Techno-Economic Analysis for Hard-Tech Innovation

Accelerating hard-tech development in the United States at marginal cost.

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EXECUTIVE SUMMARY

Hard-tech innovations are characterized by substantial scientific or engineering challenges. In practice, this can translate into long, expensive R&D timelines and high capital costs for implementation.

For the purpose of this report, hard tech refers to technologies rooted in the physical or biological sciences as applied to manufacturing or industrial innovation. Hard tech spans chemical process, bioprocess, energy, and materials industries with applications ranging from carbon capture to batteries, biofuel production, semiconductors, and beyond. Hard-tech innovation, therefore, plays an essential role in achieving important national goals, for example:

- Reducing gas emissions & attenuating global warming
- Decarbonizing industry and energy systems
- Advancing quantum computing and next-generation semiconductors
- Growing the economy
- Expanding applications for synthetic biology
- Achieving energy independence
- Strengthening national security

Large amounts of private, institutional, and government funding are directed toward developing hard-tech innovations for commercialization. Large amounts of time, talent, and lab space are correspondingly committed. According to a National Science Foundation report, the U.S. government-funded $19 billion in research & development (R&D) within the manufacturing industries during 2018.

This paper, which is based on the author's work with more than 20 science entrepreneurs in the Activate Fellowship as well as many other founders at a similarly-early startup stage, describes how a relatively small investment in early-stage techno-economic analysis (TEA) could substantially increase the impact of these larger investments, and thereby increase the rate and impact of hard-tech innovation in the United States. It provides the following specific recommendations to practitioners and policymakers:

1. Develop an online course to educate technology developers, program managers, and investors in the use and interpretation of TEA.

2. Provide innovators with access to a group of specialists to support them in developing techno-economic models and using TEA to guide development.

3. Stimulate the growth of TEA as a field by creating an online web hub and using targeted incentives.

Finally, the paper presents an example of how TEA could be used to inform policy/strategy as it relates to hard-tech innovation.

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BACKGROUND

The Role Of Economic Viability In Hard-Tech Innovation

If a technology is to be useful for solving real-world problems, it needs to be economically viable. Its benefits must outweigh its costs. Since the economic viability of hard-tech innovations is largely beholden to the laws of physics, many ideas are not worth pursuing simply because scientific or engineering constraints make them uneconomical—their benefits would not outweigh the cost of developing or manufacturing them.

When evaluating a technology for commercialization, developers and investors consider its anticipated benefits and costs along with the associated uncertainty. The earlier and more accurately they can estimate these variables, the better they can direct their efforts and resources away from dead ends and toward potentially successful, high-impact objectives. This is where techno-economic analysis is useful.

What Is Techno-Economic Analysis?

Techno-economic analysis (TEA) uses analytical modeling to examine how technical and financial parameters influence economic benefit. These parameters include:

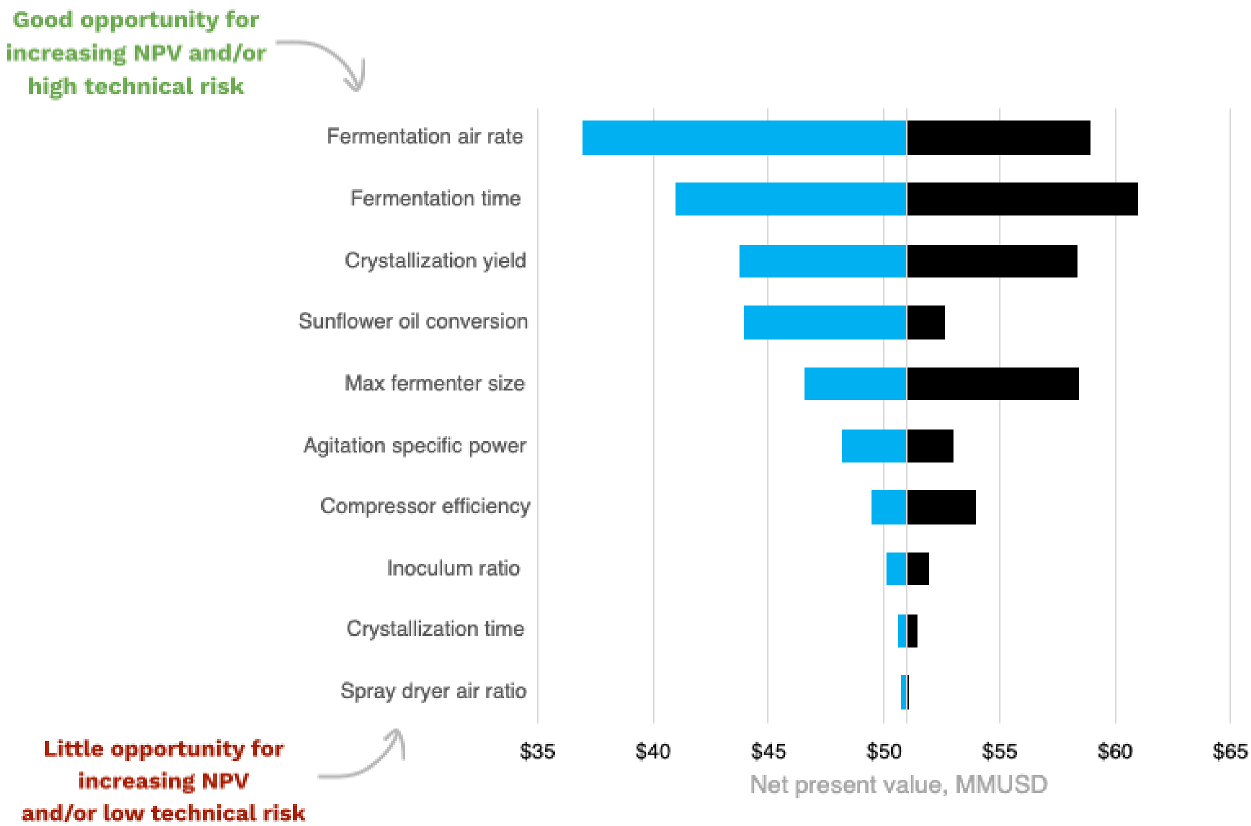
- Technical parameters: R&D results and engineering assumptions
- Financial parameters: Prices for raw materials, utilities, waste treatment, labor, etc. Factors for overhead, maintenance, etc.
- Economic benefit: Net present value, initial rate of return, profit margin, total product cost, payback, etc.

TEA is valuable for assessing economic viability, but a good techno-economic model (TEM) is more than a one-off analysis; it is a tool for understanding design tradeoffs and development risks, and for effectively guiding the development of a technology. For example, TEA sensitivity analyses, like the tornado diagram shown below, can help developers to identify technical opportunities, risks, and areas of uncertainty. This information can then be used to direct development efforts toward the most promising targets.

> **TEA's greatest value is not in making go/no-go decisions, but rather in helping innovators to understand the implications of their assumptions.**

As the technology matures, the TEM does so as well. A very simple, back-of-the-envelope level TEM is often sufficient and appropriate during the earliest stages of idea generation. A more mature technology, however, merits a more detailed and complex model. Ultimately, the information contained in the TEM can be used as a starting point for more detailed engineering design or process simulation.

A key distinction is that TEA's greatest value is not in solving for answers or making go/no-go decisions but rather in helping innovators to understand the implications of their assumptions and in providing real-time feedback on their ideas.



The tornado diagram is a type of graphical sensitivity analysis that shows the relative impact of a set of input parameters on a single result. In TEA, they are used to identify areas of uncertainty, risks & opportunities and for prioritizing R&D. The diagram above was generated from a TEA for the production of riboflavin by fermentation.

TEA in Action

The following summaries are based on work the author undertook with founders, including Activate Fellows, who were translating a breakthrough, born from university research or a government research lab, into a product aimed at solving an important problem in industry or elsewhere. These founders understand that the technology needs to be economically beneficial to be useful in the world.

Use Case 1: Bioprocess alternative to petroleum-derived commodity

The breakthrough is a bio-process for replacing a petroleum-derived commodity chemical. Before scaling up, the developers build a TEM that extrapolates commercial-scale manufacturing and capital costs from the data they have collected in the lab.

<u>Possible outcomes:</u>

1. They learn from TEA that even their most optimistic projections do not result in a process that can compete with the existing technology, so they decide to take a step back and try a different approach.
2. They learn from TEA that their technology is not yet economically viable in its current state, but, through sensitivity analyses, they learn that a disproportionate amount of their costs is attributable to one particular part of the purification process. They decide to focus their R&D efforts in this area. As they make improvements, they use their TEM to regularly reassess their progress.
3. They learn from TEA that their economic viability relies on the price of electricity being below a certain level. They decide to address this in two ways. First, they look at ways to reduce their dependence on power costs through alternative process configurations and operating conditions. Second, they explore options for securing lower-cost electricity, i.e., by co-locating with a biomass power plant.

Use Case 2: Membrane for battery applications

The breakthrough is an improved membrane for use in batteries. The developers need to understand how the manufacturing costs for their membranes compare to the value they will add when used in batteries. They build two models for TEA: one for manufacturing the membranes and one for using the membranes. These could also be two parts of a single model.

The first TEM performs a function similar to that in the previous example. The second TEM helps them understand the relationship between the technical performance of the membrane and how much it can cost to produce.

Use Case 3: Platform technology

A startup has a new platform technology, which might be used for producing a range of valuable products. Before application-specific experiments, they choose a handful of promising options and build techno-economic models for each one. Based on their understanding of the technology and market research, they put upper and lower bounds on the important input parameters. They then build tornado diagram sensitivity analyses for each.

The tornado diagrams give a clear visual representation of how they expect the uncertainty in each key parameter to impact the net present value of a commercial system. Based on this information, they choose to pursue two options with relatively high expected net present value and low uncertainty. (Net present value, or NPV, is a financial metric that estimates the total lifetime value of a project or investment.)

How Much Time And Money Is Required For TEA?

Hard-tech innovations vary widely in complexity and character. Ideally, TEA is an ongoing process that extends throughout development. From the experience of this author and TEA practitioners polled in interviews, though, an initial early-stage TEA can typically be developed with 40-80 hours of work over four to eight weeks—usually for under $10,000.

Without good TEA for guidance, companies may spend months or years pursuing dead-ends or sub-optimal R&D plans. One early lithium-ion battery startup purchased $1 million in equipment that turned out to be unsuited for the manufacturing process it later pursued. In this case, a $10,000 investment in TEA could have saved the company 100X that amount.

When Does It Make Sense To Perform TEA?

When technology is selected for development toward commercialization, it generally means that the developers believe it has the potential to be economically viable. On some level, they are drawing certain assumptions from their understanding of the technology and then concluding that further development is warranted. TEA makes the reasoning and assumptions explicit.

An up-to-date TEM represents the best current understanding of a technology. This includes the developers' best approximation of the process design and their best guesses at the values or ranges for the governing parameters. Early-stage technologies require many assumptions, but what reason is there to move forward if those assumptions do not add up quantitatively to favorable economics? TEA can, in fact, be used even before a technology has

> **Good TEA is best thought of as a tool for learning and design, and it should enhance innovation rather than stifle it.**

been conceived—to drive ideation toward an applied objective.

Sometimes people worry that premature cost modeling will stifle innovation. If TEA is used poorly, this may be the case. But TEA is just another way to make the most of the information at hand. Economic viability, like technical feasibility, is necessary for the success of a technology. Good TEA is best thought of as a tool for learning and design, and it should enhance innovation rather than stifle it.

Software Platforms For TEA: Spreadsheets & Process Simulators

Techno-economic modeling is typically performed using either spreadsheet software, like Microsoft Excel, or a process simulator, like Aspen Plus. (As noted earlier, TEA is valuable because it shows innovators who engage with it—whether that's on the back of an envelope or by using a process simulator—the consequences of their decisions.)

Many, if not most, TEA publications from universities and national labs use the process simulator Aspen Plus. It is also common for college students to be introduced to rudimentary TEA through using Aspen Plus. Process simulators are powerful tools for many applications, but, despite their publicity, they are generally not well-suited for startups or entrepreneurial/applied researchers doing early-stage TEA.

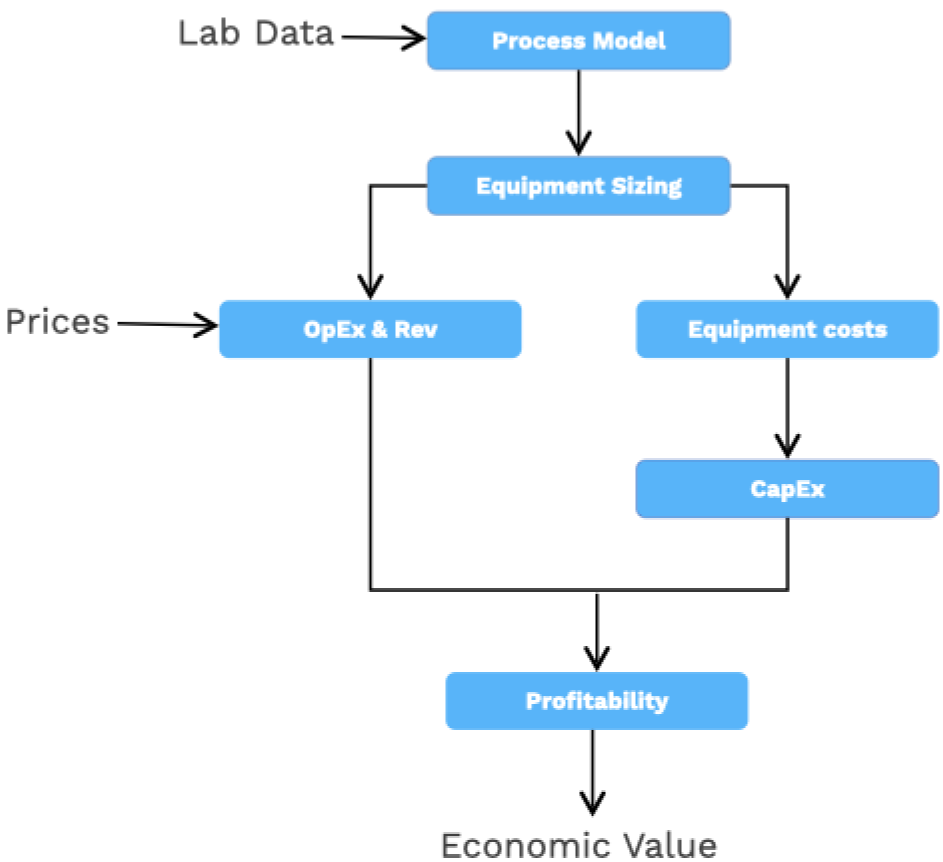
The main advantage of spreadsheet software is its flexibility. Early in development, technologies are often ill-defined. The first iterations of a TEM often call for modeling the one novel part of a process in detail while at the same time making broad generalizations about the other parts. Process simulators force a particular structure on the model that can be at odds with these requirements. Spreadsheet software affords developers the freedom to make whatever assumptions are most appropriate.

Process simulators also require expensive software licenses and specialized skills. Microsoft Excel, on the other hand, is commonplace in engineering and business. As a result, it is effectively free of cost, and the models built with it can be easily shared between colleagues and investors.

Someone familiar with spreadsheet software does cannot necessarily build a good TEM, though. Undisciplined spreadsheet development can quickly lead to indecipherable models that are nearly impossible to validate or use in collaboration. This is a common limitation experienced by aspiring TEM developers, but it can be overcome through better spreadsheet development practices.

Methodology & Accuracy

Regardless of the platform, techno-economic models tend to follow the structure shown in the figure below. The analysis begins with a model of the process/technology that uses engineering calculations to quantitatively define the system based on technical user input settings. This information is then used to estimate the equipment sizing and the amount of energy or other utilities required to operate the system. Finally, that information is used to estimate capital costs, operating costs, and economic value metrics.



Information flow within a typical techno-economic model

For chemical-type processes, capital costs are often estimated using an equipment-factored approach. That is, the cost of major equipment is estimated based on the process model, and the cost for the total system is extrapolated from there. If the process design is complete and accurate, accuracy can be as high as +/- 30 to 40 percent. This is seldom the case in early development, though, when systems have yet to be well-characterized, so the range of expected uncertainty can be considerably broader.

This may make TEA sound like a blunt instrument. When compared to a detailed cost estimate, it is. TEM results are certainly not suitable for budgeting for the construction of a plant, but they are far better than the alternative of no estimate or an intuitive guess. When considering technologies with narrow economic margins, a more detailed analysis may be warranted. However, early-stage cost estimates are almost always low, so narrow margins at the outset are unlikely to persist through later development.

Relationship To Market Analysis

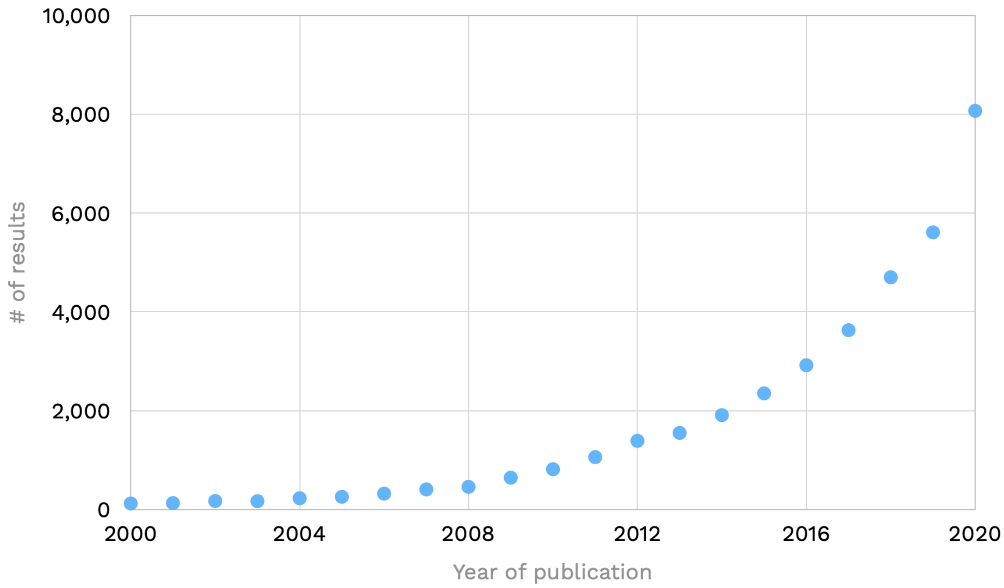
Market analysis examines the potential for selling a product. Among other factors, it estimates the size of the market and the price that customers would be willing to pay.

TEA and market analysis go hand-in-hand when evaluating the economic viability of a product – there is a chicken-and-egg relationship between them. For a product to be economically viable, there needs to be a sufficient market, and its economic benefit must outweigh its costs. The size of the market will depend on the price of the product. The economic benefit will depend on the market size and the price of the product. The price of the product is constrained by the cost of production.

History And Centers Of Excellence

TEA has been used for decades at large chemical and petroleum companies (though some practitioners use different names for it, such as integrated process and cost modeling). At companies like Dow, ConocoPhillips, and others, it is standard practice for evaluating the potential of new technologies and informing R&D decisions. (Two former Dow engineers were interviewed for this work, and the author learned TEA from a former ConocoPhillips engineer and executive.) The TEA groups at these corporations seem to be isolated and insular, though, and to rely heavily on proprietary information.

On a more public front, the National Renewable Energy Lab (NREL) has fostered a TEA culture as a means of objective and quantitative analysis. NREL regularly publishes detailed results of their TEAs which technology developers widely use as reference points.



Search results on Google Scholar for the phrase "techno-economic analysis."

The results shown above, from an informal survey of Google Scholar, indicate that TEA (or at least the phrase techno-economic analysis) has also become much more prevalent in the academic literature in recent years. It seems, however, that many of these publications simply use cost estimates generated by Aspen Cost Estimator and do not really fit the type of TEA advocated for in this paper. Nonetheless, this trend indicates a growing recognition of the importance of economic viability to successful innovation.

PROBLEM STATEMENT

This paper was motivated and informed by observations of hard-tech startups and applied researchers (1) expending substantial resources toward development without having previously built good cost models, and then (2) being unhappily surprised by the results of the models they did eventually build. The professionals interviewed suggested a number of potential reasons for this trend.

Lack Of Awareness

There seems to be a lack of awareness and understanding of early-stage TEA among technology developers and funding providers. They lack awareness of both the practice itself and its potential. In some cases, neither party seems to know (or believe) that meaningful cost modeling is an option before substantial engineering work has been completed. They may consider it an exercise for some future date when they have more data. Alternatively, they may believe that they have done as much modeling as is presently possible when they, in fact, have not.

Lack Of Education

Techno-economic modeling requires integrating a number of engineering skills in a cohesive model. It also requires a certain mindset that is characterized by iterative design thinking and creatively working around uncertainty.

> **Techno-economic modeling requires a mindset characterized by iterative design thinking and creatively working around uncertainty.**

The individual engineering skills—process design, process modeling, equipment sizing, cost estimation, and spreadsheet development—are familiar to chemical and bioprocess engineers, but they are typically not familiar to hard-tech innovators coming from other fields, like chemistry and materials science. The mindset, however, seems to be a major block for many entrepreneurs.

All of the TEA practitioners interviewed said they learned TEA on the job. Students or professors from Cornell University, MIT, UC Berkeley, and the University of Michigan were also questioned, and none were aware of TEA being taught explicitly at their institution. The closest thing to TEA taught in most curricula was cost estimation in Aspen Plus during chemical engineering capstone design courses.

Inexperienced Practice

TEA has gained some traction in recent years. Many government funding opportunities now require TEA as part of a proposal or project report, for example. However, the scientists and engineers who are asked to build the models often do not have the necessary skills or experience. As a result, their models tend to be poorly designed.

A bad TEA is often worse than no model at all. Faulty TEA conclusions can derail an otherwise promising project. More likely, however, they can impart undue confidence to developers or investors.

Reliance On A Good Story

A good story and clever marketing are more useful in some industries than in others. In hard tech, they can actually be a liability if offered as a surrogate for good cost analysis. Developing hard tech is different from developing software. It is not always possible to pivot when you are constrained by the laws of physics. Some technologies are objectively more promising than others.

For this reason and some of the others outlined above, startups are often able to get funding without good cost modeling. If that happens, they are then disincentivized from future cost modeling; digging deeper might turn up something unpleasant.

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SOLUTIONS

One of the early hypotheses of the research behind this paper was that hard-tech innovators should learn to perform TEA themselves. After interviewing practitioners, investors, and developers, however, it appears that this may not be the best approach. Many innovators have little or no experience in the relevant skillsets. Further, with the startup culture as it is, many of them would only ever have the opportunity to build one or two techno-economic models in their careers. Each would be reinventing the wheel—spending more time than is necessary and obtaining marginal results, at best.

Instead, this paper recommends providing innovators with access to a group of TEA specialists to help them develop models and to understand the thought process behind them. This approach would have a number of advantages. First, specialists would have the benefit of experience and the curated templates and resources that come with it. The TEA could be accomplished more quickly and with more reliable results. This would also preserve the innovator's time to focus on their own areas of expertise.

Second, the analysis of an unbiased third party would be seen as more credible by investors. It would provide additional confidence to the investors and the developers alike.

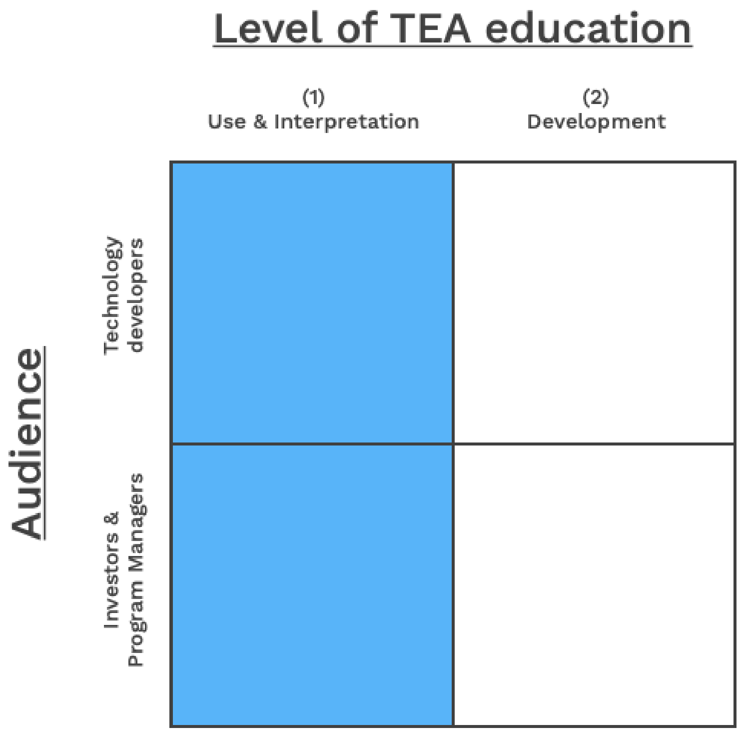
Third, if a specific government agency were to set up a TEA group, there would be a level of standardization between the models. This would allow for better comparison between technologies and, in the future, serve as a basis for improving TEA methodology itself by developing better methods, tools, and resources.

To realize the significant benefits of integrating TEA into hard-technology innovation, however, this paper also recommends a three-pronged approach, described below.

1. TEA education should be provided to appropriate audiences through a standard curriculum.
2. TEA should be deployed through centralized providers for maximum efficiency and impact.
3. TEA should be developed as a field of practice, supported by a network of practitioners through a web hub—a place for convergence, consensus, and authority in the field of techno-economic analysis.

Education

The options for TEA education may be considered in terms of the two-by-two grid below. There are two audiences and two levels of education. This paper recommends initially focusing on the two highlighted boxes—educating both technology developers and investors/program managers in the use and interpretation of TEA. These objectives would be the fastest and easiest to implement and provide immediate results.



Educate both technology developers and investors/program managers in the use and interpretation of TEA

An outline of the learning objectives for a Level 1 course is shown below. (For an outline of learning objectives that might be addressed in a Level 2 course, see the Appendix of this whitepaper.)

Outline of Level 1 TEA curriculum

1. Basics of process / technology economics.
    a. The importance of economic viability.
    b. How capital costs, operating costs, and revenue combine to determine the economic viability of a technology.
    c. Understanding capital costs (i.e., equipment, installation, engineering design, etc.)
    d. Understanding operating costs (i.e., raw materials, waste treatment, labor, utilities, overhead, etc.)
2. Techno-economic analysis.
    a. General outline of TEA methodology, level of accuracy, etc.
    b. Use cases & benefits.

    c. Cost for TEA development vs. typical R&D costs.
    d. Justification for early-stage TEA.
3. Common errors to avoid.
    a. Capital cost components that are often neglected.
    b. Operating cost components that are often neglected.
    c. Mitigating bias.

The Level 1 curriculum could be presented in a short (one hour or less) course to scientists, engineers, and business managers alike. It would provide them with a framework for understanding how the success of their technology is linked to its economics and how the economics can be estimated from what they are learning in the lab.

In 2018, Activate released an online course called Techonomics that covers many of the above objectives and others through a video series. For the purposes described in this paper, a more targeted program is likely preferable, but Activate's Techonomics provides an example of how a single online course can make an impact. One of the experts interviewed for this paper relayed a notable case, in which the carbon dioxide removal startup Heirloom Carbon viewed Techonomics and then used a template from the course to build its own model. Later, it used the model to help successfully procure funding from Breakthrough Energy Ventures, Prelude Ventures, and Lowercarbon Capital.

A simple video series—potentially an offshoot of the Techonomics series—incorporating narrated slides and screen casting could likely be produced in under 40 hours of work over four to eight weeks.

Centralization

This paper was funded by Schmidt Futures through non-profit Activate, which manages the world's first and largest entrepreneurial research fellowship program. The author, TEA professional Chris Burk, first worked with Activate in 2017 to develop the aforementioned TEA course called Techonomics to teach Activate Fellows about cost modeling. The fellows were then encouraged to build their own TEMs. This approach was successful with some of the fellows, but many did not have the skills or the time to devote to building strong models.

In early 2020, Activate tried a different approach. It contracted with the author to build a TEM with each fellow team that was interested. This program provides each team with a high-quality analysis, third-party credibility, and a certain amount of education in TEA along the way. Also, rather than a single report, the fellows are left with a model that they understand and that they can continue to use and build on into the future. It has been very well received.

A similar approach has been successfully initiated for carbon capture technologies at the University of Michigan's AssessCCUS program.

Programs like these, if adopted by government funding agencies, would provide a great service to grant recipients and at the same time increase the efficiency of hard-tech innovation and the taxpayer dollars funding it.

For the sake of argument, the U.S. Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) programs provide a convenient example. The SBIR/STTR program brands itself as America's Seed Fund. It provides funding for "small businesses to engage in Federal Research/Research and Development with the potential of commercialization." The program distributes competitive grants in two phases. Data from DOE SBIR grants awarded in 2020 are shown below.

		Grant amount	
DOE 2020 SBIR Grants	Count	Average	Total
Phase I	414	$206,000	$85,314,000
Phase II	197	$1,132,000	$223,098,000

Commercial success is difficult to define and quantify, but a 2016 analysis by the DOE reported that 17 percent of SBIR/STTR awardees surveyed achieved total sales of over $1 million. Notably, 49 percent had no sales at all. Considering the challenges of hard-tech innovation, a 20 percent success rate would be incredible, but let us assume it for argument's sake.

If 20 percent of the 2020 DOE Phase II awardees have technologies that will ultimately be economically viable, then 80 percent or about 158 do not. Now, consider that a good early-stage techno-economic model can generally be developed for under $10,000. To build such a model for every Phase I awarded would cost about $4.1 million. This is equivalent to about four grants' worth (or 2.3 percent) of the Phase II funding that was provided to those 158 technologies that will never reach commercialization.

So, in a sense, for Phase I TEA to pay for itself, it would need to identify just four out of those 158 ill-fated technologies. The innovators could use the information they learned to develop other ideas, and the Phase II funding could be directed to other more promising technologies.

At the same time, as the other 194 innovators progress into Phase II, they would be equipped with a strong TEM to help direct their research efforts toward the most promising targets and mitigate risks. Further, the credibility of a third-party analysis would benefit all awardees as they seek further investment.

To implement a centralized TEA program would initially require resources for hiring and training modeling staff, method development and standardization, and administrative tasks. The quantity of each would depend on the scope and scale of the program.

A competent model developer might be expected to spend two weeks full-time equivalent (FTE) working on a model, although this time would most likely be distributed over a period of four to eight weeks. As a reference point, at this rate, it would require about 20 full-time staff to build models for every 2020 DOE SBIR Phase I awardee. Field development, described below, would support the growth of that type of workforce.

This program would be straightforward to pilot. The pilot program should aim to evaluate the feasibility of implementation and the reception of the results. A reasonable size might be 15 projects distributed between three model developers. The factors to evaluate should include:

1. Feasibility of providing consistent service and transferring knowledge to the grant recipient
2. Actual vs. expected time required for modeling
3. Satisfaction & feedback from grant recipients
4. Satisfaction & feedback from program managers

Field Development

TEA has gained traction in recent years as innovators, investors, and funding agencies have become aware of its potential, but it remains underutilized. This is partly because there is no cohesive field. Aside from small groups within certain national labs and large corporations, practitioners are dispersed and do not communicate. Learning has to be acquired on the job. Even academic institutions do not offer TEA-specific education.

To address these issues, the final recommendations of this paper target the development of TEA as a field of practice. Establishing an online presence with a supporting organization or network would be a logical place to focus initial efforts. This “web hub” would provide a place for convergence, consensus, and authority in the field of techno-economic analysis. Initially, it would host two types of content, as shown below. First, it would contain informational material to define the field and its applications. Second, it would curate resources for people who are learning and practicing TEA. The web hub would also, however, be designed to accommodate future material that has yet to be developed, like the educational course described in Section 4.1.

The potential for future content is especially exciting. Since hard-tech innovations take so long to reach the market, the feedback cycle is very slow for early-stage TEA. More communication and consistency in the field would provide a necessary basis for studies that could lead to improved methods.

If incentives could be aligned, there is also the potential to collaborate with industry to develop better cost databases. Corporations are typically reluctant to share this type of information, but they are increasingly relying on startups to provide new ideas, so it is in their interest as well to improve the efficiency of hard-tech startups in the United States.

There is more to a field of practice than a website, though. Part of the purpose of the web hub would be to spur interest in TEA within the hard-tech community that would then spread into academic study and curricula. The author of this paper is currently writing a book on TEA toward this same end.

Other ways to directly stimulate academic interest would include awards for TEA experts, prestigious fellowships, or faculty positions for TEA experts.

Outline of TEA web hub content

1. Initial content
    a. General information
        i. What is TEA? Why is it useful? How is it performed? What are its limitations?
        ii. Best practices for TEA
    b. Curated practical resources
        i. Published TEA (i.e., from NREL and academia)
        ii. Published TEA guidelines
        iii. Educational articles
        iv. Relevant textbooks & descriptions of content
        v. Links to online TEA tools and guidance in their us

2. Future content
    a. Educational material
        i. Video course as described in Section 4.1
        ii. More detailed courses
        iii. Articles by practitioners and other interested parties
    b. Resources for practitioners
        i. Case studies and TEA meta-analyses
        ii. Cost databases
        iii. Model templates

To launch a website with the initial content described above would require resources for content development, website design, and website hosting, at a minimum. Content development could likely be accomplished in 100 hours over six to ten weeks.

POLICY & STRATEGY

Policymakers seek to influence hard-tech development according to national interests. They do this through targeted funding of R&D (e.g., the SBIR program) and through policy instruments (e.g., regulations, taxes, mandates, trading systems, loans, and grants). Scientifically sound analysis is essential for informing their decisions as they work to assemble effective and efficient policy frameworks. To this end, TEA has the potential to provide insights in areas that might otherwise rely on educated guesswork.

There is a precedent for using TEA in policy decisions. Techno-economic energy systems models have been used to inform U.S. energy policy since the 1970s, when the National Energy Modeling System (NEMS) was introduced. According to its documentation, "NEMS projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics."

Although energy systems modeling and this paper's version of TEA both promote quantitative objective decision-making, the similarities do not go much further. Out of necessity, energy systems models are complex and expansive in scope, and they are maintained by teams of professionals. Their source code is often publicly available, but their complexity, detail, and computational requirements make them practically inaccessible for all but specialized professionals and academics. The techno-economic models that might be used to inform hard tech development policy could be far simpler, more focused, and more accessible.

Policy-Targeted Modeling

Earlier parts of this paper described the type of TEA that an early-stage company would use to assess economic benefit, R&D opportunities, risks, and areas of uncertainty. While this level of modeling is invaluable to the individual company, it would be too specific for policy work.

Policy work calls for more general and standardized models that could be used for entire classes of technologies. Technologies within a particular class would need to be similar enough that the performance characteristics of their components could be captured by the same standardized parameters. Three interesting and relevant candidates include carbon removal technologies, battery technologies, and fermentation technologies. (Fermentation technologies include biochemicals and biofuels processes.)

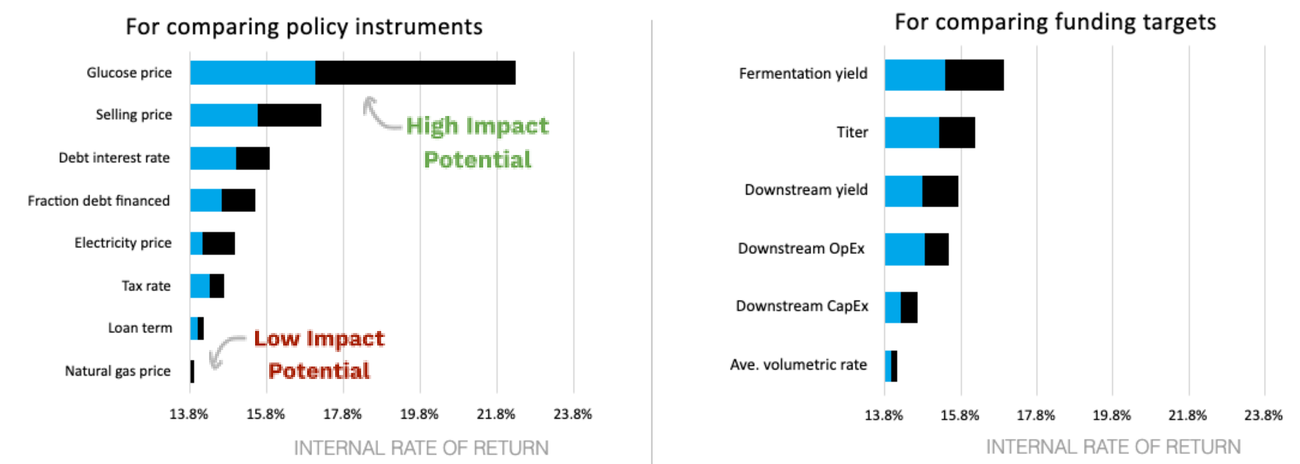
With respect to the policy-targeted models themselves, transparency and accessibility are essential. The models should be open-source and designed using standard spreadsheet software. This would confer benefits that extend even beyond the goal of informing policy decisions. For one, it would allow the models to be independently verified, thereby promoting trust and reducing the likelihood of errors. At the same time, independent professionals and academics would be able to propose and develop updates and improvements to the models. This might even be coupled with incentives in the form of prize money or other awards for submissions. In this way, over time, the models would organically become more accurate, usable, and effective. Additionally, making the models open-source would benefit individual companies since they could use them as templates for building their own more specific models.

Using Tea To Inform Policy Decisions

The use of TEA to inform policy decisions might be best illustrated through a specific example. Professor Michael Lynch of Duke University developed an online calculator for TEA of fermentation processes. The BioprocessTEA Calculator is designed as a web app with proprietary source code, but it would be straightforward to accomplish the same level of analysis in the form of an open-source spreadsheet tool. In his paper introducing the Bioprocess TEA Calculator, Lynch presents an example TEA for diethyl malonate (DEM), an important pharmaceutical and agrochemical intermediate. This example will be used as a basis for the further examples below. Note that these are for illustration only and are not intended to realistically represent the factors influencing the DEM process.

TEA using models as described above could improve policy decisions in at least two ways. First, it could allow policymakers to analyze and compare the effects of the available policy instruments. Second, it could help them craft and set metrics for solicitations targeted toward the most impactful technologies. In either case, a primary goal is to identify the parameters that have the highest impact on the metrics of interest. The tornado diagram is a form of sensitivity analysis that is especially well suited to this.

A tornado diagram is a special type of bar chart that is used to compare the relative impact of a set of inputs on a single result. The two tornado charts below were generated using the Bioprocess TEA Calculator. Internal rate of return (IRR) is used as the result parameter in both cases. IRR is a financial metric that is often used to evaluate large capital investments, such as for building a bioprocess plant. In the diagrams below, the y-axes represent the IRR values when all parameters are set to their baseline values. The bars then represent the IRR values that result from changing each parameter to its alternate settings.



Input case settings	Units	Baseline	Option 1	Option 2
Selling price	/kg	$2.50	$2.60	$2.70
Tax rate	-	21%	17%	14%
Fraction debt financed	-	60%	50%	40%
Debt interest rate	-	8%	4%	1%
Loan term	yr	15	18	20
Glucose price	/lb	$0.18	$0.15	$0.10
Natural gas price	/MMBtu	$3.10	$2.80	$0.00
Electricity price	/kWh	$0.11	$0.08	$0.00

Input case settings	Units	Baseline	Improved	Best
Fermentation yield	-	90%	92%	94%
Titer	g/L	150	165	175
Downstream yield	-	90%	92%	94%
Downstream OpEx	x total OpEx	20%	17%	15%
Downstream CapEx	x total CapEx	20%	18%	16%
Ave. volumetric rate	g/L/h	5.0	7.5	9.5

The Bioprocess TEA Calculator does not automatically generate tornado diagrams, but this functionality can be built into spreadsheet models. Tornado diagrams are more typically constructed using the middle case setting as a basis to demonstrate deviation from an expected case. In a forward-looking diagram, such as this, it seems more logical to use baseline/current values as a basis.

The tornado diagram on the left shows how modifying various financial parameters would impact IRR. If policymakers wanted to encourage investment in DEM production, this sort of diagram could help guide their efforts. For example, glucose subsidies or reduced finance rates would have a much bigger impact than natural gas subsidies or tax breaks. Again, these analyses are for illustration only. Purpose-built models could more precisely target the relevant policy instruments.

The tornado diagram on the right shows how improvements in key process metrics would impact IRR. If policymakers wanted to accelerate the development of DEM production technology, they could use this type of analysis to help them target R&D funding. For example, they might preferentially put out solicitations for technologies that would increase titer and fermentation yield rather than those that would focus on volumetric rate.

Companies, funding agencies, and policymakers might also learn from comparing these two diagrams. It may be that at a certain performance level, the highest impact financial variables (in this case, glucose price and selling price) are more impactful than any of the technical metrics.

For tornado diagrams to provide meaningful information, the input settings need to be well reasoned. For comparing policy instruments, the input settings would be based on the effects of actual available measures. For comparing funding targets, they would be based on data, expert judgment, or both.

Tornado diagrams only consider the effects of varying parameters individually. However, the models themselves could also be used to compare scenarios where any number of variables are changed at the same time.

Closing Thoughts On TEA

Science and technology policymakers are concerned that venture investing is overly concentrated in software and internet startups relative to hard-tech startups, such as those in advanced materials, advanced manufacturing, hardware, semiconductors, and cleantech. Understanding the drivers of cost and value could allow policymakers and program managers to accelerate innovation in an entire sector, not just a single product, in the same way, that cloud computing and open-source software lowered the costs of internet startups.

For example, the venture capital firm a16z has noted that, “A good rule of thumb [for biomanufactured products] is that it is hard to make the economics work out for products with prices below $10/kg and to safely account for scale-up issues and competition, prices would ideally be > $100/kg... This limited price range severely restricts the variety of products that can be made using synthetic biology. Better production processes would help make the bioeconomy truly economical!” This suggests that government investment in R&D for novel, low-cost biomanufacturing technologies could expand the size of the bioeconomy, as opposed to merely advancing a particular bioproduct.

TEA is the method through which insights like this can be developed and validated.

CONCLUSION

Hard tech innovation is essential to our national and global interests. This paper makes a case for funding targeted programs to improve early-stage TEA at hard-tech startups. This price tag is negligible compared to the amount of funding the federal government provides annually toward hard tech R&D. The impact, however, could be far-reaching.

At an innovator level, early-stage TEA helps select the best ideas and bring them to market efficiently. At a national level, early-stage TEA helps direct resources toward the most promising innovations, thereby increasing the rate and efficiency of hard tech innovation. At either level, the costs are clearly small when compared to the potential benefits.

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APPENDICES

Outline For An Online Course In TEA Development

Earlier this paper described a Level 1 TEA course for teaching technology developers and investors how to use and interpret techno-economic analyses. This section describes a course for teaching technology developers to build techno-economic models themselves.

The first item in the curriculum (spreadsheet development for TEA) is critical and may be the most challenging to teach. In the context of techno-economic modeling, spreadsheet development is akin to software development. Best practices are essential to building software that can be debugged, scaled, and understood by others; the same is true for spreadsheet models. Many practitioners do not realize this, which is why it is so easy to find incomprehensible and error-ridden spreadsheets.

Outline of Level 2 TEA curriculum

Prerequisites: Level 1 TEA course described in Section 3.1.

1. Spreadsheet development for TEA
    a. Best practices for spreadsheet calculations
    b. Spreadsheet organization & hygiene
    c. User interface considerations
2. Capital cost estimation
    a. Components of capital investments and definition of scope
    b. Scaling relationships for estimating equipment or system costs
    c. Multiplying factors for estimating other capital components
3. Operating cost estimation
    a. Estimating raw materials costs
    b. Estimating waste treatment costs
    c. Estimating utility costs
    d. Estimating labor costs
    e. Estimating other operating costs (overhead, etc.)
4. Financial calculations
    a. Depreciation
    b. Approaches for quantifying economic benefit
    c. Non-discounted metrics
    d. Discounted cash flow analysis
5. Sensitivity analyses
    a. Basic sensitivity analyses
    b. Tornado diagrams
6. Technology/process modeling
    a. Process diagrams & major equipment
    b. Selecting input parameters
    c. Estimating equipment sizes
    d. Calculating utility rates
7. Using techno-economic analysis to inform R&D decisions

The curriculum above might best be taught through a series of videos accompanied by a combination of spreadsheet exercises, examples, and templates. It might require 15 to 25 video segments, totaling 1.5 to 2.5 hours, and 10 to 20 spreadsheet examples. To produce this content would likely take in the range of 120 to 150 hours, not including web development.

Additional TEA Resources

Educational material

- Techonomics from Activate Global — www.activate.org/techonomics
- AssessCCUS from University of Michigan — assessccus.globalco2initiative.org/tea

Tools available online

- Bioprocess TEA Calculator — www.bioprocesstea.com
- CatCost from ChemCatBio — catcost.chemcatbio.org
- BioSTEAM — https://biosteam.readthedocs.io

Guidelines

- Zimmerman, A.W., et al. 2020. "Techno-Economic Assessment Guidelines for CO2 Utilization." *Frontiers in Energy Research* 8. doi:10.3389/fenrg.2020.00005

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ABOUT ACTIVATE

Founded in 2015, Activate is a 501(c)3 nonprofit organization that partners with U.S.-based funders and research institutions to empower scientists to bring their research to market in order to confront the climate crisis and other urgent needs.

The Activate Fellowship provides two years of funding, technical support, networking, and community. Activate takes no equity in fellows' startups.

Activate's entrepreneurial fellowship model originated at Cyclotron Road, a division of Lawrence Berkeley National Laboratory and founding Activate partner. Activate supports 40 new Activate Fellows each year in Berkeley, Boston, New York, and across the U.S. For more, visit www.Activate.org.

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Schmidt Futures bets early on exceptional people making the world better. Founded by Eric and Wendy Schmidt, Schmidt Futures is a philanthropic initiative that creates public value from private philanthropy through risk transfer—showing that brilliant people in networks can solve hard problems in science and society by connecting across fields, competing and challenging ideas, bringing multiple types of capital to bear, and applying science and technology thoughtfully through tools such as AI. For more, visit www.schmidtfutures.com.

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