NREL
NATIONAL RENEWABLE ENERGY LABORATORY

MAKING SUSTAINABLE ENERGY CHOICES

Insights on the Energy/Water/Land Nexus
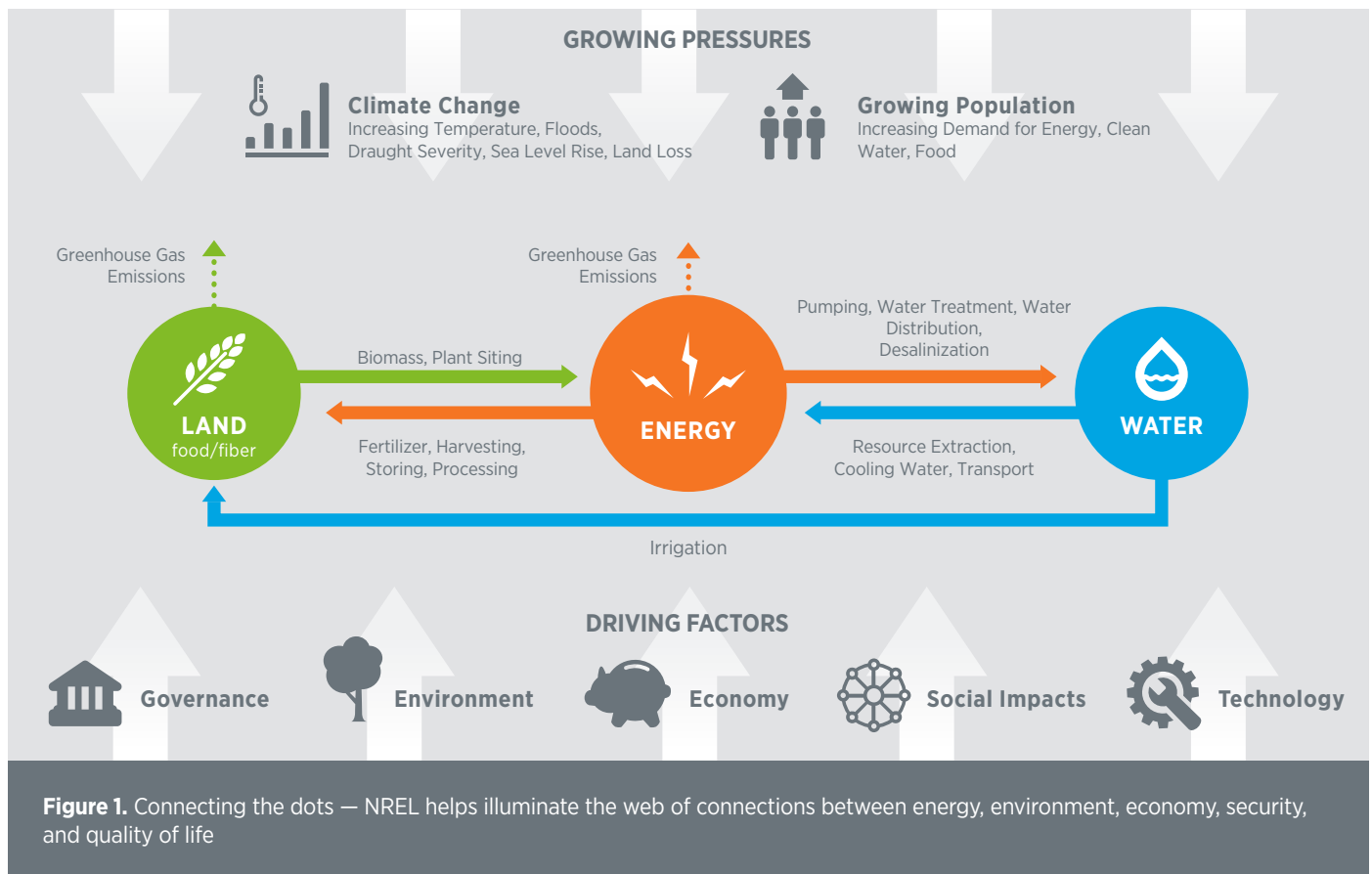
Navajo Generating Station: Helping Stakeholders Understand Complex Implications of Energy Options

NREL's analytical support helped the U.S. Environmental Protection Agency (EPA) establish a final best available retrofit technology (BART) rule for reducing NO_x emissions from Arizona's Navajo Generating Station, a 2,250 MW coal plant near Page, AZ. The initial effort, which began in 2012, focused on objectively assessing a broad range of interrelated technical, environmental, and economic issues related to potential options for power in the region— primarily replacing the coal-fired plant versus installing NO_x reduction retrofits. Several factors make this case unusually complex. The Navajo Generating Station came into being at the initiative of the federal government, which retains the largest share of ownership. Low-cost energy from the station powers a major water delivery project that helps sustain a multistate water agreement. In addition, the plant and the coal mine that supplies it are located on tribal lands and support tribal jobs and economies. NREL helped federal agencies unravel the complex interconnections and understand the implications for various courses of action in terms of power supply and prices, water supply and prices, air quality, and economic impacts. This work helped to attract diverse support for EPA's final rule. A follow-on effort, which will examine strategies for transitioning the federal government's share of the station to clean energy alternatives, is now underway.

Electric Sector Factors Emissions, Land, Water into Energy Choices

Lowering carbon emissions is one of many drivers for deploying renewable energy technologies. However, more robust energy decisions also factor in water and land use. Life cycle assessment (LCA) provides a well-established and comprehensive framework to compare the impacts of energy technologies. Using LCA methodologies, including techniques the laboratory has developed, analysts can examine emissions, water, and land impacts of energy on a "cradle-to-grave" basis—from raw material extraction, manufacturing, transport, and construction to operation and end-of-life disposal.

On a life cycle basis, renewable technologies, nuclear generators, and coal generators with clean coal technologies produce fewer carbon emissions than traditional fossil fuel combustion technologies. However, water used in power plant operations varies widely based on the electricity generation technology and cooling system. Life cycle comparison of water consumption illustrates the potential for renewable electricity generation technologies to reduce the water intensity of the U.S. energy sector (Figure 2). Solar photovoltaic and wind technologies have the lowest total life cycle water use. But as can be seen, the technologies with the lowest carbon emissions don't always have the lowest water consumption.

Calculating land use impacts is more challenging, and results vary widely—particularly for wind and geothermal systems— depending on assumptions used. NREL's preliminary work in this area indicates that land use for renewables makes up a small fraction of total U.S. land area. In addition, recent studies have identified workable strategies for minimizing land use for large-scale renewable deployment, including co-location of PV and wind on farms and ranches, and deployment on underutilized or degraded land sites (such as highway medians or landfills).
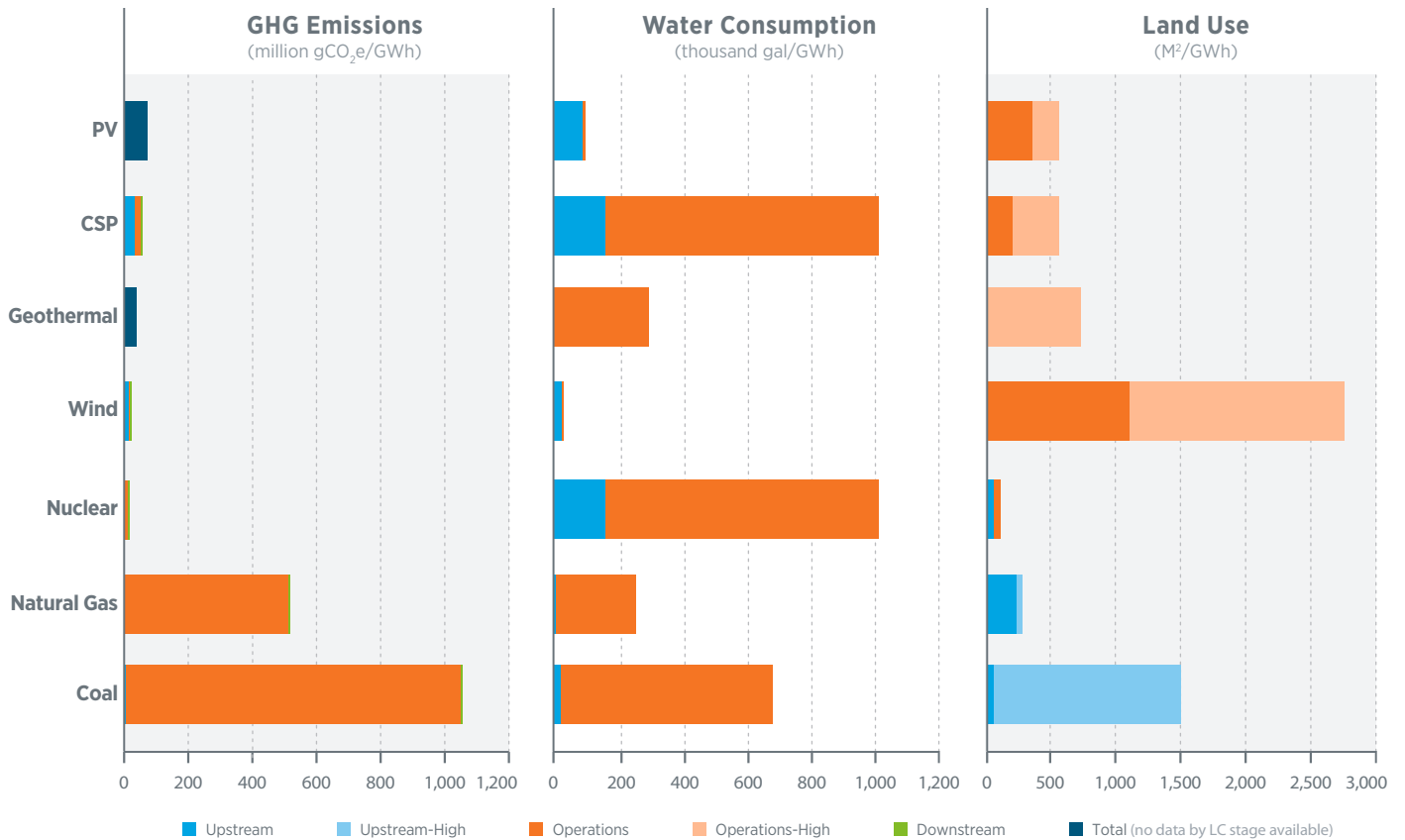
Figure 2. Life cycle emissions, water use, and land use comparisons for electricity generation technologies.[1] The low and high estimates reflect a range in published analyses.

1. Lifecycle GHG emissions: IPCC Special Report on Renewables (and NREL website) http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch09.pdf
    Lifecycle Water: http://iopscience.iop.org/1748-9326/8/1/015031/pdf/1748-9326_8_1_015031.pdf
    Lifecycle Land: http://www.iea.org/publications/freepublications/publication/Renew_Policies.pdf

Future Impacts of Today's Energy Choices in a Changing Climate

Water Use in Low-Carbon Futures

NREL has completed a series of studies to better understand the impact of different low-carbon electricity generation pathways on future power sector water use. Figure 3 compares the water consumption impacts of a "business-as-usual" baseline scenario to three alternative scenarios based on use of different generating technologies to comply with assumed carbon constraints. The different scenarios lead to significantly different water profiles due to the wide variation in water use between thermochemical power plants and low- or no-water technologies such as wind and energy efficiency measures.

Overall, investing in renewable energy and energy efficiency to meet carbon emission reduction targets is projected to result in significant water savings, lower energy costs, and net savings to consumers. Investing in new nuclear and coal with CCS facilities is projected to result in the highest long-term water consumption and highest electricity costs. Shifting from once-through cooled thermal generation to recirculating cooling technologies by 2050 reduces water withdrawals in all scenarios considered.

Business-as-usual Water Consumption for Electricity Producers (billions of gallons)

| 0-39 | 40-79 | 80-119 | 120-159 | 160-199 | 200-239 | 240-279 | 280-319 | 320-359 | 360-400 |
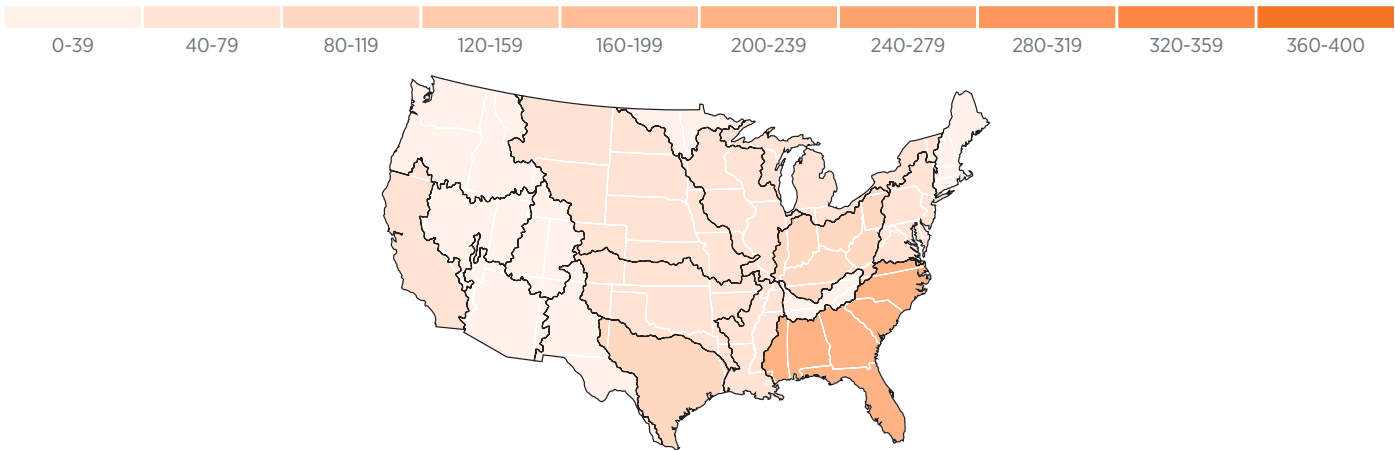
Scenarios - Change from Business-as-usual in Consumption (%)

| -100 to -81 | -80 to -61 | -60 to -41 | -40 to -21 | -20-0 | 0-75 | 76-150 | 151-225 | 226-300 | 301-400 |

CARBON CONSTRAINTS ONLY

CARBON CONSTRAINTS +
NUCLEAR AND COAL WITH CCS

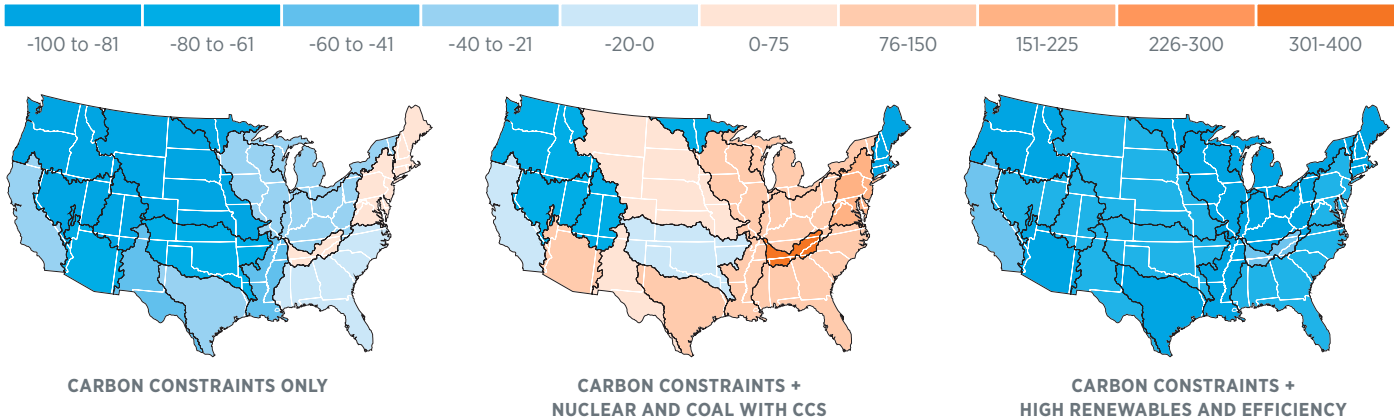CARBON CONSTRAINTS +
HIGH RENEWABLES AND EFFICIENCY

Figure 3. Future electricity choices can place different demands on regional water supplies (forecast for 2050). In general, relying primarily on nuclear and coal with CCS to meet assumed carbon constraints increases water consumption and withdrawals. Carbon constraints alone and carbon constraints with high renewable and energy efficiency show more consistent reductions in water use.

Jordan Macknick, Sandra Sattler, Kristen Averyt, Steve Clemmer, John Rogers. (2012). "The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050." *Environmental Research Letters* (7:4). NREL/ JA-6A20-56211.

Will Climate Change Alter the Water Supply Available for Electricity Generation? It Depends on Where You Live.

Electricity generation can be water intensive, and climate change could lead to changes in precipitation or increases in surface water temperatures that limit the amount of water that is available and suitable for electricity generation. To support long-term, "what if" decision-making, NREL developed and demonstrated an integrated modeling approach to investigate the trade-offs among climate, water, and electricity systems [see text box]. Analysts found that, at both national and regional levels, *average* climate

change projections have little impact on capacity growth and water withdrawal and consumption in 2050. In general, abundant unappropriated surface water rights overshadow the comparably small changes in surface water resources. Potential climate impacts were notable only for select southwestern states (Arizona, California, Nevada, New Mexico, and Texas), which tend to be more arid and where water supplies tend to be more strictly allocated. NREL can use the methodology developed for this study to investigate more extreme climate scenarios and a more rigorous representation of legal and physical water availability.

INTEGRATING WATER REQUIREMENTS AND CONSTRAINTS INTO THE REEDS MODEL

NREL analysts and partners developed a platform for assessing power plant cooling water withdrawals and consumption under different electricity pathways at geographic and time scales appropriate for both electricity and hydrology/water management. This platform uses estimates of regional electricity generation by the Regional Energy Deployment System (ReEDS) as input to a hydrologic and water management model—the Water Evaluation and Planning (WEAP) system. In WEAP, this electricity use represents thermoelectric cooling water withdrawals and consumption within the broader, regional water resource context. Linking the electricity and water models—including translating electricity generation results from ReEDS-relevant geographies to the water-relevant geographies of WEAP—allows analysis of water use by the electric sector at the regional watershed level, which can be used to examine the water resource implications of future electricity pathways.

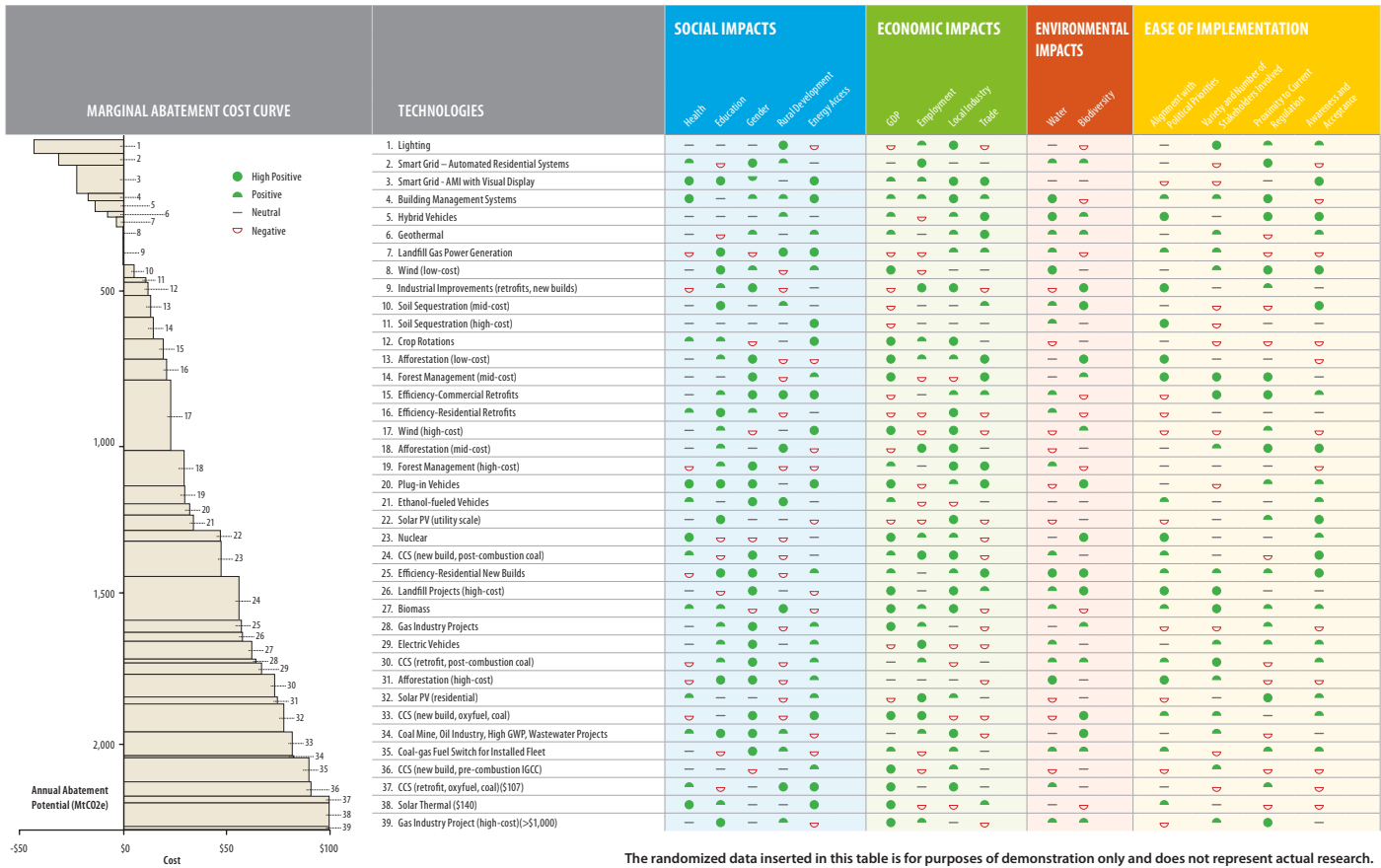# BioSpatial H$_2$O Model Quantifies Bioenergy Water Requirements

Bioenergy adds more dimensions to analysis of the energy/water/land nexus. In addition to the water used to produce biofuels or generate biopower (for example in fermentation, distillation, and cooling processes), bioenergy requires water—both from irrigation and rainfall—to grow the biomass feedstock. This generally competes with water used for irrigation of food, feed, and fiber crops. Consequently, expanding biomass feedstock production has important implications with regards to managing water resources. To estimate crop water requirements in future scenarios, NREL developed a unique model, BioSpatial H$_2$O, based on a database of detailed climate, soil, and plant physiological data in a system dynamic modeling framework. The model improves water consumption analyses by providing results at several geographic levels, disaggregated over multiple water sources, and over time. BioSpatial H$_2$O facilitates estimates of annual crop requirements for water, and helps quantify how much of that water is suitable for other human needs, such as cooling power plants. Ultimately, this powerful model enables a more robust understanding of bioenergy water consumption and will help decision-makers evaluate tradeoffs between bioenergy systems, other sources of energy, and other agricultural commodities.

Energy and Water

Thermal power plant cooling accounts for 41% of total U.S. water withdrawals. Withdrawal is the amount of water removed from sources like aquifers and lakes for use, but then returned to the source.

Water and Land

Irrigation accounts for 81% of U.S. water consumption. Consumption is the amount of water removed from the source—for example, through evaporation or incorporation into products—such that it is not available for reuse at the same location or downstream.

Figure 4

MARGINAL ABATEMENT COST CURVE

High Positive
Positive
Neutral
Negative

Cost axis: -$50, $0, $50, $100

Annual Abatement Potential (MtCO2e): 500, 1,000, 1,500, 2,000

TECHNOLOGIES

	SOCIAL IMPACTS					ECONOMIC IMPACTS				ENVIRONMENTAL IMPACTS		EASE OF IMPLEMENTATION				
	Health	Education	Gender	Rural Development	Energy Access	GDP	Employment	Local Industry	Trade	Water	Biodiversity	Alignment with Political Priorities	Variety and Number of Stakeholders Involved	Proximity to Current Regulation	Awareness and Acceptance	

1. Lighting
2. Smart Grid – Automated Residential Systems
3. Smart Grid - AMI with Visual Display
4. Building Management Systems
5. Hybrid Vehicles
6. Geothermal
7. Landfill Gas Power Generation
8. Wind (low-cost)
9. Industrial Improvements (retrofits, new builds)
10. Soil Sequestration (mid-cost)
11. Soil Sequestration (high-cost)
12. Crop Rotations
13. Afforestation (low-cost)
14. Forest Management (mid-cost)
15. Efficiency-Commercial Retrofits
16. Efficiency-Residential Retrofits
17. Wind (high-cost)
18. Afforestation (mid-cost)
19. Forest Management (high-cost)
20. Plug-in Vehicles
21. Ethanol-fueled Vehicles
22. Solar PV (utility scale)
23. Nuclear
24. CCS (new build, post-combustion coal)
25. Efficiency-Residential New Builds
26. Landfill Projects (high-cost)
27. Biomass
28. Gas Industry Projects
29. Electric Vehicles
30. CCS (retrofit, post-combustion coal)
31. Afforestation (high-cost)
32. Solar PV (residential)
33. CCS (new build, oxyfuel, coal)
34. Coal Mine, Oil Industry, High GWP, Wastewater Projects
35. Coal-gas Fuel Switch for Installed Fleet
36. CCS (new build, pre-combustion IGCC)
37. CCS (retrofit, oxyfuel, coal)($107)
38. Solar Thermal ($140)
39. Gas Industry Project (high-cost)(>$1,000)

The randomized data inserted in this table is for purposes of demonstration only and does not represent actual research.

Figure 4. NREL's Development Impacts Assessment tool makes it easy to assess carbon mitigation strategies according to a customizable set of additional priorities.

Systems Approaches to Making Energy Decisions in Broader Contexts

Mathematical models like ReEDS and BioSpatial H_2O enable analyses of a variety of energy futures. NREL is also engaged around the world using less data- and resource-intensive tools and approaches to enable energy decisions within broader contexts. Low emission development strategies (LEDS) lay out pathways for countries to achieve long-term national development goals, while also minimizing greenhouse gas (GHG) emissions historically associated with economic growth. LEDS are typically economy-wide approaches, encompassing all economic sectors, aligned with a country's development priorities such as poverty alleviation, job creation, and energy security.

NREL's Development Impacts Assessment tool provides a user-friendly approach to visualizing and comparing carbon mitigation strategies according to a customizable set of client priorities, such as development priorities or ease of implementation. The tool does this using simple graphics to indicate a positive, neutral, or negative impact of each mitigation option on the competing client priorities. Originally designed to leverage existing optimization tools that focus primarily on cost and carbon mitigation (e.g., marginal abatement cost curves and technical needs assessments), practical application in the field has shown that these detailed data are not a prerequisite to populating the tool. In fact, a particular value of the tool is its ability to leverage qualitative impact assessments and data.

Helping Policymakers and Investors Evaluate Energy Choices in Framework of Sustainability

Renewable energy technologies have the potential to reduce the environmental impacts of the energy sector. NREL is engaging stakeholders, developing tools, and conducting robust analysis to help today's energy leaders understand the trade-offs of energy choices in the context of broader social, economic and environmental priorities and increasing pressures of a changing climate.

Learn More about the Energy/Water/Land Nexus

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LEGEND:

▲ Energy ● Water ● Climate ≡ Land ■ Social