36

Figure 5. Areas of Potential Wind Turbine Technology Improvements. Source: http://www.nrel.gov/docs/fy08osti/41036.pdf.

7. NREL Advances Feedforward Control in Turbines
8. Trends, Opportunities, and Challenges for Tall Wind Turbine and Tower Technologies

NREL analysts help guide and advance renewable energy R&D efforts—comparing tradeoffs among proposed technology development pathways, tracking progress toward performance and cost targets, and illuminating the impacts of proposed innovations to focus R&D investments on critical technical challenges facing advanced energy technologies.

Learn More

Solar

An Analysis of the Cost and Performance of Photovoltaic Systems as a Function of Module Area https://www.nrel.gov/docs/fy17osti/67006.pdf

A Bottom-Up Cost Analysis of a High Concentration PV Module http://aip.scitation.org/doi/pdf/10.1063/1.4931548 http://www.nrel.gov/docs/fy15osti/63947.pdf

Evaluating the Economic Viability of CdTe/CIS and CIGS/CIS Tandem Photovoltaic Modules https://onlinelibrary.wiley.com/doi/10.1002/pip.2849

Techno-Economic Analysis of Three Different Substrate Removal and Reuse Strategies for III–V Solar Cells http://onlinelibrary.wiley.com/doi/10.1002/pip.2776/full

Economic Competitiveness of III–V on Silicon Tandem One-Sun Photovoltaic Solar Modules in Favorable Future Scenarios http://onlinelibrary.wiley.com/doi/10.1002/pip.2808/full

Pathway to 50% Efficient Inverted Metamorphic Concentrators Solar Cells https://doi.org/10.1063/1.5001425

Raising the One-Sun Conversion Efficiency of III–V/Si Solar Cells to 32.8% for Two Junctions and 35.9% for Three Junctions https://www.nature.com/articles/nenergy2017144

Technology Advances Needed for Photovoltaics To Achieve Widespread Grid Price Parity https://onlinelibrary.wiley.com/doi/10.1002/pip.2755

The Role of Advancements in Photovoltaic Efficiency, Reliability, and Cost https://www.nrel.gov/docs/fy16osti/65872.pdf

On the Path to Sunshot https://energy.gov/eere/solar/downloads/role-advancements-photovoltaic-efficiency-reliability-and-costs

Biomass

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons https://www.nrel.gov/docs/fy14osti/60223.pdf

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons https://www.nrel.gov/docs/fy15osti/62498.pdf

The Techno-Economic Basis for Coproduct Manufacturing to Enable Hydrocarbon Fuel Production from Lignocellulosic Biomass, ACS Sustainable Chemistry & Engineering https://pubs.acs.org/doi/10.1021/acssuschemeng.6b00243

Aeration Costs in Stirred-Tank and Bubble Column Bioreactors, Biochemical Engineering Journal https://www.sciencedirect.com/science/article/pii/S1369703X17302103?via%3Dihub

Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion https://www.nrel.gov/docs/fy16osti/64772.pdf

Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products https://www.nrel.gov/docs/fy14osti/62368.pdf

Acid-Catalyzed Algal Biomass Pretreatment for Integrated Lipid and Carbohydrate-Based Biofuels Production, Green Chemistry http://pubs.rsc.org/en/Content/ArticleLanding/2015/GC/C4GC01612B#!divAbstract

Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model https://www.nrel.gov/docs/fy12osti/55431.pdf

Conceptual Process Design and Techno-Economic Assessment of Ex Situ Catalytic Fast Pyrolysis of Biomass: A Fixed Bed Reactor Implementation Scenario for Future Feasibility https://link.springer.com/article/10.1007%2Fs11244-015-0500-z

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Thermochemical Research Pathways With In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors https://www.nrel.gov/docs/fy15osti/62455.pdf

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction: Thermochemical Research Pathway to High-Octane Gasoline Blendstock Through Methanol/Dimethyl Ether Intermediates https://www.nrel.gov/docs/fy15osti/62402.pdf

Comparative techno-economic analysis and process design for indirect liquefaction pathways to distillate-range fuels via biomass-derived oxygenated intermediates upgrading https://onlinelibrary.wiley.com/doi/abs/10.1002/bbb.1710

Wind

Trends, Opportunities, and Challenges for Tall Wind Turbine and Tower Technologies https://www.nrel.gov/docs/fy17osti/68732.pdf

Technology Improvement Opportunities for Low Wind Speed Turbines and Implications for Cost of Energy Reduction: July 9, 2005–July 8, 2006 http://www.nrel.gov/docs/fy08osti/41036.pdf

2016 Cost of Wind Energy Review https://www.nrel.gov/docs/fy18osti/70363.pdf

2016 Wind Technologies Market Report https://energy.gov/sites/prod/files/2017/10/f37/2016_Wind_Technologies_Market_Report_101317.pdf

Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation https://www.nrel.gov/docs/fy17osti/68123.pdf

NREL Advances Feedforward Control in Turbines https://www.nrel.gov/docs/fy15osti/63379.pdf

National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401
303-275-3000 • www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC

Front page photo by iStock-844319742 • NREL/BR-6A20-65707 • **August** 2018