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Transitioning to Biofuels: A System-of-Systems Perspective

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Transitioning to Biofuels: A System-of-Systems Perspective

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Abstract. Today, almost 60% of the petroleum consumed in the United States is imported. The U.S. transportation sector currently consumes for over two-thirds of the 11 million barrels of oil used in the U.S. each day. Global demand for transportation fuels is increasing dramatically as developing countries expand their economies and become more energy intensive. Clean energy systems are needed to support sustainable global economic growth while mitigating impacts on air quality and greenhouse gas emissions. Biofuels offer a near-term solution for reducing U.S. oil consumption. Transitioning to a significantly larger biofuels industry will require the creation of a robust biomass-to-biofuels system of systems that operates in concert with the existing agriculture, forestry, energy and transportation markets. Using the fuel supply chain infrastructure as a framework, the current petroleum-based transportation economy, a vision for biomass-based fuels and the challenges associated with such a massive market and infrastructure transformation are discussed.

Introduction

Ready access to affordable oil is the cornerstone of the U.S. economy. In 2004, the U.S. consumed almost 21 million barrels of crude oil and refined products per day (EIA, 2006a) — almost one-quarter of the world's total crude oil consumption of 85 million barrels per day. Approximately 60 percent of the U.S. demand was supplied by imports (EIA, 2006a). The transportation sector, which receives nearly all of its energy from petroleum products, accounts for two-thirds of U.S. petroleum use. As President Bush aptly noted in his 2006 State of the Union Address, "America is addicted to oil."

The rest of the world is rapidly following suit. Global demand for petroleum and other liquids is projected to grow from 83 million barrels oil equivalent per day in 2004 to 118 million barrels per day in 2030 (EIA, 2007). Most of this growth will occur in developing countries, driven both by population growth and by the realization of economic development aspirations. But U.S. demand also continues to grow, with petroleum demand expected to top 26 million barrels per day by 2025 (EIA, 2006b). In light of increasing worldwide oil demand, our increased reliance on imported sources of energy threatens our national security, economy and future competitiveness. How this growing demand for energy is met poses one of the most complex and challenging issues of our time.

Transitioning from our current petroleum-based transportation fuel economy to a future fuel economy that incorporates significant amounts of alternative and renewable transportation fuels can be characterized and addressed as a system of systems (SoS) problem. This paper provides a working definition of SoS; describes the current transportation fuel SoS; provides a vision for a future biofuels SoS, and describes how system dynamics can be used to understand and guide the transition to a new transportation fuel SoS.

System of Systems Overview

System of Systems is a capability- or enterprise-based approach to solving complex problems, in which multiple complex systems interact both independently and as an integrated whole. While SoS has its roots in the established systems engineering discipline, as outlined in Table 1, addressing SoS goes beyond traditional systems engineering in a number of ways.

Table 1. Differences Between Traditional Systems Engineering and System of Systems Engineering (SOSECE, 2007)

	System Engineering Perspective	**System of Systems Engineering Perspective**
Scope	Product/Product	Enterprise/Capability
	Autonomous/Well-bounded	Interdependent
Objective	Enable fulfillment of requirements	Enable evolving capability
	Structured project process	Guide integrated portfolio
Time Frame	System lifecycle	Multiple, interacting system lifecycles
	Discrete beginning and end	Amorphous beginning Important history and precursors
Organization	Unified and authoritative	Collaborative network
Development	Design follows requirements	Design is likely legacy-constrained
Verification	System in network context	Ensemble as a whole
	One time, final event	Continuous, iterative

The field of SoS engineering is still emerging and the SoS community has not yet come to agreement upon a single commonly-accepted definition of SoS. As a starting point, the International Council on Systems Engineering (INCOSE) defines SoS as follows:

> "System of systems applies to a system of interest whose system elements are themselves systems; typically these entail large-scale inter-disciplinary problems with multiple, heterogeneous, distributed systems." (INCOSE, 2006)

A key aspect of SoS that is not called out in this definition is the importance of context in developing a desired physical capability. According to the System of Systems Center of Excellence, "SoS engineering addresses a complex system in terms of relationships, politics, operations, logistics, stakeholders, patterns, policies, training and doctrine, context, environment, conceptual frame, geography and boundaries." (SOSECE, 2007) This broader definition is needed to characterize and transform the transportation fuel system of systems.

Transportation Fuel Sector as a System of Systems

Conceptually, the transportation fuel SoS can be represented as shown in Figure 1 and described in terms of capability and context.

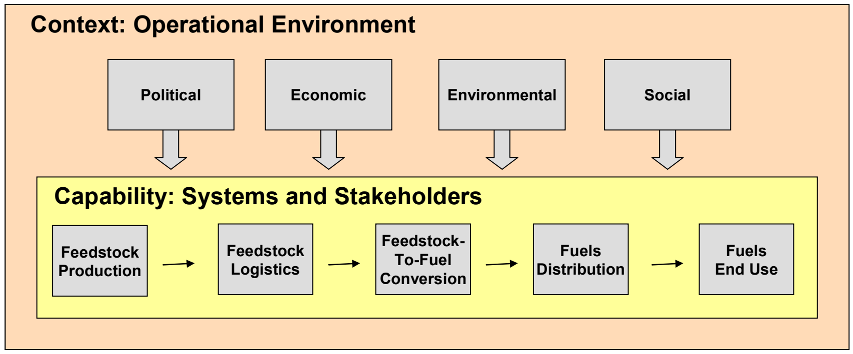

Figure 1: Transportation Fuel System of Systems

Capability

The physical systems and infrastructure included in the transportation SoS can be organized around five interdependent systems that comprise the feedstock-to-fuel supply chain. The primary objective of each system is described in the context of the existing transportation SoS, which moves crude oil from its source to the final processed fuel used by consumers, as illustrated in Figure 2.

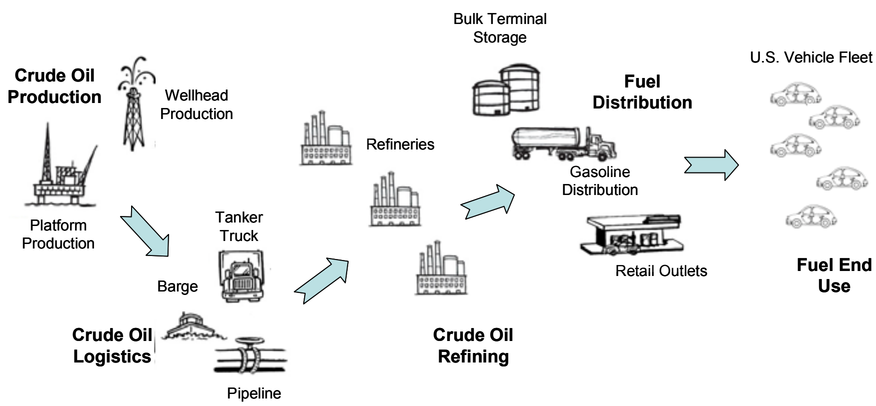

Figure 2: The existing Petroleum-Based Transportation Fuel SoS

Feedstock Production System. The objective of the feedstock production system is to produce large quantities of high-quality raw feedstock. In the current petroleum-based fuel economy, this includes all of the exploration and production infrastructure (e.g., drilling rigs, production platforms) required to extract crude oil from reserves around the globe.

Feedstock Logistics System. The objective of the feedstock logistics system is to collect, store and transport raw feedstock from the production point to the fuel production facility. In the current petroleum-based system, this includes all of the infrastructure required to move crude oil from the field to the refinery. The nation’s extensive network of petroleum transmission pipelines are the primary means of moving crude oil from oil fields on land and offshore to refineries where the oil is turned into fuels and other products. The crude oil logistics system also includes ports, storage tanks, barges and tankers depending on where the oil supply originates.

Feedstock-to-Fuel Conversion System. The objective of the feedstock-to-fuel conversion system is to process raw feedstock into transportation fuel. For the current petroleum-based system, this includes all the infrastructure (e.g., reactors, distillation columns, etc.) required to operate a refinery. Refineries process the crude oil feedstock into gasoline, diesel fuel, heating oil, jet fuel, liquefied petroleum gases and other petroleum-based products. U.S. refining capacity stands at approximately 17 million barrels per day. (EIA, 2004a) Gasoline represents nearly 45 percent of the domestic production of all refined products. (EIA, 2005)

Fuel Distribution System. The objective of the fuels distribution system is to move transportation fuel from the refinery to the consumer point-of-use. In the current petroleum-based system, this includes all the infrastructure (e.g., pipelines, storage tanks, fuel dispensers) required to transport, store and dispense transportation fuel. There are approximately 95,000 miles nationwide of refined products pipelines, which move gasoline, diesel fuel and other petroleum products to consumer markets. (API, 2006) The majority of gasoline is shipped by pipeline to bulk storage terminals near consuming areas. At these terminals the gasoline is loaded into tanker trucks and then delivered to one of the approximately 167,000 retail outlets in the U.S., where the gasoline is unloaded into the underground tanks at the gas station. (EIA, 2005)

Fuel End Use System (Vehicle). The objective of the fuels end-use system is to provide high-performance, reliable, affordable and safe vehicles to consumers. For the current petroleum-based transportation fuel system, this includes all of the infrastructure (e.g., automotive and supporting industries—rubber, computer chips, steel etc.) required to manufacture and distribute vehicles to consumers. In 2005, almost 66 million cars and commercial vehicles were produced worldwide (12 million of these vehicles were produced in the U.S.). (BTS, 2001a) In 2005, almost 250 million highway vehicles were registered in the U.S. (BTS, 2001b)

Context

The transportation fuel SoS must operate within the context of political, economic, social and environmental conditions that influence its physical domain. A brief description of each perspective with respect to the transportation fuel SoS follows.

Political Context. Government policies, incentives, laws and regulations have affected the transportation fuel SoS for many decades. Global politics are, and will continue to be, a key consideration in the political operating environment, driven by the fact that over two-thirds of the world's remaining global oil reserves lie in the Middle East. (Rifkin, 2002) Significant government incentives that directly support the U.S. petroleum based industry have been in place for years. Between 1968 and 2000, the petroleum industry received over $150 billion dollars in tax breaks—for exploring for and producing petroleum within the U.S. and for development costs and production of non-conventional fuels. (GAO, 2000) Since the 1970s, laws and regulations related to the Transportation Fuel SoS have been primarily driven by increasing concerns for the environment, safety and energy efficiency (e.g., mandated vehicle emissions requirements and fleet average fuel economy standards).

Economic Context. The transportation fuel SoS operates within a global marketplace. With an estimated total value of between $2 trillion and $5 trillion, the petrochemical industry is the largest business in the world. (Rifkin, 2002) The automobile industry is also a major contributor to global and U.S. economies. In 2005, the total sales of automobiles were about 4% of the U.S. gross domestic product, equivalent to around $500 billion dollars in sales; an estimated 7.5 jobs are created in other industry for every autoworker employed in the U.S. (Ford Motor Company, 2007) On the down side, U.S. reliance on imported oil has measurable negative impacts on the U.S. economy. The last three major oil price shocks, driven by political events in the Middle East, sent the U.S. economy into economic recession. The U.S. spends an estimated $200,000 per minute on foreign oil, accounting for about one-fourth of the annual trade deficit. (UCS, 2002) In the future, petroleum prices are expected to rise as worldwide oil demand continues to increase and oil supplies begin to wane, further increasing cash flow out of the U.S. economy.

Environmental Context. The current petroleum-based transportation fuel SoS has had many negative impacts on the environment. Oil extraction, refining and transportation operations contribute to land destruction and toxic contamination at the extraction point, oil spills in oceans around the world, and toxic air and water emissions from oil refining operations. (Clean Water Action, 2007) Millions of acres of farmland and wildlife habitat have been lost to roads and highways across the U.S. and vehicle emissions are major contributors to air and water pollution, as well as global climate change. Today, the transportation sector accounts for about a third of total U.S. emissions of carbon dioxide (an important greenhouse gas). (DOE, 2007a) Not surprisingly, the transportation fuel SoS operates under a multitude of environmental protection laws and regulations regarding oil production, transport, and use. Pressure from environmental advocacy groups continues to motivate government action to mitigate and minimize the environmental impacts of the transportation sector through sustainable, energy-efficient and clean alternatives.

Social Context. Affordable transportation fuel and personal mobility are virtual "rights" in the U.S. today. Even as traffic congestion and air pollution plague our cities, oil and the automobile are the foundation of our commercial and social lives. Today, the average American consumes about 25 barrels of oil per year; for perspective, the average person in China uses less than 2 barrels of oil per year. (Nationmaster, 2007) Modern food production and distribution are almost exclusively dependent on oil and natural gas and today, agriculture is one of the world's most energy-intensive industries. (Worldwatch, 2007) Recognition that this oil-dependent lifestyle cannot be sustained into the future is slowly building—driven in part by the pinch consumers feel as the costs of food, gasoline and consumer products rise in response to higher oil prices, as well as increasing concern for the environment. For example, since 2004, the popularity of sport utility vehicles (SUVs) has waned and consumer demand for more fuel efficient vehicles has risen. (Worldwatch, 2007) Nonetheless, consumers maintain their high expectations regarding performance, comfort, safety, reliability, cost, and size of the vehicles they purchase and drive. This illustrates the primary challenge from a social perspective—overcoming our natural resistance to change and managing expectations as alternative transportation fuels enter the market.

Vision for a Future Biomass-Based Transportation Fuel SoS

Biomass is the only domestic, sustainable, and renewable primary energy resource that can replace liquid transportation fuels currently produced from petroleum sources. Biomass resources include crops like corn; agricultural and forest residues like corn stover (stalks and leaves that remain after the corn grain is harvested) and forest thinnings; and non-edible perennial crops like switchgrass and poplar, which can be grown as energy crops. The U.S. has the potential to produce over 1.3 billion tons of biomass annually —enough to replace over 30 percent of current U.S. gasoline consumption—sustainably, and without impacting food, feed, and fiber uses. (Perlack, 2005)

Biomass-based fuels offer number of environmental advantages over conventional petroleum fuels. Most importantly, biofuels generate fewer greenhouse gas (GHG) emissions than conventional fuels on a full fuel-cycle basis (includes the energy used to produce the feedstock, as well as the energy used to produce the fuel (e.g., coal, natural gas, biomass)). Ethanol made from cellulosic feedstocks (e.g. corn stover, switchgrass) has the potential to reduce greenhouse gas emissions by as much as 86%, relative to gasoline. (Wu et al., 2006)

In the U.S. Department of Energy's 2030 vision for biofuels, a robust biomass-based energy industry and supporting infrastructure will be in place, fully operational and capable of producing 60 billion gallons of cellulosic ethanol annually (equivalent to 48 billion gallons of gasoline). The future *capability* envisioned for each system of the biomass-to-biofuels supply chain is described below.

Biomass Feedstocks Production System. In 2030, a variety of sustainable, cost-effective, regionally-available, lignocellulosic feedstocks will be integrated into the current agricultural and forestry industries and available for biofuels production. Agricultural resources (corn stover, straw, switchgrass) and forest resources (forest thinnings, logging residues, urban wood residues) dedicated to biofuels production will total 600 million dry tons. The feedstocks with the greatest ultimate ethanol production potential include agricultural residues, perennial energy crops and forest residues, as shown in Figure 3.

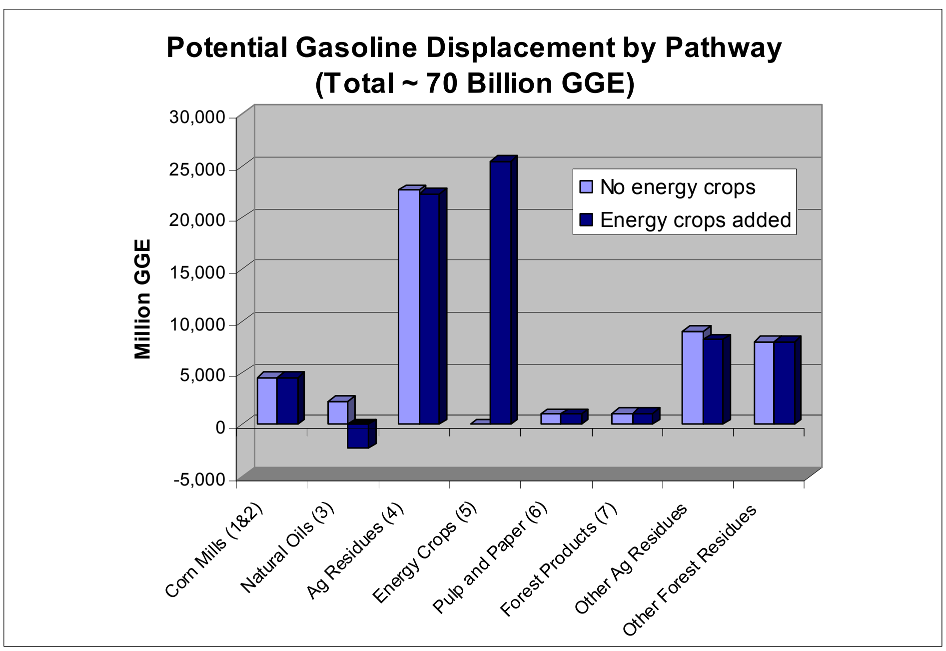

Figure 3. Potential Gasoline Displacement by Pathway

Biomass Feedstocks Logistics System. In 2030, mature technologies for collection, storage, and preprocessing both wet and dry biomass feedstocks will be integrated into the agricultural and forestry industries and in use in all regions of the country. Approximately 30 billion ton-miles of transport will be in place to deliver 600 million dry tons of "reactor-throat ready" feedstock to biofuels production facilities.

Biofuels Production System. In 2030, an estimated 300 commercial cellulosic biofuels production plants will be producing 48 billion gge (gallons of gasoline equivalent, i.e. equivalent to gasoline on BTU basis) of biofuels per year. These plants will integrate advanced biochemical (e.g., fermentation) and thermochemical (e.g., gasification) conversion technologies to maximize production of ethanol from biomass. Co-products will include heat and power, and, in some cases, materials/chemicals/products that improve the overall plant economics.

Biofuels Distribution System. In 2030, shipping biofuels through pipelines will be standard practice as an integrated component of the nation's petroleum distribution system. In total 48 billion gge of biofuels will be shipped from production facilities to bulk terminals either through dedicated lines or through common carrier pipelines. At the terminal, biofuels will be loaded into tanker trucks and then delivered to one of the 100,000 dedicated biofuel pumps in retail outlets across the U.S.

Biofuels End Use System. In 2030, 230 million biofuels-compatible vehicles will be on the road, consuming 48 billion gge of biofuels annually. These vehicles will run on biofuel/gasoline blends and biofuel/hybrid platforms and will have the same or better performance than today's conventional fuel vehicles.

Where Are We Now? Status of Existing Biofuels Industry

Ethanol and biodiesel are the only biofuels in commercial production today. The existing U.S. ethanol industry is the focus of this discussion. Ethanol is widely used throughout the U.S. as a blend component of gasoline to reduce vehicle emissions and improve octane rating. Consequently, the supply chain from the farmer's field to the customer's vehicle is mature and integrated into the existing fuel supply infrastructure system as illustrated in Figure 4.

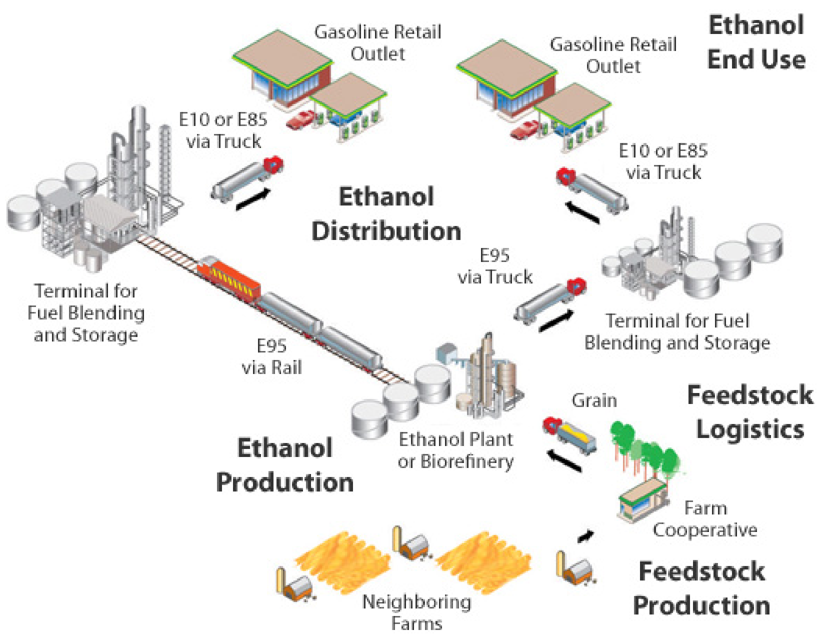

Figure 4. Current Corn-to-Ethanol System-of-Systems

Ethanol Feedstock Production System. Starch crops like corn and sorghum are the predominant ethanol feedstocks today. In 2005, 1.43 billion bushels of corn were used for ethanol production, representing nearly 13% of the U.S. corn crop. With an average yield of 147.9 bushels of corn per acre, about 10 million acres of the total 81.8 million acres of corn planted in 2005 was used to produce fuel ethanol. Ethanol represents the third largest market for U.S. corn, behind only livestock feed and exports. Ethanol production also consumed 15% of the nation's grain sorghum crop. (NCGA, 2007)

Ethanol Feedstock Logistics System. The equipment and systems used to harvest, collect, transport and store corn have been optimized for grain harvest over many years. The basic field equipment includes combines (which cut, gather, thresh, separate, and clean the corn), grain carts (which shuttle corn grain from combines to grain trucks or grain receiving facilities), and grain trucks (which haul the grain to ethanol production facilities). Corn is typically stored in bins or buildings to preserve the quality of the grain during storage.

Ethanol Production Systems. Two commercial production processes are used to convert the starch in grains to ethanol: dry milling and wet milling. In dry milling, the entire corn kernel or other starchy grain is ground into meal and processed without separating out the various component parts of the grain. The major co-product from the dry milling process is Distillers Dried Grains (DDG). In wet milling, the grain is soaked in a dilute sulfurous acid solution, which facilitates the separation of the grain into its many component parts. The co-products of wet milling include corn oil, corn germ, corn gluten feed, and high-fructose corn syrup. In 2005, 4 billion gallons of ethanol were produced in 95 wet and dry mill facilities (production capacity of 79% from wet and 21% from dry) in 19 states across the country. (RFA, 2006)

Ethanol Distribution System. Today, most fuel ethanol is used as gasoline blending stock to increase fuel octane and help meet gasoline oxygenate requirements in urban ozone non-attainment areas. Typical reformulated gasoline (E10) contains 5-10% ethanol and accounts for about 2% by volume of all gasoline sold in the U.S. Ethanol is also blended with gasoline to create E85, a blend of 85% ethanol and 15% gasoline. Today, approximately 75% of ethanol is moved by rail and the remaining 25% by truck, with barge and ship movements representing transfers of rail or truck shipments. (RFA, 2006) An estimated 13 million gallons of E85 fuel were consumed in the U.S. in 2004. (Motor Age, 2004) There are currently more than 1,100 E85 fueling stations (out of 170,000 total fueling stations) across the U.S., predominantly located in the Midwest, as illustrated in Figure 5. (DOE, 2007b)

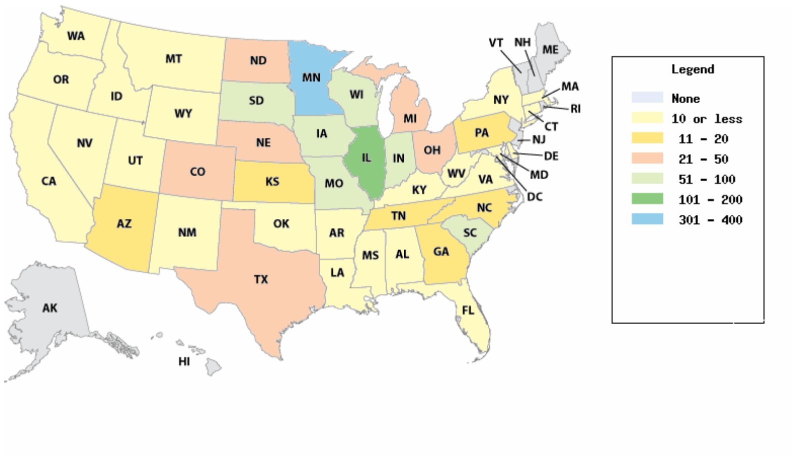

Figure 5. E85 Fueling Station Locations

Ethanol End Use System. Since the early 1990's, more than 5 million flexible fuel vehicles (FFVs) have been sold in the United States. (RFA, 2006) In 2004, an estimated 147,000 E85 FFVs were registered in the U.S. (EIA, 2004b) In 2006, Ford Motor Co. and General Motors Corp. announced an aggressive push to manufacture a record-breaking number of E85 FFVs – a total of 650,000 new vehicles. (General Motors, 2006)

Transitioning to a Biomass-Based Transportation Fuel SoS

Challenges

Transitioning to a biofuels SoS will require initially integrating with and ultimately transforming industries of the current transportation fuel SoS supply chain – i.e., petroleum fuels production and distribution industries and the automobile industry. A future biofuels SoS will also require transformation of the well-established industries that will provide biomass feedstock – agricultural, forestry, waste management – and produce biofuels – corn ethanol industry.The challenges associated with the envisioned transition to biomass-based transportation fuels are summarized from the perspective of the six SoS characteristics outlined in Table 1.

Scope. The scope encompasses the U.S. government and industry coordinated efforts to transform the transportation fuels sector of the U.S. economy by developing the capability to displace significant quantities of petroleum-based transportation fuels with renewable alternatives in combination with more energy efficient technologies and systems.

Objective. No single solution is envisioned for the future and the optimum mix of technologies and systems will likely change over time. A phased approach will allow new energy systems to be integrated into the existing transportation fuel infrastructure as technologies and systems advance to the point of commercial readiness. For example, today, ethanol produced from grain is already established in the fuel marketplace (both as a blending agent and fuel for flexible fuel vehicles [FFVs]). Real-world experience gained with these technologies and systems will be used to guide the RD&D needed to enable the next generation of alternative and renewable fuels.

Timeframe. Numerous initiatives to reduce our dependence on petroleum have been proposed and implemented since the early 1970s. Development of energy efficient and renewable technologies has typically been included as an integral part of these initiatives. Progress made to date will be leveraged as this work continues in the coming years. New advanced fuel technologies will be under development (early stages of system life cycle) at the same time commercially-ready technologies are being demonstrated and deployed (middle stages of system life cycle). For example, fundamental R&D to understand plant cell wall degradation is being conducted to optimize energy crops of the future at the same time some of the individual systems of the biomass-to-biofuels SoS, namely flexible fuel vehicles that can run on E85, are already available to customers (RFA, 2006)

Organization. The transformation from a petroleum- to a non-petroleum-based transportation fuel SoS will require the focused, coordinated and collaborative action of a multitude of diverse stakeholders. For example, the existing transportation fuel SoS comprises a global network of producers, refiners, marketers, traders, automobile manufacturers and consumers. In the future, the stakeholders involved will expand as each new type of fuel comes into play. The many stakeholders with key roles in the development of the future biofuels SoS are shown in Figure 6.

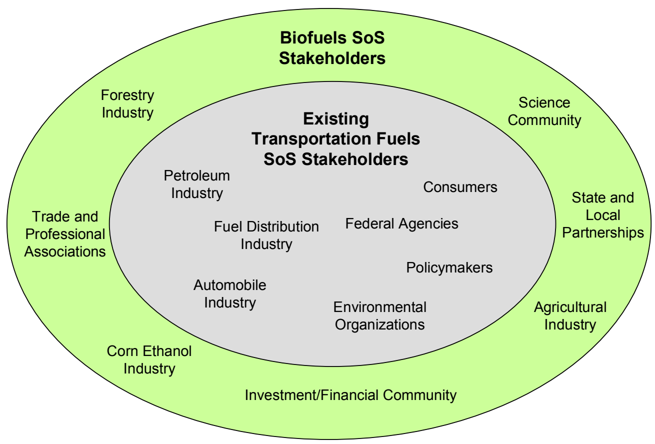

Figure 6. Stakeholders in the Transportation Fuel SoS Transition

Development. The existing petroleum-based, feedstock-to-fuel supply chain is a decades-old, fully mature, highly networked, and relatively efficient SoS. As such, it contains great inertia– resulting from sunk costs in the current infrastructure and consumer expectations regarding performance, cost and safety – that will influence the energy economy well into the future. Initially, new technologies must be designed to operate within the existing SoS and compete effectively with the existing system to enable a transition to new fuels to begin to occur.

Verification. The ultimate success of the federal government's efforts will be measured by the overall reduction in our nation's petroleum consumption. Consequently, at any point in time, the transportation fuel SoS can only be verified as a unified whole, based on the effectiveness of the interrelated systems working together. The new SoS will be evaluated on an ongoing basis as technologies and systems are developed, improved and implemented within the SoS over time.

Phased Transition Strategy

Agricultural and forest residues like corn stover, wheat straw and forest thinnings are considered the best near-term cellulosic feedstocks because of their availability and low cost. Perennial energy crops like switchgrass and hybrid poplar are longer-term options because they require reallocation of existing land use as well as a number of years to mature before they are ready to harvest. The initial transition strategy (2007-2017), as laid out by the US Department of Energy, is focused on developing, demonstrating and deploying cellulosic ethanol. In the longer term (2017-2030), additional biofuels (e.g. biobutanol, Fischer Tropsch biofuels) will likely be incorporated as technologies are developed and the transportation fuel SoS evolves.

Using System Dynamics Understand the Transition

System dynamics is a methodology for analyzing the behaviour of complex feedback systems over time. Energy policy analysis is well suited for a system dynamics approach because designing and implementing national energy policies requires knowledge of the complexities of our nation's energy sector, along with an understanding of the cause and effect relationships of national policies on economic growth, technology development and deployment, national security, international trade, environmental sustainability and global climate change. System dynamics can help decision makers sort through the complexity of these connections by providing a framework and set of tools to investigate how and why complex real-world systems behave the way they do over time. The goal is to leverage this added understanding to design and implement more efficient and effective policies.

The Biomass Scenario Model (BSM) was developed as a prototype to investigate the dynamics associated with the potential evolutionary trajectories of a biofuels industry in the United States. The model uses a system dynamics framework, built on the STELLA software platform (ISEE, 2007), to represent the dynamic interactions of the five major systems that comprise the envisioned biomass-to-biofuels system-of-systems. The framework creates the potential to analyze and understand feedback effects between disparate processes as the industry evolves over time. The U.S. DOE Biomass Program’s overarching goal for each system in the supply chain and the objective of the corresponding BSM module are summarized in Table 2.

Table 2. Biomass Program Goals and BSM Objectives by Supply Chain Element

Supply Chain Element	Biomass Program Goal	Current BSM Module Objective
Feedstock Production	Produce large, sustainable supplies of regionally available biomass.	Provide a basis for the production of cellulosic feedstocks, respecting the constraints imposed by the agricultural land base in a manner consistent with economics.
Feedstock Logistics	Implement biomass feedstock infrastructure, equipment and systems (biomass harvesting, collection, storage, preprocessing and transportation).	Account for the cost associated with moving biomass feedstock from the point of production (i.e., farm gate) to the point of conversion (i.e., plant gate) *(Note: The current BSM focuses on feedstock transportation only—it does not account for the other logistics areas.)*
Biofuels Production	Deploy cost-effective, integrated biomass-to-biofuels conversion facilities.	Represent biomass-to-ethanol conversion process and the logic associated with the decision to add new plant to the system.
Biofuels Distribution	Implement biofuels distribution infrastructure (storage, blending, transportation, and dispensing).	No model structure currently exists around fuel transport from point to production to point of use. (The simplifying assumption is that fuel transportation will not limit the development of the biofuels industry.)
Biofuels End Use	Expand public availability of biofuels-compatible vehicles with same performance as petroleum fuels.	Represent the consumption of fuel ethanol based on the potential demand for ethanol as E10 and E85 and the impacts of vehicle mix and efficiency.

From the OBP perspective, this supply chain provides the basic framework to align and coordinate the efforts of the large and diverse group of stakeholders that will play a critical role in realizing the President's challenging biofuels goals. In the context of system dynamics, the BSM supply chain framework creates the potential to analyze and understand feedback effects between disparate processes as the industry evolves over time. A highly simplified representation of key feedbacks captured within the supply chain framework is shown below, in Figure 7.

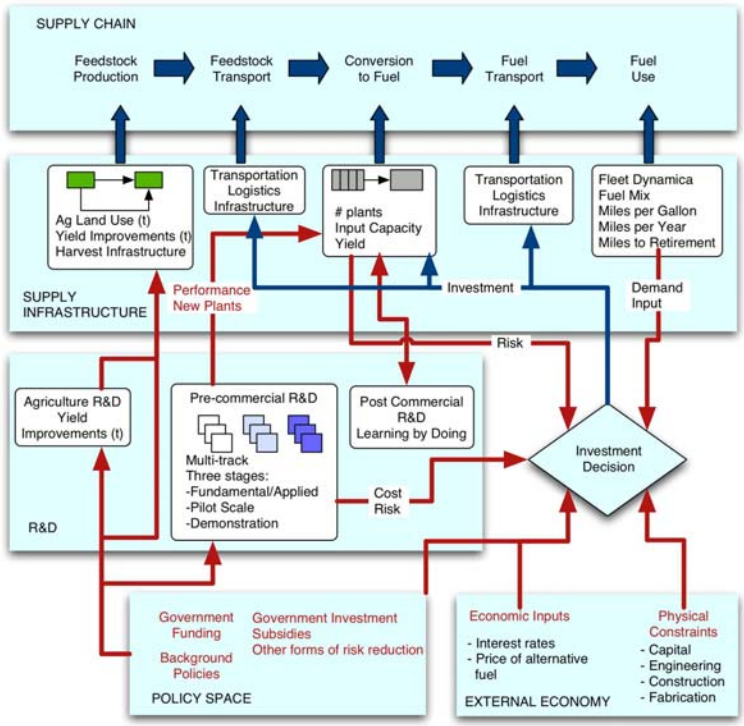

Figure 7. Schematic of Biomass Scenario Model

In the current BSM, the dynamics of the growth across the supply chain are determined by the timing of the build-up of the infrastructure associated with each system. From a System of Systems perspective, this build up of the supply chain infrastructure is the *capability* that must be deployed to realize a future biofuels industry. This capability is developed in the *context* of the competing oil market, vehicle demand for biofuels and various government policies over time. In the model, the build up of the infrastructure is determined by the dynamics of investor decisions. Investor response is driven by the performance and cost competitiveness of the fuels (which are driven by technology advancements due to R&D progress) along with the potential demand for them in the marketplace. Specific government policies and external economic factors (e.g., interest rates, price of gasoline) are evaluated as to their impact on the relative attractiveness of investing in new biofuels technology.

The logical framework for the model is based on input from stakeholders with expertise across the biomass-to-biofuels supply chain – from farming, forestry, financing, and process engineering, to transportation and automobile manufacturing. Data for the model is derived from more detailed and narrowly-focused studies of individual systems of the supply chain including feedstock logistics analyses, agricultural economics analyses, process models, life cycle assessment, economic models and market analyses. Incorporating additional aspects of the "real-world” operational context into the model will lead to a more robust characterization and improved understanding of the full impacts of transitioning to a biomass-based transportation fuel SoS. These include:

- *Environmental Context:* Key environmental issues associated with the biomass-to-biofuels system include soil sustainability, water impacts of feedstock production and conversion processes, and greenhouse gas emissions.
- *Social Context:* The success of the transition to a biofuel-based SoS is linked to society’s willingness to change – e.g., farmers must switch from cash crops to energy crops and consumers must select alternative vehicles over conventional vehicles.

Scenarios evaluated in the BSM help policy makers to envision, in broad terms, the emergence of a sustainable biomass-based industry and plausible future conditions. Its relatively intuitive nature is well suited to the “what if” scenario building needed to understand the possible paths for a new biofuels SoS. The power of the model is not primarily in the specific numbers it generates, but rather in the insight it provides into how specific actions facilitate or impede the take-off of a biomass-based transportation fuel industry.

Summary/Conclusions

A significant shift in the transportation energy sector is on the horizon as oil supplies tighten and the growth in worldwide energy demand accelerates. Increased pressure for environmentally and economically sustainable technologies and concerns about national energy security will also shape our future transportation systems. There is no single “best” solution to the transportation fuel conundrum the world is facing today. A system-of-systems framework can effectively guide this complex evolutionary process, in which advanced energy technologies and systems will be continually integrated into the existing transportation fuel infrastructure as they become commercially available. The system-of-systems approach addresses the physical systems of the transportation fuel supply chain, as independent systems and as an integrated whole, in the context of ever-changing political, economic, social and environmental conditions. The system-of-systems framework also aids in aligning and coordinating the efforts of the many diverse stakeholders that will be required to develop and implement future transportation fuel systems. The success of today’s transportation fuel transformation efforts will be determined many decades from now, by the effectiveness of new fuels, technologies and systems working together in a unified transportation fuel system-of-systems, in reducing U.S. petroleum consumption.

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Transitioning to a larger biofuels industry requires a robust biomass-to-biofuels system of systems that operates within existing agriculture, forestry, energy, and transportation markets. Using the existing fuel supply chain infrastructure as a framework, this paper discusses a vision for biomass-based fuels and the challenges associated with a massive market and infrastructure transformation.

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