How technoeconomic analyses pave the way to a low-carbon future

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Levels of planet-warming carbon dioxide in the air continue to rise. Cutting emissions by moving away from fossil fuels is a priority—but so is removing carbon that's already been emitted. Of the many emerging technologies on the table, which ones will be most effective, and where? What about costs? What kinds of investments will have the most impact?

Scientists at the Department of Energy's (DOE's) Lawrence Berkeley National Laboratory (Berkeley Lab) are answering these kinds of questions with technoeconomic analysis, a data-driven way to predict the best routes to decarbonization.

"Berkeley Lab is building many clean energy technologies that could have an enormous impact on our path to a low carbon future. Technoeconomic analysis helps us to focus our research on those technologies that are most likely to be developed into successful and affordable products," said Berkeley Lab Director Mike Witherell.

A bridge from innovation to mature technology

Technoeconomic analysis uses computer models to evaluate the cost implications and potential environmental impacts of emerging technologies. These models can build on initial research results for a technology and calculate the costs of scaling it up. This type of predictive analysis can be used to support decision-making by researchers, industry stakeholders, regulators, and policy-makers.

A combination of robust computing power and more sophisticated techniques have made technoeconomic analysis an increasingly powerful approach. Accordingly, Berkeley Lab's team, centered in the Lab's Energy Technologies Area with staff across the Earth & Environmental Sciences and Biosciences Areas, has expanded to include 20 scientists from a broad range of disciplines who work in partnership with teams across Berkeley Lab and with other institutions.

The research often requires a blend of engineering design, process design and simulation, cash flow analysis, life-cycle assessment, and geospatial analysis.

"With a novel technology, we can't just take an analogy for an industry and guess at how it performs. We really need to be building brand new engineered systems and the process models around them," said Hanna Breunig, Berkeley Lab research scientist. "This requires team science and new computational approaches to start predicting performance."

Whereas earlier technoeconomic analysis projects generally relied on existing software with limited inputs and outputs, today Berkeley Lab researchers are creating tailored, multilayered computer models to get a more complete picture of a technology. Even more importantly, the team has been bolstering these models with data from early-stage research at the Lab. This creates a feedback loop where the data strengthens the models, and vice versa.

Berkeley Lab's history of technoeconomic analysis over the past two decades is now proving useful in a variety of key climate change mitigation strategies. This includes negative emissions technologies such as direct air capture and enhanced weathering, a process that speeds up chemical reactions that remove carbon naturally. It also includes decarbonizing manufacturing; biofuels and bioproducts; hydrogen production and storage; and methods to support a circular economy where more materials can be recycled, avoiding the need to make new ones.

"When technologies are so nascent and they are being commercialized rapidly, we are getting data from all directions," said Corinne Scown, a Berkeley Lab staff scientist. "So we have to get a handle on what the major drivers are for costs, energy balances, and emissions really quickly. That requires the kind of technological expertise and abilities that we've been building."

High-temperature thermal energy storage

In recent study, Breunig and colleagues presented a concept for a high-temperature thermal energy storage system that could bank large amounts of energy for periods of weeks to months. Breunig and study co-author Sean Lubner, a Berkeley Lab affiliate, hypothesized that new composite materials could be engineered to meet the needs of such a system.

The systems analysis was used to reverse-engineer targets for key material parameters such as electrical conductivity, material price, and durability from a system's levelized cost target. The result was both a patent on the integrated system and candidate materials, and a prototype based on the most promising material.

Infinitely recyclable plastics

Other recent technoeconomic analysis work has focused on an infinitely recyclable plastic called poly(diketoenamine), or PDK. The material was invented at Berkeley Lab a few years ago. Now researchers including Baishakhi Bose, a postdoctoral scholar at Berkeley Lab, are conducting analyses to zero in on the most cost-effective versions of the material, as well as where the material might work best (mattresses and automotive parts are two candidates).

"With technoeconomic analysis, we can generate scenarios that can help us determine whether PDK compounds being explored in the lab would be cost-competitive with plastic compounds currently in the market," Bose said. "The technoeconomic analysis studies are also helping us understand which stages of the PDK production process need improvement."

Removing carbon from the air

Breunig and colleagues in the Earth & Environmental Sciences Area are developing best practice guidance for a technique called enhanced weathering, where pulverized rocks are added to soil, to maximize carbon removal and potentially improve soil quality and boost crop yields.

Researchers at Berkeley Lab, Lawrence Livermore National Laboratory, and several other labs and universities are collaborating on a forthcoming report, Roads to Removal, that will evaluate the prospects for both engineered and nature-based methods to take carbon dioxide out of the air. Given that concentrations of carbon dioxide have risen 50% in less than 200 years, the world needs viable removal options such as direct air capture, biomass carbon removal and storage (BiRCS), and improved forest and cropland management practices.

"The report has the potential to be really impactful, not just because of our ability to say how much carbon we think we could remove up to 2050, but also where infrastructure investments like carbon dioxide pipelines will be most needed," Scown said.

Hydrogen production & storage

In ongoing work for DOE's HyMARC program, Berkeley Lab Research Scientist Peng Peng and Breunig are developing a computational approach for evaluating sorbent materials for hydrogen storage applications. Their work has been used by colleagues in Material Sciences and elsewhere to begin co-designing the sorbents and engineered storage system for target applications such as backup power systems to replace diesel generators.

Biofuels & bioproducts

In the case of biofuels, a technoeconomic analysis could tell you the minimum price a particular biofuel would need to deliver a solid return on investment. Or it could predict how the cost and emissions impact would change at an ethanol biorefinery if the facility were also to make biogas from manure and food waste. The carbon intensity of bio-based products and fuels is the most critical metric for securing tax incentives, but requires careful life-cycle assessment and carbon accounting of supply chains and processes that can be highly spatially and temporally heterogeneous.

Scientific basis for policy decisions

In addition to lighting the path toward commercial development of emerging technologies, analyses like these provide key information for researchers, policymakers, and industry as they allocate resources to develop and deploy climate solutions.

"It wasn't until technoeconomic analysis started coming out that it became clear hydrogen has a strong role to play in supporting power grids, heavy duty vehicles, and shipping," Breunig said. "That view emerged directly from looking at the technical performance and cost compared with other technologies like batteries."

Public-private partnerships are also an important way to strengthen technoeconomic analysis and help move technologies forward. "It works best if you're able to partner with companies and make sure that you are incorporating some of their lessons learned back into the modeling," Scown said.

In a project with the California-based Zero Waste Energy Development Company (ZWEDC), Berkeley Lab researchers studied the carbon and air pollutant emissions impacts for different ways of managing organic municipal solid waste, such as landfilling, composting, and anaerobic digestion.

As part of the project, they modeled operations of the ZWEDC facility in San Jose and then explored alternative strategies for that facility. The results revealed just how beneficial it is to divert organic waste from landfills from a climate standpoint, but also some of the air quality challenges composting can present. Going forward, the team is exploring options for using manure to generate energy and opportunities for carbon sequestration.

Analyses can also estimate effects that are critical to the well-being of local communities such as local job creation, changes in criteria air pollutants, and effects on water systems. Other effects captured in analyses include risks to the supply chain for critical materials, product recyclability, among many other insights.

Technoeconomic analysis helps in assembling a road map that spans the near- and long-term opportunities. The results can build a strong case for moving ahead with the "low hanging fruit," Scown says, of solutions like biomass for carbon removal that are ready to deploy today. On the other end of the spectrum, technoeconomic analysis can play a central role in charting the path forward for early-stage technologies like those for direct air capture and hydrogen.

"This is going to be a multi-decade issue to solve," Breunig said. "There's great value in having the computational skills and the diversity of team members to support an innovation pipeline."

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