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A Feedstock Readiness Level Tool to Complement the Aviation Industry Fuel Readiness Level Tool

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Abstract The Feedstock Readiness Level (FSRL) tool was developed by the US Department of Agriculture, US Federal Aviation Administration, and Research and Innovative Technology Administration to describe the steps involved in bringing plant-based feedstocks to market for aviation biofuels production. A candidate feedstock is assigned a FSRL level from 1 through 9, indicating an increasing level of maturity towards commercialization. The FSRL level also communicates the state of development of a feedstock concurrent with its readiness for use with a conversion process. There are four components to the FSRL (production, market, policy, and linkage to conversion process), each with one to four tollgate descriptions per readiness level. The FSRL tool was structured to complement the Fuel Readiness Level (FRL) tool in use by the aviation industry as an internationally recognized communication best practice. Similarly, the FSRL can be used to identify gaps in any feedstock supply chain designed for any biofuel or conversion process that provides a market for feedstocks. This integrated feedstock and conversion technology approach can facilitate a coordinated allocation of resources to effectively plan for and develop a viable aviation biofuels industry.

Keywords Aviation · Biofuel · Feedstocks · Technology · Readiness

Abbreviations

CAAFI®	Commercial Aviation Alternative Fuels Initiative®
FAA	Federal Aviation Administration
FRL	Fuel Readiness Level

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FSRL	Feedstock Readiness Level
TRL	Technology Readiness Level
USDA	United States Department of Agriculture

Introduction

For commercial and military aviation to achieve success in reaching cost-target and utilization goals for biofuels made from plant-based feedstocks produced on agricultural and forestlands, new, coordinated supply chains will need to be formed among a diversity of supply chain participants and stakeholders, many of whom have not previously worked together. Efficient supply chains whose participants closely interact in an interdependent fashion will help ensure that transaction costs are minimized so that biobased aviation fuel prices are competitive with petroleum-based fuels. Because the production of bio-based feedstocks is dynamic and greatly influenced by climate and competing commodity markets and land uses, all aviation biofuel supply chain participants need to understand the factors that influence the readiness of candidate feedstocks to be utilized by commercial-scale aviation biofuel refiners and users and to be able to communicate effectively about feedstock development potential and the risks associated with feedstock production.

The United States Department of Agriculture (USDA), Federal Aviation Administration (FAA), and the Research and Innovative Technology Administration (RITA) have collaborated to develop a Feedstock Readiness Level (FSRL) tool that describes the steps needed to bring a candidate biofuel feedstock to the market. The FSRL tool builds upon the concept of the Technology Readiness Level (TRL) scale [1] and its application to the Commercial Aviation Alternative Fuels Initiative® (CAAFI®)[1] Fuel Readiness Level (FRL) tool [2].

The TRL scale is a series of systematic metrics that support the assessment of technology maturity so that consistent comparisons among different kinds of technologies can be made. Based on technology readiness, CAAFI developed a gated process for the FRL to govern communication of technology maturity leading to qualification, production, and deployment readiness of alternative aviation fuels. The FRL scale was developed using a process engineering, mechanical systems approach based on the development, testing, and certification of alternative fuels. The aviation-fuel-specific FRL has been widely accepted as a best-practice communication tool domestically [3] as well as internationally [4].

[1] CAAFI is a coalition of airlines, aircraft and engine manufacturers, energy producers, researchers, international participants, and US government agencies that share information in support of the development and deployment of alternative jet fuels (http://caafi.org/).

The FSRL is intended to expand upon the FRL framework to provide additional information on alternative fuel development that may be facilitated or constrained by feedstock availability and related supply chain development. The FSRL is integrated with and complements the FRL and can also be used as a checklist of best practices to facilitate the development and commercialization of a candidate feedstock in concert with a conversion technology and its testing and certification as an aviation biofuel. Even though the aviation industry FRL was used to guide the development of the FSRL, the FSRL can also be used to evaluate the development of any candidate feedstock for bioenergy uses or any new crop sought to be brought to market. The development of new feedstocks for bioenergy is a complex process and one for which few precedents exist. The FSRL identifies important production, market, and policy/regulatory components that should be addressed to develop a new feedstock for a specific end use. The FSRL does not weight the importance of any component or readiness level, and the number of tollgates within each activity level does not correspond to the complexity or relative importance of that activity. The importance of a given readiness aspect may vary by feedstock, region, and stage of development of the biofuels industry as a whole. We anticipate that, as the industry develops, additional hurdles to achieving biofuel feedstock commercialization will emerge, so the FSRL tool may need to be modified over time as the industry develops.

Materials and Methods

The need for a FSRL tool came from the desire among CAAFI stakeholders to understand and evaluate the readiness of an aviation biofuel feedstock separately from the readiness of a technical fuel conversion process. Industry experts recognized an apparent disconnect between the level of development for a fuel conversion process (reflected by the FRL) and the actual availability of agricultural, forest-based, or other plant-based feedstocks[2] for use in the production of aviation biofuel using the same conversion process. Small quantities of some aviation biofuels had been successfully used in test flights and could receive a FRL score of approximately 5 or higher, but there was no short-term prospect of having sufficient feedstock supplies to make commercial-scale amounts of that fuel. Therefore, the CAAFI Research and Development team proposed the

[2] Plant-based feedstocks include perennial grasses (e.g., switchgrass and *Miscanthus*), energy cane (a high-biomass form of sugar cane), biomass sorghum (including sweet sorghum), oil crops (seed crops including *Brassica* species and soybean, and algae), woody biomass (including forest residues and purposely grown wood species), and crop residues (e.g., corn stover and cereal straw).

concept of Feedstock Readiness Level as a means to identify and repair disconnects between biofuel technical readiness and the readiness of needed feedstocks. CAAFI presented a list of specifications and made a request on 26 February 2010 to partner with USDA in the development of the FSRL. A memorandum of understanding between USDA and FAA was enacted to develop the FSRL tool [5].

The FSRL tool was structured to complement the FRL tool using a similar nine-step readiness level scale (Table 1). Unlike the FRL, the FSRL tool has four components (production, market, policy (e.g., program support and regulatory compliance), and linkage to conversion process) instead of one to describe all of the steps and gateways involved with the development of a feedstock supply. The need for four interlinked and parallel FSRL components reflect differences between an industrial process that converts a feedstock to a biofuel as seen with the FRL versus dynamic plant-based systems in agriculture and forestry that involve multiple biophysical, economic, and social factors that affect feedstock supply availability.

All terms used for FSRL descriptions and tollgates were based on USDA experience with new crop and woody species research, production/management, marketing, and policies. The nine FRL level descriptions were translated into terms appropriate for describing the activities needed to bring a candidate feedstock to market when linked to a specific conversion technology. The nine readiness levels were categorized into four FSRL Activities reflecting parallel research and commercialization activities that are a part of the FRL [2]. The number of gateway actions for each FSRL component varied from one to four per FSRL level and are not necessarily equal in number for each FSRL component or technology readiness level. The FSRL does not weigh the importance of any component or readiness level, and the number of tollgates for each readiness level activity does not correspond to the complexity or relative importance of that activity.

As with the TRL and FRL, the FSRL can be used at multiple scales, either for any general technology or process or for a specific company or individual conversion facility, depending on whether the goal is to evaluate an entire biofuel industry sector or an individual project. To evaluate an entire feedstock sector, the FSRL provides general information on activities-to-date across the country for a specific feedstock. For example, combined information from multiple commercial efforts or research projects can be used to assess the status of the feedstock, the potential market, or policy-related eligibility or permitting achieved for that feedstock (e.g., qualification for USDA crop assistance programs[3]).

[3] Examples of USDA assistance programs are the Farm Service Agency Biomass Crop Assistance Program, Natural Resources Conservation Service Environmental Quality Incentive Program, and Risk Management Agency Crop Insurance.

The four FSRL components are scored individually, so unequal levels of readiness may occur. For example, it is possible for a feedstock scored in the *production* component to have scored high (completed all steps through production system validation) without having performed any activities related to market readiness. It is also possible that some activities within a component (for example, MARK 2.1–2.4) may occur in parallel rather than sequentially. Such discrepancies highlight gaps that need to be addressed across the feedstock supply chain in the same way that discrepancies between FSRL and FRL highlight gaps in the developmental readiness of a particular aviation biofuel conversion process.

When discrepancies exist among FSRL components during scoring, the lowest score should be reported to accurately communicate the actual readiness of the feedstock. However, FSRL users will utilize the tool as guidance to ensure that appropriate attention is given to the development of all aspects of feedstock supply chains. Without timely attention to and resolution of discrepancies among the FSRL components' readiness levels, the most rapid possible development and deployment of feedstock supplies for a project may be hindered and costs increased.

The USDA intends to execute a series of case examples evaluating suites of feedstocks using the FSRL. These test cases will provide additional guidance to those interested in using the FSRL. Once completed, the test cases and accompanying narratives will be available on USDA's Agricultural Research Service website and on www.caafi.org.

Results and Discussion

The intent and structure of the FSRL tool are discussed in this paper. The FSRL tool will help clarify the efforts required to bring new feedstocks to market and provides a framework to evaluate the stage of readiness of a biofuel feedstock in conjunction with the technical readiness of an associated fuel or other biobased conversion process. This information can be used to inform supply chain participants of the readiness of a feedstock relative to their needs and help facilitate the development of business plans that accurately reflect the availability of a feedstock supply to a biorefinery.

The FSRL tool is comprised of four components that concurrently impact the commercial development of a feedstock from initial identification to full market deployment: (1) production (PROD)—addresses those factors that are directly related to the growing and harvest of the candidate feedstock; (2) market (MARK)—addresses factors affecting the movement of feedstocks from a field, forest, municipal waste site, or algae production facility at the time of harvest to bioconversion facilities where utilized, and the resulting

Table 1 The FSRL tool and companion CAAFI® FRL tool. The FSRL tool provides a means of tracking progress of new feedstocks towards established production in the commercial sector that are linked to commercial-scale biofuels production—towards the creation of a complete supply chain. The FSRL tool is comprised of four components: (1) production, (2) market, (3) policy—program support and regulatory compliance, and (4) linkage to conversion process. The four FSRL tool components are parallel with the FRL tool components, including the readiness of the biofuel conversion process technology that will be utilized including fuel testing and certification readiness. This approach provides an integrated way to demonstrate the mutual requirements of feedstocks and conversion technologies needed to bring advanced biofuels into commercial production and use

Fuel Readiness Level				Feedstock Readiness Level			FSRL components with tollgates			
FRL scale	Description	Fuel testing and certification	Tollgate	Activity	Scale	Description	(1) Production	(2) Market	(3) Policy—program support and regulatory compliance	(4) Linkage to conversion process
1	Basic principles		Feedstock and process basic principles identified	Preliminary feedstock evaluation	1	Basic principles	Identify potential feedstock for a specific conversion technology	Identify current feedstock producers, feedstocks and coproduct users, and wastes	Identify regulatory requirements to producing a new feedstock[a]	Identify potential conversion technology to utilize feedstock
2	Concept formulated		Feedstock and complete process identified		2.1	Concept formulated	Estimate likely range of production environments and competing land uses	Assess feedstock market alternatives	Evaluate feedstock for compliance with regulatory requirements for likely production environments	Test feedstock quality for specific conversion technology
					2.2		Identify production system components	Identify potential coproducts	Estimate production impacts on multiple resources concerns[b]	
					2.3		Develop enterprise budget for potential feedstock	Identify waste disposal requirements	Formulate a plan including best practices to address regulatory requirements	
					2.4		Identify possible consequences of expanded production, articulate responses to trade-offs	Identify harvest techniques, post-harvest collection, transportation, and storage logistics options	Comply with any feedstock pre-importation regulations	
3	Proof of concept		Small fuel sample available from lab—basic fuel properties validated	Feedstock experimental testing	3.1	Proof of concept	Screen candidate genetic resources for feedstock yield	Estimate feedstock production costs	Determine potential for societal resistance to use of the candidate feedstock	Test feedstock in conversion process at the experimental bench-scale
					3.2		Screen candidate genetic resources for biofuel conversion potential	Evaluate current and alternative future scenarios for establishing a feedstock sector—feasibility study	Formulate a plan to address societal concerns	
4.1	Preliminary technical evaluation	Preliminary specification of properties	System performance and integration studies		4.1	Preliminary technical evaluation	Perform coordinated regional feedstock trials to determine potential for yield improvement and dependability of feedstock supply	Identify biorefiners for targeted feedstock market development and link feedstock producers to feedstock	Identify federal, state, or other special incentive programs[c]	Performance estimated for feedstock through a conversion process

Table 1 (continued)

Fuel Readiness Level				Feedstock Readiness Level			FSRL components with tollgates			
FRL scale	Description	Fuel testing and certification	Tollgate	Activity	Scale	Description	(1) Production	(2) Market	(3) Policy—program support and regulatory compliance	(4) Linkage to conversion process
								brokers to supply biorefineries		
					4.2		Compare performance of candidate feedstock with alternative feedstock choices	Identify specific alternatives for reducing production and supply uncertainties (i.e., contracts and loan guarantees)	Develop conservation plan to address resource concerns for a feedstock production system	Determine conversion efficiency and unique effects on fuel properties
4.2			Entry criteria/ specification properties evaluated		4.3		Implement agricultural extension and education programs to promote feedstock production	Implement education programs to establish interest in production and demand for feedstock purchase	Draft NEPA (EA or EIS) and other required permitting documents	Co-product production and utilization performance estimated
5.1	Process validation		Laboratory production development	Pre-commercial feedstock assessment	5.1	Production system validation	Define range of adaptation for feedstock and identify production uncertainties	Develop and refine post-harvest logistics and storage	NEPA documents, conservation plan, and other required permit applications submitted	Pilot-scale testing
5.2			Subscale production demonstrated		5.2		Conduct on-farm, field-scale production cost trials and assess production impacts on resource concerns	Assess maximum market potential for feedstock and coproducts	NEPA documents, conservation plan, and other required permit applications approved	
5.3			Scalability of production demonstrated		5.3		Establish partial budget costs and returns	Evaluate waste disposal and other costs	Prepare and submit service program applications	Scaled-commercial testing
5.4			Pilot plant capability enabled		5.4		Establish price points for feedstock market competitiveness with competing land uses	Develop feedstock off-take options and pathways to realizing market potential	Service program applications approved and payments received	
6.1	Full-scale technical evaluation	Fit-for-purpose properties—ASTM balloting process	Fit for purpose properties evaluated		6.1	Full-scale production initiation	Establish source material nurseries and begin feedstock production scale-up process	Ancillary service providers apply knowledge gained to advise producers and other supply chain participants	All regulatory compliance is complete	Performance confirmed for feedstock conversion and effects on fuel properties, engines, and components
6.2		Component/rig testing—OEM review and approval	Turbine hot section testing							
6.3			Component/ rig/emissions testing		6.2		Produce feedstock planting materials to meet demand	Determine feedstock production capacity when linked to market outlets—price and quantity		
6.4		Engine/APU testing—ASTM research report	Engine/APU testing							
7	Certification/fuel approval		Fuel class/type listed in		7	Feedstock availability	Commercial-scale production and	Utilize risk management tools to reduce	Continue service program	Sustainable full-scale production of

Table 1 (continued)

Fuel Readiness Level				Feedstock Readiness Level			FSRL components with tollgates			
FRL scale	Description	Fuel testing and certification	Tollgate	Activity	Scale	Description	(1) Production	(2) Market	(3) Policy—program support and regulatory compliance	(4) Linkage to conversion process
	(determine go or no-go)	Fuel class listed in international fuel specifications	international fuel standards	Feedstock commercial deployment			feedstock delivery to conversion facility—payments made for feedstock	uncertainty of feedstock production	participation as needed	biofuel and co-products
8	Commercialization		Business model validated for production go-ahead—airline/military purchase agreements secured		8	Commercialization	On-going monitoring and research to improve production system performance while managing multiple resource concerns	Market established—make necessary adjustments to the supply chain as the feedstock market evolves[d]	Maintain regulatory compliance and make adjustments as needed	
9	Production capacity established		Full-scale plant operational		9	Sustainable feedstock production capacity established	Full array of private services support feedstock production sector—understanding of feedstock sector evolves—make adjustments as commercial-scale biofuel production expands	Market functions to support sustainable feedstock production	Federal, state, and private programs function with minimal disruption from unintended economic, environmental or social consequences	

[a] Examples of considerations for regulatory compliance include pre-importation regulations, invasive species; gene escape; US Environmental Protection Agency Feedstock Certification for greenhouse gas reductions under the Energy Independence and Security Act and Renewable Fuel Standard 2; and US Department of Agriculture Natural Resources Conservation Service (NRCS) conservation plan support

[b] Multiple natural resources concerns include the USDA-NRCS conservation planning framework SWAPAE+H (soil, water, air, plant, animal, energy, plus human effects). Various decision tools are available to estimate feedstock production impacts on metrics of soil erosion, fuel use, pest risk assessment, and greenhouse gas emissions

[c] Examples of service agency programs include USDA Farm Service Agency, Biomass Crop Assistance Program, USDA-NRCS, Environmental Quality Incentive Program, and USDA Risk Management Agency, Crop Insurance Program

[d] Monitor and analyze market transactions, producer decisions, technical developments, and resources availability

development and establishment of commercial markets; (3) program support and regulatory compliance (policy; POLY)—addresses factors that promote or discourage the production and availability of feedstocks; and (4) linkage to a conversion process (LINK)—addresses factors affecting matching of a candidate feedstock to a specific conversion process to ensure that feedstock supply development is coordinated with the quality and quantity specifications of a specific conversion technology and a biorefinery facility that will utilize the feedstock.

The FSRL tool was developed to complement the CAAFI FRL tool. Both the FRL and FSRL tools utilize the 1 to 9 TRL scale. The FSRL descriptions intentionally used the same general FRL descriptions, except for slight differences in readiness levels 5 to 9 that reflect more accurately the progressive development of a feedstock and its production system across an agricultural area, forest, or other landscape as opposed to the original FRL descriptions of an industrial process involving production, testing, and certification of a particular fuel produced from an alternative feedstock. However, both tools are scalable and so may be applied at the industry-wide level or specific to a conversion facility site and its supporting feedstock supply area.

The nine FSRL readiness levels are grouped into four activity categories: preliminary evaluation (FSRL 1, 2), experimental testing (FSRL 3, 4), pre-commercial assessment (FSRL 5, 6), and commercial deployment (FSRL 7–9). The four FSRL activity categories differ from the FRL categorizations for research and development (FRL 1–5), certification (FRL 6, 7), and business and economics (FRL 8, 9) based on CAAFI committee responsibilities [2] but similarly integrate research and commercialization activities into a single progressive development process. Also, like the FRL, the FSRL provides a gated process to govern communication of feedstock readiness maturity from initial identification of a candidate feedstock through evaluation and testing to production and full commercial deployment.

Preliminary Feedstock Evaluation (FSRL 1-2)

Once a candidate feedstock is identified (PROD 1), determinations are made for where (PROD 2.1) and how it can be grown (PROD 2.2), estimated costs of production (PROD 2.3), and early identification of possible consequences of production on existing land uses (markets, natural resources, and social impacts) (PROD 2.4). These considerations provide an initial screening of feedstocks based on their biomass yield characteristics and range of adaptation that can then be used to estimate fuel yield production potential for a region. Such information could also provide the basis for an initial techno-economic analysis of the upstream feedstock supply contribution to the supply chain. The intent is to plan for the building of sustainable supply chains and to plan for minimizing and managing unintended consequences that may result from an expanding feedstock sector that supports the aviation biofuels industry.

Concurrent with PROD evaluations, MARK evaluations identify what feedstock production may already exist within a targeted production area, and for what uses, to understand what the potential competition for the feedstock could be prior to its development (MARK 1). This information can guide a preliminary assessment of market outlet alternatives (MARK 2.1), potential co-products that can be produced (MARK 2.2), waste disposal requirements (MARK 2.3), and determination of logistics requirements. Logistics considerations identified within the FSRL encompass available mechanized harvesting techniques, any post-harvest storage, and delivery of the feedstock to the biorefinery. Other logistics requirements can include biomass densification (including mechanical, torrefaction, or other chemical preprocessing of feedstocks), preliminary processing of plant oils such as degumming, and management of transport and handling to reduce losses (MARK 2.4). The scheduling of just-in-time delivery or storage of feedstocks prior to processing to stage feedstock supply with conversion facility operations schedule should also be evaluated. Conversion facility operation plans may specify multiple feedstock sources to meet operational requirements and diversity feedstock supply to reduce the risks of interrupted source. These assessments provide the basis for estimating the potential for feedstock development and deployment and for preliminary identification of barriers to the expansion of a dedicated feedstock sector.

The FSRL only identifies the need for logistics and transportation infrastructure considerations directly related to feedstocks when developing delivery plans from the place of production to conversion facilities. A broader logistics and transportation infrastructure readiness level tool that considers in detail all of the activities and infrastructure needs across the biofuel supply chain, including not only feedstock handling, storage, processing, and delivery to biorefineries but also all transportation infrastructure requirements and scheduling, post-conversion operations including handling of waste and co-products development along with biofuel production, blending of biofuels into the fuel product stream, and delivery of biofuels to fuel end users, should be developed. Such integrated logistics and transportation considerations spanning the entire length of aviation fuel supply chains are beyond the scope of feedstocks and the FSRL.

As aviation biofuel production expands and business plans for using a new feedstock are being developed, an early awareness of the existing policy incentives and disincentives that established state and federal policies provide is critical to planning and is reflected in the FSRL POLY component. Early identification of regulatory requirements related to feedstock production (POLY 1) provides ample time to address any regulatory restrictions that could impede the rapid development and deployment of a feedstock supply. This is particularly crucial if the producer intends to utilize government service agency programs that require a conservation plan or filing of an environmental assessment or environmental impact statement. The specific regulations that would govern the production of a feedstock in a specific environment are evaluated (POLY 2.1), estimates made for the impacts of production on multiple resources concerns (including those that may have specific regulations) (POLY 2.2), with formulation of a plan for applying best practices to address all regulatory requirements (POLY 2.3). All POLY tollgates for preliminary feedstock evaluation activities are addressed prior to growing a candidate feedstock in a production area linked to a biorefinery. For imported feedstock materials, specific attention is given to compliance with all pre-importation requirements (POLY 2.4). Compliance with pre-importation regulations is critical to prevent the introduction of problematic invasive weeds, insects, or diseases that could threaten domestic agricultural and forestry sectors, as well as natural and wilderness areas. Long-established procedures are already in place to handle the importation, trade, and cultivation of agricultural and forest-based plant materials, and quarantine requirements are enhanced by regulations such as the USDA's listing of species "not authorized [for importation] pending risk assessment" (NAPPRA) [6].

Due to the need for linkage of any feedstock to one or more conversion technologies and the resultant expected certified fuel that will be produced (LINK 1), an initial evaluation of the quality/anti-quality constituents that can be expected should be made for the expected market outlet (LINK 2). The feedstock and its production system should also be analyzed for greenhouse gas (GHG) emission contributions that can be used to provide downstream supply chain participant information on feedstock contributions to the life cycle analysis. This information can be used to help determine the qualification for possible receipt of renewable identification number (RIN) and demonstrate sufficient GHG reductions that may be needed for certain markets or uses.

While RIN qualification is based on EPA's blanket qualification of particular feedstock conversion pathways, GHG emissions should also be measured on the individual facility or company level to ensure that the actual production processes being used are accurately reflected in the GHG accounting reported to downstream supply chain participants and the EPA for RFS qualification purposes [7]. Greenhouse gas and sustainability evaluations by an individual organization must occur later in feedstock development (e.g., POLY and LINK 5–8) to document environmental performance.

Information about FSRL 1 and 2 are relatively easy to obtain from available published research for similar agricultural or forestry systems that are already understood and which have public sources of costs and returns information. The different participants in the supply chain can use this information to build business-specific estimates related to feedstock costs. The production, costs, and returns estimates of the preliminary feedstock evaluation FSRL levels can be informed but speculative—field-validated information is required later in development.

Feedstock Experimental Testing (FSRL 3–4)

Growing a candidate feedstock in experimental field trials provides a first estimate of the actual production potential in a specific growing environment (PROD 3.1). A range of genetic materials is often tested together using established experimental design procedures to identify statistically reliable differences in yield among feedstock genotypes,[4] enabling selection of the best materials for further evaluation and cultivation. It is recommended that a candidate feedstock be compared with one or more already established feedstocks for a specific growing environment to provide a basis for estimating potential performance improvement and to identify the best-adapted candidate. Initial small-scale testing is relatively inexpensive to conduct, but the results often overestimate yields that would be expected under full-scale commercial production conditions.[5] Initial experiments demonstrate feedstock performance under highly controlled field conditions and are the equivalent of proof of concept for small fuel sample testing under the FRL. The resulting harvest of a candidate feedstock is evaluated for harvested yield and percentage of convertible constituents that are used to estimate biofuel yield (PROD 3.2). Both of these indicators are important since feedstock yield alone does not necessarily translate to biofuel yield. Standardized testing methods for estimating biofuels yield should be agreed upon by organizations participating together or alone in feedstock genetic development and testing programs.

At the same time, feedstock-specific production costs and expected returns from producing the feedstock will be estimated based on the initial production trials (MARK 3.1) to provide supply chain participants with the information needed to develop business plans and assess the feasibility of a

[4] Genetically different populations of one feedstock species may perform differently in different production environments.

[5] This may be due to small-scale experiments being conducted under controlled conditions with careful management, use of small-scale equipment, and manual harvest and on relatively highly productive soils found on experimental farms. Conditions across fields, farms, and landscapes are highly variable and not as easily controlled and managed, which results in lower average performance at commercial scales than under controlled experimental conditions.

new crop or other feedstock source and its potential production when integrated into an operating farm or forest production environment (MARK 3.2).

Once the initial yield potential screening has occurred (PROD 3.1), the candidate feedstock needs to be tested for performance over a range of environments and compared to other established feedstocks in regional trials to refine yield estimates derived from the preliminary trials and to determine the relative production potential (PROD 4.1). Coordinated comparisons of different feedstocks over a region help determine whether a candidate feedstock is actually superior to another established or candidate feedstock and confirm relative performance in multiple production environments (PROD 4.2). Without these comparisons, a feedstock with the greatest potential for a specific environment may not be utilized, which may threaten the economic viability of a supply chain and the competitiveness of the aviation biofuel with petroleum-based or other alternative fuels. The information obtained from these studies can be used in initial feasibility studies for feedstock supplies and expected biofuel yields.

In conjunction with the regional testing, there should be a systematic exposure to candidate feedstocks of those who are interested or expected to participate in the production sector through extension and education programs for growers and the allied industries to support full-scale production (PROD 4.3). Education for producers and industry partners is most critical if a feedstock greatly differs from crops or woody species that are already being produced in a region that has well-established methods for production, harvest, and handling and if the novel feedstock would require changes to the existing infrastructure when produced.

The time required to scale up production of feedstocks (PROD 6.1, discussed below) depends on the rate that materials can be multiplied—seed-propagated species typically scale up faster than vegetatively propagated materials. The time required to establish a base production area to support a biorefinery is at least twice the time required to construct a conversion facility [8], so synchronization of the feedstock supply expansion to coincide first delivery with the start of the operation of a new facility is critical. For these reasons, the co-participation of feedstock producers and biorefiners is critical to establish the new, needed supply chains (MARK 4).

Feedstocks cannot be produced without a biorefinery market that provides specifications for feedstock characteristics and quality, so feedstock producers and biorefiners must be linked (MARK 4.1). Biorefiners will desire efficient supply chain transactions, so some sort of feedstock broker arrangement may be needed to facilitate feedstock supply exchange and ensure that appropriate logistics channels are in place for delivery. Some sort of contracting arrangements will likely be instituted to ensure adequate supplies for the biorefinery that meet facility operation schedules and to reduce producer risks when growing feedstocks (MARK 4.2). Just as education and outreach programs are required to develop interest in the production of feedstocks and to build expertise, education programs will also be needed to support feedstock contracting and marketing information, leading up to commercial production scale-up (MARK 4.3).

In support of the PROD and MARK components, the sequence of POLY actions for feedstock experimental testing activities includes determination of the potential for societal opposition to the production of a feedstock (POLY 3.1) and formulation of a plan to address those concerns (POLY 3.2). During this activity period, any incentive programs that could be utilized by producers and biorefineries are identified (POLY 4.1) and conservation plans to address all resources concerns for the environment where the candidate feedstock will be produced (POLY 4.2) are developed. Conservation plans also help to formulate the practices that will be used to support the drafting of National Environmental Policy Act (NEPA) [9] documents or other permitting documents that may be required (POLY 4.3). Achieving these tollgates, in addition to helping avoid unnecessary delays in bringing new feedstocks to market, provide the information necessary to prepare needed documents to apply for service agency program assistance (see POLY 5 below), develop more refined business plans, and address concerns that are commonly raised about the expanded biofuel production on the environment [10] and food prices [11].

The LINK component provides for bench-scale testing of the candidate feedstock (LINK 3) as production is being scaled up to estimate conversion efficiency, determine unique effects of the feedstock on fuel properties (LINK 4.1), and ensure that the feedstock can be utilized as anticipated. Bench-scale testing also provides an estimate of the amounts of co-products that would be produced (identified initially in MARK 2.2) and a preliminary assessment of co-products that provide additional value-added income for the supply chain participants (LINK 4.2). During the feedstock technical evaluation activity period, biorefinery technology providers should give specifications for feedstock supply delivery schedules and quality/anti-quality characteristics to enable appropriate coordination with and planning by feedstock producers. Integrated analyses involving feedstock and conversion technology scientists are needed to estimate and improve feedstock conversion efficiency and value-added co-product development to help reduce the price of the final biofuel. Co-product development is critical to provide additional revenue to increase the competitiveness of the biofuel supply chain [12, 13] with other established or potential land uses and competing markets (LINK 4.3).

The costs to achieve FSRL 3 and 4 will likely be dominated by the costs associated with regional field trials

(PROD 4.1). Significant coordination is required for such feedstock performance trials when conducted across large geographic areas. Coordinated efforts help ensure that useful information is generated effectively to direct the choices of feedstock to be produced. Research coordination can be achieved through established national research organization networks, with linkage to and participation by regional or state-level organizations, including collaborations among both public and private institutions and the business sector.

Pre-commercial Feedstock Assessment (FSRL 5–6)

Once a candidate feedstock has passed preliminary evaluation and their experimental results have provided support for further development, specific pre-commercial assessments are necessary to compile the information that will be required to secure financing and service agency program participation. For the LINK component, conversion technology utilizing the candidate feedstock is tested at successively greater volumes from pilot- to scaled-commercial production volumes (LINK 5), with the performance of the fuel confirmed for its effects on fuel properties, engine performance, and components (LINK 6). In parallel, the feedstock production system must be validated, which includes defining the actual range of feedstock adaptation for production conditions (preliminarily evaluated in POLY 2.1) and the yield potential to support one or more biorefineries (PROD 5.1). On-farm, field-scale trials (e.g., [14]) are needed to establish to-scale production budget costs and returns and to estimate production impacts on multiple resource concerns[6] (PROD 5.2). The costs and returns of production and the potential costs of resource impact mitigation can then be used in calculations for expected price-points required for the feedstock to compete with returns from alternative land uses (PROD 5.3).

When production costs are combined with logistics costs (handling feedstock from the time of harvest until utilization at the biorefinery) (MARK 5.1), the feedstock pricing structure can be developed based on the anticipated volume of biofuels and co-products that will be produced (MARK 5.2) and associated waste treatment and handling costs (MARK 5.3). MARK 5.2 also takes into account the potential international markets for the feedstock. With these, the actual break-even point for the biofuel feedstock crop to compete with alternative land uses may be determined (PROD 5.4). This approach is needed to inform the development of off-take agreements and other financial tools for realizing the market potential of the feedstock (MARK 5.4). It is also during the production system validation period that NEPA documents, conservation plans, and any other required permit applications are submitted (POLY 5.1) and approved (POLY 5.2). Specific sustainability evaluations for the better-defined feedstock production process, including GHG life cycle inventories, can be performed in conjunction with these permit applications for the purposes of GHG reporting to other supply chain participants and any voluntary sustainability certification options. With successful completion of these, various service programs may be accessed (POLY 5.3) and, with successful applications, payments received (POLY 5.4).

Full-scale production initiation involves those processes that require time to achieve full-scale cultivation to supply the planned feedstock needs of one or more biorefinery operations. The amount of time required to achieve full-scale production varies from the establishment of source planting materials (PROD 6.1) through the series of propagation increases to commercial-scale feedstock production (PROD 6.2), depending on whether the feedstock is propagated by seed or vegetative materials—seed propagation is generally more rapid. The costs of feedstock material increases also vary depending on the method of propagation—vegetative propagation is generally more expensive than seeded propagation. As large-scale production of dedicated feedstocks expands, the development of more efficient propagation procedures (e.g., [15]) may reduce the time needed to scale up expanded acreages and reduce producer crop establishment costs.

Expanding expertise will be accumulated from business as well as from public education and extension services to advise biomass producers and other supply chain participants in the developing sector (MARK 6.1). As production capacity and market outlets are confirmed and the supply chain component operations become efficient, it will be possible to make more accurate estimates of total feedstock supply and price (MARK 6.2). At this stage, it is anticipated that the prices of available feedstocks will respond to the market and that all regulatory compliance is complete (POLY 6).

The greatest cost associated with pre-commercial feedstock assessment tollgates will be conducting on-farm field-scale production cost trials (PROD 5.2), but the availability of existing field-scale production cost information can be used from similar feedstocks or other commodities whose costs have already been established. Other costs associated with FSRL 5 accomplishments are computational and based on information obtained from earlier tollgate activities. Specifically, costs associated with MARK and POLY in FSRL 5 and 6 are based on information obtained at earlier FSRL level activities; so, these are therefore likely to be relatively low. Actual costs for PROD at FSRL 6 will be dominated by the pre-commercial staging of planting materials for

[6] The USDA, Natural Resources Conservation Service Conservation Planning Framework addresses multiple resources concerns for soil, water, air, plants, animals, renewable energy, and human resources (SWAPAE+H). Guidance is given through a series of technical guides. http://www.nrcs.usda.gov/technical/efotg/index.html

feedstock commercial deployment FSRL component toll-gate activities. During early deployment of the feedstock production sector, some kinds of feedstock may require very expensive vegetative propagation and multiplication of planting stocks to achieve full-scale production areas to support a market. Advances in propagation technology and development and transition to seed-propagated varieties of otherwise vegetatively propagated species (e.g., Mendel Biotechnology development of a seeded *Miscanthus* [15]) may significantly reduce the time and costs of feedstock crop establishment as may the development of a dedicated propagation industry. In the interim, service agency incentive programs such as the USDA Biomass Crop Assistance Program [16] may help offset some of the initially high establishment costs and create early opportunities to help accelerate the establishment of a dedicated feedstock sector (POLY 5).

Feedstock Commercial Deployment (FSRL 7–9)

When commercial-scale biorefineries are operating with full output of their biofuels and co-products (LINK 7–9), all other FSRL components should be functioning in an ongoing cycle of adjustment and expansion. Adequate supplies of feedstock planting materials (PROD 7) are available for successive seasons of continued and improved production to support biorefinery needs (PROD 8), and a full complement of private industry and public services are available to support all feedstock supply chain components (PROD 9). Strong linkages between feedstock producers and biorefineries through contracts, facilitated by efficient transaction costs and consistent sector-related public policies, help manage risks (MARK 7) and allow the market to adjust with sector expansion as necessary to changes in competing sectors, inclement weather, public policies, and other external factors (MARK 8). In order to qualify as MARK 9, biofuel supply chains should function in a resilient manner, ensuring that expected amounts of biofuels are sustainably produced at competitive prices.

With achievement of commercial-scale feedstock deployment and implementation of service agency programs (POLY 7), changes in production systems and supply chains are made as needed to continue meeting service program requirements and to maintain regulatory compliance (POLY 8). Federal, state, and private programs and other instruments such as contracts function and anticipate external policy changes, with minimal disruption from unintended economic, environmental, or social consequences by the emerging renewable biofuels sector (POLY 9). Thus, FSRL steps 7 through 9 represent the maturation of the feedstock production sector and supporting supply chain to provide reliable, sustainable, cost-effective feedstocks to the aviation biofuel industry.

The cost to achieve FSRL 7, 8, and 9 depends on the specific feedstock supply matched to commercial biorefinery operation and quality specifications. For example, feedstock costs are anticipated to comprise 50 to 60 % (or more) of commercial hydroprocessing final fuel costs [17] (Pearlson et al., manuscript submitted for publication). Integration of all supply chain components through optimal systems architecture, with interdisciplinary techno-economic analysis to identify and target cost reduction opportunities, provides an approach to reduce feedstock production and biorefinery operation costs. As greater portions of agricultural, forestry, or other rural landscapes are utilized to produce biofuel feedstocks, there are likely to be greater interactions and impacts on competing markets and land uses [18]. Coordinated investments in feedstock (PROD 8) and conversion technology research and their integration should be considered to reduce aviation biofuel production costs and increase competitiveness with conventional and other alternative feedstock-based aviation fuel sources. Past investments in research have provided great gains in agricultural and forestry production [18], so it can be assumed that similar research investments in dedicated feedstocks should greatly increase the successful production of aviation biofuels and their competitiveness with petroleum and other alternative fuels.

Conclusion

The FSRL tool was developed to describe the steps involved to bring plant-based feedstocks to market for use in commercial and military aviation biofuels production. The tool identifies the key production, market, policy, and conversion-process-linkage components involved with feedstock supply development and provides a framework for coordination among research, government, and industry to assess feedstock status and streamline biofuel production scale-up. The FSRL tool was developed to complement the CAAFI FRL tool and can be used to identify gaps in aviation biofuel supply chains that are due to disconnects between either capacity to supply a feedstock for a particular conversion process (measured by FSRL) or the commercial development of a fuel conversion process (measured as FRL) to provide a market for a feedstock. This integrated feedstock and conversion technology approach allows for the identification of all feedstock production costs and activities to scale up production and for the allocation of resources to effectively develop the needed supply chains to create a viable aviation biofuels industry. The FSRL was specifically developed for the aviation fuel industry but can be used to identify gaps in any feedstock supply chain designed for any biofuel or other conversion process that provides a market for feedstocks. The FSRL Tool is available for downloading at www.caafi.org.

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