Workshop Report

JGI Plant Transformation Workshop: May 20-21, 2025

Executive Summary

Domestic biomass crops such as sorghum, switchgrass, Miscanthus, and poplar can provide United States industries with renewable feedstocks while also supporting low-input farming systems and strengthening supply chains for biofuels, biochemicals and biomaterials. The U.S. leads globally in biomass crop genomics, yet progress in engineering traits is constrained by slow, genotype-dependent transformation methods and lengthy Design-Build-Test-Learn (DBTL) cycles. At a May 2025 workshop, a panel of experts recommended establishing a DOE Plant Transformation Capability (PTC) to overcome these barriers. The PTC would unite two missions: advancing research to achieve genotype-independent, automated methods, and delivering scalable transformation services through a user-facility model. With expected gains of 10–100x in efficiency, including transformation and cost reduction, the PTC would accelerate the path from discovery to engineered plants, expand community access and training, and support downstream applications and workflows including field trials and regulatory navigation. By enabling rapid and predictable crop engineering, the PTC would strengthen U.S. supply chains, enhance industrial competitiveness, and ensure that DOE's genomic investments deliver national impact.

Introduction: Unlocking the Potential of Biomass Crops

Domestically produced biomass crops can provide renewable feedstocks for U.S. industries, supporting materials, chemicals, plant-based plastics, fuels, and energy for aviation and shipping and biomanufacturing. These crops are typically robust, low-input perennials that can thrive on marginal land, creating economic opportunities for farmers while strengthening domestic supply chains. Unlike food crops, they can be engineered to serve as biofactories for industrial applications such as cellulose and hemicellulose for fuels and packaging, lignin for foams and carbon fiber, and extractives for chemical processes and bioproducts. Significantly, biomass crops could be engineered to produce novel products or increased amounts of naturally occurring products that could not be achieved through conventional plant breeding.

The United States has established global leadership in feedstock genomics, with DOE-supported initiatives producing some of the most comprehensive reference genomes, pan-genomes, and functional annotations for biomass crops. Yet despite this progress, most of these crops remain genetically close to their wild counterparts and have seen limited improvement compared to food crops. Their long generation times, obligate outcrossing, and/or polyploidy make breeding complex and slow. Conventional breeding methods are therefore poorly suited to meet the growing demand for tailored traits such as optimized cell wall composition, enhanced stress tolerance, and higher productivity.

Advanced biotechnology and gene editing provides opportunities to accelerate improvement. Genome-enabled studies have already identified numerous candidate genes associated with key traits for large-scale biomass production and basic research has identified potential ways to create plants that produce novel building blocks for industrial applications. However, a significant gap remains between this knowledge and its translation into agronomically viable applications. The most critical bottleneck is the lack of scalable plant transformation capabilities. Transformation, the process of introducing designed DNA segments into plant genomes, is essential for in planta testing and implementing engineered traits. Without expanded transformation capacity, the substantial investments in genomics cannot be fully leveraged for DOE-relevant applications.

Recognizing this challenge and building on the findings of the 2024 DOE workshop report *Overcoming Barriers in Plant Transformation: A Focus on Bioenergy Crops*[1], the DOE Joint Genome Institute (JGI) convened a workshop at Lawrence Berkeley National Laboratory in May 2025. Experts in plant transformation and DOE crop science met to define the design and scope of a dedicated *Plant Transformation Capability (PTC)* that would accelerate genome engineering, expand community access, and support open science. This report summarizes the findings and recommendations from that workshop.

Economic Opportunity and Supply Chain Security

Strategic Value of Biomass Crops. Domestic biomass crops represent a strategic resource for the U.S. economy and national security. Grown on marginal or underutilized land, they can provide renewable raw materials for construction products, packaging, fuels, and industrial chemicals. Expanding domestic production will reduce vulnerabilities in supply chains, decrease reliance on imported petroleum-based products, and support rural economies through recurring revenue streams for farmers.

Most biomass crops are resilient perennials with low input requirements that do not compete with food crops for prime farmland. They provide reliable harvests while improving soil health and reducing environmental impacts compared to annual row crops. Their broader integration into U.S. agriculture will strengthen supply chains for energy security and advanced manufacturing, while expanding the land base that supports domestic production.

Barriers Limiting Deployment. Deployment of biomass crops has been slowed by biological and technical barriers. Most biomass crops remain genetically close to their wild relatives and have undergone limited domestication, leaving traits such as yield, stress tolerance, and optimized composition underdeveloped. Breeding progress is hindered by obligate outcrossing, polyploid genomes, and long generation times that make trait optimization difficult and slow. Moreover, genome engineering through transformation in these species is labor-intensive and has been restricted to a few of the least recalcitrant genotypes, limiting progress in tailoring them for industrial use. Deployment of engineered crops has been limited by regulation and lack of contaminant advances.

Opportunities for Accelerated Improvement. There are significant opportunities to overcome these limitations. Advanced genomics has already identified genes that control traits of interest for yield, stress tolerance, and cell wall composition. Because biomass crops are not food crops, there is greater flexibility to deploy edited and engineered traits for industrial applications including the production of designer molecules. Unlocking this potential requires accelerating our understanding of biological pathways and increasing the speed at which crops can be customized through trait engineering. One of the most pressing bottlenecks is the slow and genotype-dependent nature of plant transformation, the process required to introduce designed DNA changes into plants. A DOE-funded PTC, designed to accelerate and automate transformation, would provide the capacity and expertise to overcome these barriers. By enabling rapid and predictable engineering of biomass crops, such a capability would directly support U.S. economic competitiveness, strengthen domestic supply chains, and secure economic leadership.

Rationale and Vision for Enabling the Future of Biomass Crop Engineering

National Need for a Plant Transformation Capability: A DOE PTC would become a cornerstone national resource, accelerating and expanding the frontiers of genome engineering in biomass crops. Its mission would bring together two complementary goals. First, to provide publicly accessible, scalable transformation services that are fully integrated with existing DOE user facilities. Second, to pursue bold applied and basic research aimed at improving transformation technology including genotype-independence, reducing tissue culture, and automated transformation methods. By combining innovation with service, the PTC would convert what is now a slow and limited process into a high-capacity, predictable capability that operates at the speed and scale required to meet U.S. strategic priorities.

Anticipated Outcomes and Impacts: The impact of such a capability would be far-reaching. With automation and coordinated effort, transformation efficiency could increase by one to two orders of magnitude, reducing costs and shortening the time from data mining and construct design to greenhouse-ready plants from years to months. This acceleration would unlock the ability to rapidly test and deploy traits that enhance yield, resilience, and biomass composition, enabling U.S. industries to tailor crops directly for advanced manufacturing, chemicals, composites, and materials.

A Hub for Knowledge Transfer and Workforce Support: The PTC would serve as a hub for knowledge transfer and workforce development. Through protocols, workshops, internships, and user training, it would broaden access to transformation expertise beyond a small circle of specialists. By lowering barriers to entry, it would enable a wide spectrum of researchers to engineer DOE-relevant crops, multiplying the community's capacity to innovate.

The PTC would also support downstream applications by providing advice for field trials and biocontainment strategies. It will also use tools and technologies designed with minimal intellectual property restrictions. These resources would enable engineered lines to move efficiently into breeding programs and commercialization pathways, ensuring that DOE's investments in genomics translate into tangible, real-world outcomes. Together, these efforts would not only eliminate a critical bottleneck but also strengthen U.S. leadership in translating genomic insight into engineered crops.

Recommendations for a Plant Transformation Capability

Core Recommendations

Why Current Services are Insufficient: Workshop participants agreed that existing plant transformation services are inadequate for DOE-relevant crops. Commercial offerings are limited or nonexistent for species such as switchgrass, Miscanthus, and poplar, and even when services are available, they are typically restricted to a single genotype. This limitation prevents research on regionally adapted or high-performing lines that are critical for DOE applications. In addition, current services have low capacity, high costs, and long timelines, which make them poorly suited to the needs of the DOE research community. Fee-for-service models are not sustainable for biomass crops, where commercial demand is low despite their high national strategic importance.

The Dual Role of the PTC: Workshop participants emphasized that the PTC must fulfill two complementary roles. First, it should provide accessible, scalable transformation services through a user-facility model, ensuring that researchers across DOE and the broader community can access advanced plant engineering pipelines (Fig. 1). Second, it

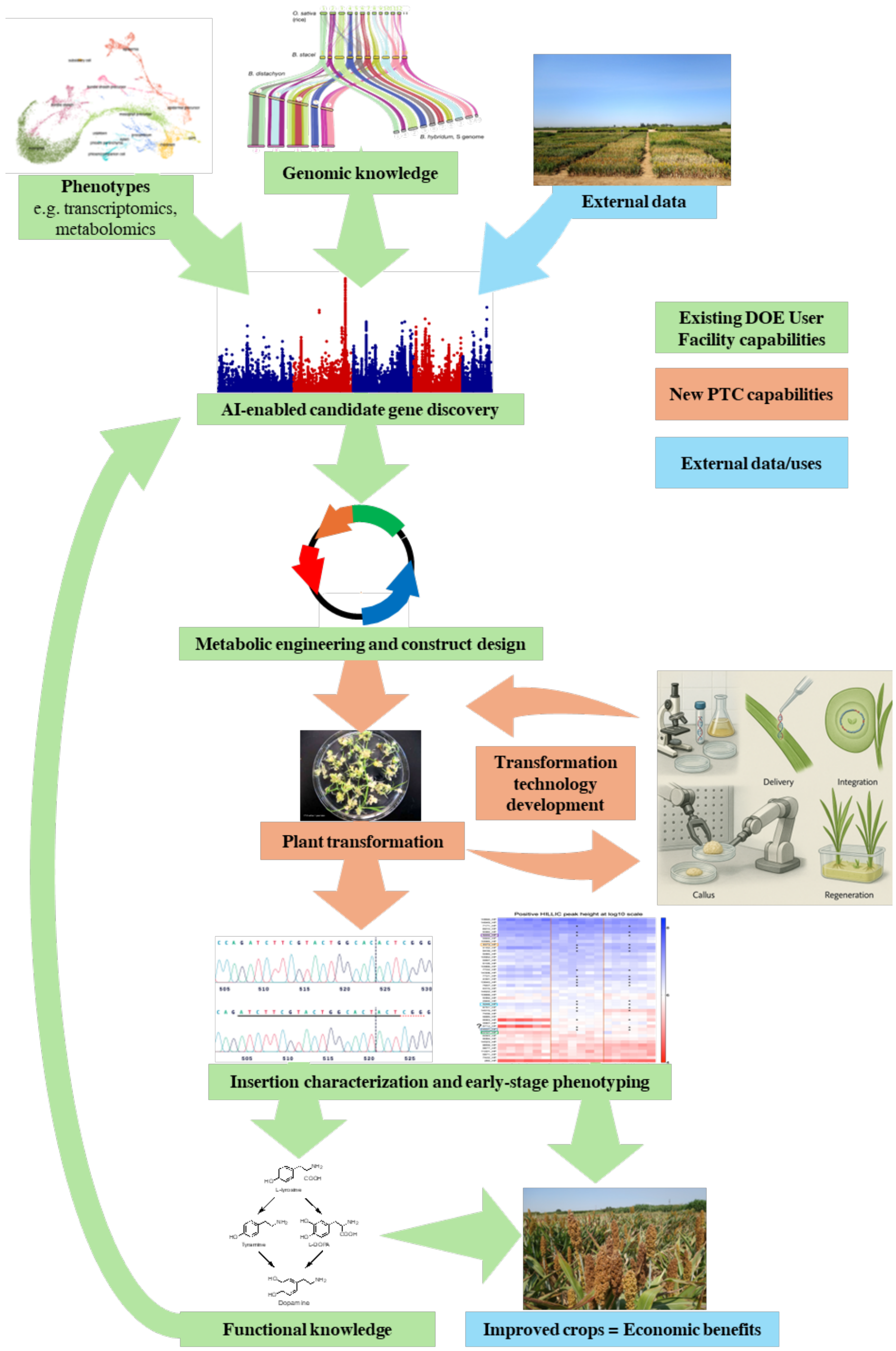

Figure 1. Synergistic integration of plant transformation into existing DOE User Facility capabilities. Plant transformation will link existing DOE capabilities/resources in genomics, phenomics, and synthetic biology to allow users to seamlessly go from genomic interrogation to functional knowledge and improved crop varieties. Integration with existing DOE capabilities will also facilitate early characterization of transgenic lines substantially decreasing downstream time and effort.

should pursue targeted research and development to advance transformation technologies, so that methods become faster, more reliable, and broadly applicable to challenging crops. This balance between service and innovation is essential to address immediate needs while building the capabilities required for long-term progress.

High-Priority Research Areas: Participants identified three research areas as central to the success of a PTC (Fig. 2):

- Efficiency and Cycle Time: Develop methods that increase throughput by one to two orders of magnitude, reduce Design-Build-Test-Learn cycles from years to months, and integrate automation and high-throughput delivery systems. Alternative approaches such as virus-based methods, delivery into meristem cells, nanomaterial delivery, and transient assays should be tested to reduce reliance on lengthy stable transformations.
- Genotype Independence: Create methods that can be applied across multiple varieties within a species, eliminating the current bottleneck of working only in a few transformable lines. Genotype-independent approaches would open access to regionally adapted germplasm and make DOE research more broadly applicable. These efforts could leverage multiomic data to identify novel molecules for specific use in DOE crops.
- Predictability in Engineering: Establish genomic landing pads, standardized libraries of promoters, terminators, and insulators, and validated workflows for

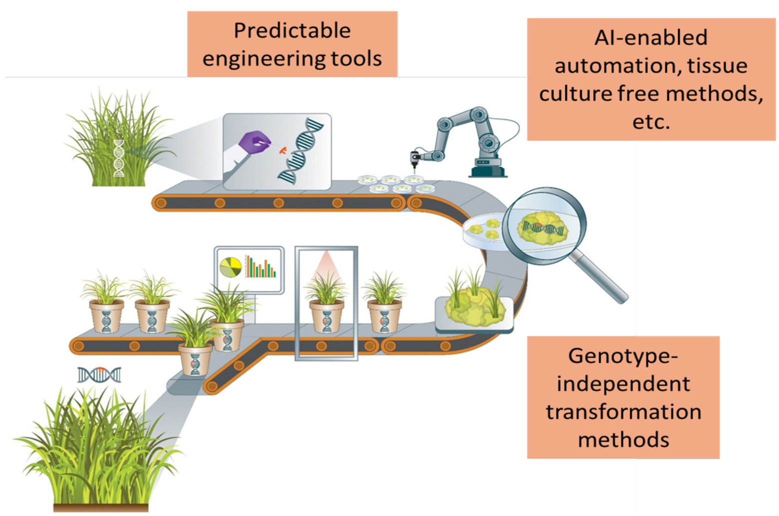

Figure 2. Future transformation pipeline highlighting transformation technology development priorities identified during the workshop.

insertion and edit confirmation. These resources would reduce the variability and inefficiency that now characterize transformation, enabling more reproducible engineering outcomes. Additional enabling research should also focus on understanding the molecular mechanisms that underlie transformation efficiency and on systematically capturing both successful and unsuccessful outcomes. Standardized datasets will be essential for training AI-assisted plant modeling (i.e., design tools) that can guide more efficient engineering strategies across species. In addition, participants emphasized that the PTC should extend its impact beyond the laboratory by providing materials and tools that enable field trials. This includes helping the community develop biocontainment strategies and offering transformation technologies with minimal intellectual property constraints so that PTC-produced lines can be integrated into commercial breeding programs. Users also identified regulatory support as an important function, with the PTC serving as a source of practical guidance, such as summaries of transformation technologies and parts appropriate for USDA APHIS applications, to help researchers navigate regulatory requirements more efficiently.

Target Species for Initial Focus

Primary Focus Crops. Workshop participants agreed that the PTC should begin with a clear focus on four biomass crops of highest strategic importance: **sorghum**, **switchgrass**, ***Miscanthus***, and **poplar**. These species combine substantial DOE investment in genomics and breeding with some of the most significant technical challenges for transformation. Sorghum has limited commercial transformation options, but access is costly and typically restricted to a few model genotypes, which constrains its utility for DOE research. Switchgrass and Miscanthus, both obligate outcrossers with polyploid genomes and long generation times, are particularly difficult to improve through breeding alone. Current transformation methods for these perennials work in only a few genotypes, leaving much of the available germplasm inaccessible to engineering. Poplar, a fast-growing woody perennial with strong potential for fiber and industrial applications, faces similar barriers, with pipelines that are slow, genotype-specific, and difficult to scale. By concentrating on these four crops, the PTC would directly address species where breakthroughs would have the greatest immediate impact on DOE's mission and the broader U.S. biomass/feedstock and biomanufacturing base.

Secondary Crops and Model Systems. Participants noted limited support for allocating PTC resources to relatively easy-to-transform species such as **pennycress**, **camelina**, and **carinata**. Although transformation in these crops is more straightforward than in biomass perennials, many labs are not set up or versed on their transformation, and scaling remains difficult. In addition, these crops add an opportunity for offseason production that may be valuable for some rotation strategies. Additional capacity would provide the most value if integrated with existing DOE user facilities. For this reason, workshop participants suggested including these crops at only a modest level, primarily to accelerate trait validation and provide complementary systems for engineering efforts. Several model systems were also highlighted, including ***Brachypodium distachyon***, ***Panicum hallii***, and ***Setaria viridis***. Most of these species are relatively straightforward to transform once pipelines are established and can serve as efficient platforms for early-stage trait discovery and proof-of-concept studies. Leveraging models in this way would reduce the number of stable lines required in more recalcitrant crops, conserving PTC resources while broadening scientific impact.

Adaptive Approach. Participants emphasized that the PTC's portfolio of target species should not remain static. Instead, priorities should be revisited periodically by a steering committee using surveys and discussions to reflect the evolving needs of the BER research community and DOE strategic directions. This adaptive framework would allow the PTC to stay focused on crops with the highest potential impact while retaining the flexibility to incorporate new species as research and industry/DOE priorities shift. Such responsiveness would ensure that the PTC remains both a forward-looking research driver and a responsive service provider, maintaining alignment with DOE's long-term goals.

Community Access and Use

Access Model. Workshop participants emphasized that the PTC should operate under a user-facility framework, ensuring broad access while maintaining alignment with DOE priorities. Similar to JGI, access would be provided through a competitive proposal process that allows merit-based selection and transparent allocation of capacity. This model would balance resources among DOE BER-funded projects and open calls that welcome participation from the broader research community. Such an approach would maximize scientific impact while ensuring that PTC capabilities are available to researchers across institutions.

Integration with DOE programs. The PTC would not operate in isolation but rather as part of the larger DOE user facility ecosystem. Close coordination with facilities focused on genomics, phenotyping, metabolomics, and computational biology would allow users to integrate transformation outputs seamlessly into larger projects as is currently done with several user facilities through the FICUS program. This integration would help accelerate end-to-end workflows, from gene discovery to engineered plants ready for field testing, while ensuring that the PTC remains aligned with DOE programmatic priorities.

Community Benefits. Beyond providing transformation services, the PTC would deliver value through training and knowledge transfer. The facility would disseminate standardized, detailed protocols that lower barriers to entry for labs new to plant transformation. It would also provide hands-on training opportunities through workshops, internships, and rotations, creating a pathway for researchers to develop expertise and bring it back to their home institutions. Regular user meetings would foster exchange of information and highlight new methods, reinforcing the PTC's role as a community hub.

Broader Impacts. By consolidating expertise and infrastructure, the PTC would reduce duplication of effort across laboratories and increase the efficiency of DOE investments. The PTC would generate standardized data sets which could be used to train AI/ML models and optimize protocols and expedite trait discovery. It would expand the pool of researchers able to work directly with engineered biomass crops, thereby strengthening the DOE research community as a whole. Through its training programs, it would also help cultivate the next generation of plant biotechnologists, ensuring that expertise in advanced transformation methods is widely distributed rather than concentrated in a few specialized labs.

Potential Partners and Collaborations

Existing Transformation Laboratories. Although relatively few laboratories currently maintain pipelines for DOE-relevant biomass crops, they represent valuable expertise that should be connected to the PTC. Workshop participants agreed that the PTC should act as a central hub, coordinating with these facilities, exchanging protocols, and sharing data to avoid duplication of effort. By linking scattered capabilities into a coherent network, the PTC would help standardize methods and extend access to a much broader research community.

Phenotyping and Analysis Facilities. Collaborations with advanced phenotyping centers would expand the impact of PTC outputs by enabling detailed functional characterization of engineered lines. Facilities such as ORNL's Advanced Plant Phenotyping Laboratory (APPL), the University of Nebraska–Lincoln's Lemnatec 3D system, and the Danforth Plant Science Center's Bellwether facility offer state-of-the-art imaging and analytical tools. These resources could capture plant growth dynamics, stress responses, and compositional traits, providing data that complement transformation outcomes and accelerate trait validation.

Data and 'Omics Resources. The PTC should partner with DOE-supported data platforms e.g. the BER Data Lakehouse, and public repositories to ensure that information from transformation experiments is broadly accessible. Integration of genomic, transcriptomic, metabolomic, and phenotypic data will be essential for advancing predictive biology. These efforts could take advantage of existing and ongoing efforts in these plants by the JGI and bioenergy centers. Standardized data capture from the PTC and its collaborators, including both successful and unsuccessful outcomes, would add significant value to these resources and support the development of AI-driven design tools.

Private Sector, Extension, and Education. Engagement with the private sector offers opportunities to adapt proprietary tools and methods for DOE biomass crops. Plant biotechnology companies have developed transformation technologies and molecular tools that, if adapted for public-sector pipelines, could accelerate progress. Training programs such as NSF's iCORPS could also be leveraged to build entrepreneurial capacity and support technology transfer. Beyond research, the PTC could partner with extension services to connect outputs to farmers and industry stakeholders while also contributing to public education. Although the PTC itself would not directly release biotechnology products, it could play an important role in improving public understanding of plant engineering technologies and easing their eventual implementation.

Operational Model

The consensus from the workshop identified two essential activities for the PTC:

1. **Access Through a User-Facility model.** The PTC should operate under a user-facility framework, offering scalable no-cost access to transformation services to the research community. This approach provides clear advantages over fee-for-service models, including seamless integration with existing DOE capabilities, economies of scale, workforce flexibility to adjust capacity as needs evolve, and the ability to prioritize community-wide goals rather than individual PI projects.

2. **Research to Improve Transformation Technology.** There was broad agreement that dedicated research is needed to overcome current limitations in transformation efficiency, genotype dependence, and predictability. The PTC should be structured to maximize the impact of funding by prioritizing innovation in genotype-independent methods, tissue-culture-light pipelines, and automation, ensuring that capabilities continue to advance rather than remain static.

Implementation Options. Two potential options for implementation were discussed. The majority view favored a **user-facility-led consortium (i.e. establishing the PTC)**, involving a small number of partners with complementary expertise and infrastructure. This model acknowledges that no single facility has expertise across all crops or the full range of technical capabilities needed for large biomass species. By leveraging existing DOE infrastructure such as project management, sample handling, data integration, and legal frameworks, the consortium model would reduce costs and accelerate biotechnology advancements.

The minority view was to **fund existing facilities directly** to produce transgenics for DOE-funded scientists. While conceptually simpler, this approach was considered less effective because it would miss opportunities for innovation, slow progress in technology development, limit data access and create logistical challenges in coordinating work across multiple sites. It would also limit workforce flexibility to meet shifting demands across species. Without leadership by a DOE user facility, connections to other DOE capabilities would be weakened, reducing integration and impact. Participants concluded that this approach would largely preserve the status quo rather than foster the coordinated, forward-looking effort needed to accelerate crop transformation.

Illustrative Example of How the PTC Would Operate

Workshop participants emphasized the importance of designing the PTC around practical workflows that show how researchers would engage with the capability from start to finish. A typical project might begin with a **competitive proposal process**, through which a research group applies to access transformation services for a DOE-relevant biomass crop. Once approved, the PTC would coordinate with the user to define experimental objectives and, if needed, provide assistance with **construct design**. Construct development could draw on standardized **part libraries** and genomic **landing pads** created by the PTC.

The PTC would then perform **transformation**, and regenerated lines would be verified through molecular assays before being provided to the user. Each project would be accompanied by standardized datasets documenting both successful and unsuccessful outcomes. These datasets would be integrated into DOE-supported data platforms (e.g. data lakehouse), expanding community knowledge and enabling the development of predictive design tools (AI/ML). Users would also receive detailed **protocols**, **training opportunities**, and **guidance** to support downstream applications such as trait validation and greenhouse or field trials.

At the workshop, participants also highlighted the potential value of a **germplasm** repository, **long-term storage of constructs**, and the **distribution** of cuttings and rhizomes. It was strongly recommended that biological materials generated by the PTC be deposited and made available to the community, potentially through partnerships with existing stock centers.

To support deployment, the PTC could also provide advice on **regulatory considerations**. For example, it should supply summaries of transformation methods and genetic parts suitable for APHIS applications, helping users navigate approval processes more efficiently. While the PTC would not directly release biotechnology products, it could support user research to develop biocontainment strategies. The PTC will also use transformation reagents and technologies with minimal intellectual property restrictions so that engineered lines can be incorporated into breeding programs or commercialization pipelines.

This illustrative model highlights how the PTC would serve as more than a service provider. It would operate as an integrated hub that drives technological innovation, generates and shares data, trains the next generation of researchers, and ensures that DOE's investments in genomics are translated into tangible outcomes with real-world impact.

Conclusions and Path Forward

The United States stands at a pivotal moment in its ability to **harness plant biotechnology for national economic and strategic advantage**. With major investments in feedstock genomics already in place, the creation of a DOE Plant Transformation Capability (PTC) offers the opportunity to unlock that knowledge and translate it into plant biodesign that strengthens domestic supply chains, supports advanced manufacturing, and **reinforce U.S. leadership in biomass crop engineering**. By overcoming long-standing barriers to transformation, the PTC would directly serve the national interest in economic growth, biotechnology, energy security, and industrial competitiveness.

Workshop participants agreed that the PTC should combine two essential functions: dedicated research to provide accessible services delivered through a **user facility framework** and **pioneer next-generation transformation technologies**. Together, these functions would create a powerful resource that accelerates crop engineering/design, reduces costs and timelines, and enables breakthroughs in species that have resisted conventional methods. This dual mission of service and innovation was seen as critical for meeting immediate community needs while laying the groundwork for long-term progress.

The PTC's impact would extend well beyond transformation pipelines. By acting as a hub for standardized protocols, open datasets, and hands-on training, it would **broaden access to advanced biotechnology** and expand the community of researchers able to engineer DOE-relevant crops. Integration with other DOE user facilities would create a seamless continuum from gene discovery to field-ready lines. Guidance on regulatory requirements, biocontainment strategies, and public engagement would further enable downstream application, while partnerships with extension services could help connect outputs directly to farmers, industry, and the public.

In conclusion, the PTC represents more than an infrastructure investment. It would provide a strategic capability to accelerate progress in plant transformation and strengthen the nation's capacity to engineer biomass crops. By coordinating research, infrastructure, and community support, the PTC would enhance U.S. leadership in plant biotechnology, **expand economic opportunities**, and provide the scientific foundation needed to build **resilient domestic supply chains** and advance national economic and security priorities.

Footnotes

[1]https://www.genomicscience.energy.gov/plant-transformation/

Workshop Attendees

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