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Biofuel: A Comparative Case Study

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June 2013**

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BIOFUEL: A COMPARATIVE CASE STUDY

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Submitted in partial fulfillment of the requirements for the degree of

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**NAVAL POSTGRADUATE SCHOOL
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BIOFUEL: A COMPARATIVE CASE STUDY

ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

ADM – Archer Daniels Midland

AEC – Atomic Energy Commission

BNEF – Bloomberg New Energy Finance

CEG – Clean Energy Group

CFR – Council on Foreign Relations

CO₂ – Carbon Dioxide

DoA – Department of Agriculture

DoD – Department of Defense

DoE – Department of Energy

DoN – Department of the Navy

EERE – Energy Efficiency and Renewable Energy

EIA – Energy Information Administration

EISA – Energy Independence and Security Act

EPA – Energy Policy Act

F-76/DFM – Diesel Fuel Marine

FY – Fiscal Year

IPP – Industrial Participation Program

JP5 – Jet Propulsion Fuel Five

KPP – Key Performance Parameter

LCFS – Low Carbon Fuel Standard

MILCON – Military Construction

MILPERS – Military Personnel

MIT – Massachusetts Institute of Technology

MTR – Materials Test Reactor

N₂O – Nitrous Oxide

NABTR – National Algae Biofuel Technical Roadmap

NAVAIR – Naval Air Systems Command

NDAA – National Defense Authorization Act

NEHI – National Environmental and Health Implications

NIEH – National Institute of Environmental Health

NIH – National Institute of Health

NIS – National Innovation System

NNI – National Nanotechnology Initiative

NNIN – National Nanotechnology Initiative Network

NREL – National Renewable Energy Laboratory

NSS – National Security Strategy

O&M – Operations and Maintenance

O₂ – Oxygen

OECD – Organization for Economic Cooperation and Development

OPEC – Organization of Petroleum Exporting Countries

OTA – Congressional Office of Technology Assessment

PESTEL – Political, Economic, Social, Technological, Environmental, and Legal

PRDP – Power Reactor Demonstration Program

RDT&E – Research, Development, Test, and Evaluation

RFS – Renewable Fuel Standard

RIMPAC – Rim of the Pacific

SECDEF – Secretary of Defense

SECNAV – Secretary of the Navy

SLOCs – Sea Lines of Communication

SST – Super Sonic Transport

TAC – Biomass Research and Development Technical Advisory Committee

UAE – United Arab Emirates

UN – United Nations

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I. INTRODUCTION

Rising fuel costs, Mideast turmoil, and increased environmental concerns over the last decades have left the U.S. seeking cheaper, safer, and cleaner sources of energy. One potential source receiving serious consideration is algal biofuel. While a seemingly cleaner source of energy, algal biofuel is much costlier than petroleum-based fuels because of the relative infancy of the biofuel industry. The U.S. government, as part of clean energy initiatives, and in an effort to build the biofuel industry, began purchasing algal biofuel for military use. This led us to ask the question: Can the government influence the commercialization of biofuels?

A. PURPOSE

As American's grow more environmental conscious, they desire clean sources of energy. Despite this demand, the market has failed to provide an economical source of clean energy. In response to this market failure the government has entered the market to promote the development of clean energy. One such clean energy source is biofuel. This paper evaluates the methods the government uses to promote commercialization of biofuels and recommends improvements based upon the analysis of nuclear power and nanotechnology commercialization efforts.

B. STRUCTURE

1. Background Chapter

In this chapter, we developed the basis of the government's interest in biofuels and the key actions of government. We analyzed President Obama's *Blueprint for a Secure Energy Future* (The White House, 2011) and 2010 *National Security Strategy* (The White House, 2010). In the legislative section, we explained Congress's role based on congressional ability to authorize and appropriate funds. We analyzed five laws passed by Congress specifically addressing energy initiatives. The final section reviewed the role of the Department of the Navy in biofuel development. We noted Secretary of the

Navy Mabus's vision (Mabus, 2009) for the Navy's role in the use of alternative energy sources. The chapter ends with a description of U.S. Navy biofuel operational tests.

2. Literature Review

We dedicated the literature review to familiarizing the reader with biofuels. The first section is about biofuels in general, describing the difference between first- and second-generation biofuels. The next section is a description of the algae-based biofuel industry. We looked at the maturity of the algae-based biofuel industry and discussed current production and costs. We described challenges faced by the algae-biofuel industry including the valley of death and technological barriers. Finally, we closed the chapter by addressing why government intervention is important to algae-based biofuel commercialization.

3. Methodology

The methodology chapter begins with a discussion of our choice to approach our research from a qualitative instead of quantitative perspective. We then described grounded theory and why our method used a grounded approach and case study analysis. We outlined the six steps of the case study approach and our use of the PESTEL (Political, Economic, Social, Technological, Environmental, and Legal) model during our analysis.

4. Analysis

The analysis chapter is dominated by the PESTEL analysis of nuclear power and nanotechnology. Both industries were analyzed using the PESTEL factors to identify general findings for each factor. We compared our generalized findings to alternate studies with different findings. The chapter closes with a PESTEL analysis of the biofuel industry utilizing the general findings identified in our two comparison industries.

5. Conclusion

Our final chapter summarizes our findings and provides recommendations for changes to government policies on biofuel commercialization. We included assumptions

we made throughout the course of our research and identified the limitations of our study. In closing, we identified areas for further study in relation to the biofuel industry.

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II. BACKGROUND

Why are we asking whether the government can influence the commercialization of biofuels? In this chapter, we explain the path from an initiative established by President Obama, supported by Congress, and embraced by the Department of the Navy (DoN). We also introduce plans laid out by the president, Congress, and Secretary of the Navy (SECNAV) Ray Mabus.

A. EXECUTIVE BRANCH

Following his inauguration on January 20, 2009, President Obama inherited a country with rising energy imports, consumption, and costs. Recognizing the growing dependence on energy within the United States, he developed several policies to reduce America's energy dependence and charged the federal government with leading the energy revolution.

1. National Security Strategy

Published in May 2010, the *National Security Strategy* (The White House, 2010) calls for the development of clean energy technology. In the NSS (2010), President Obama stated,

The United States has a window of opportunity to lead in the development of clean energy technology. If successful, the United States will lead in this new Industrial Revolution in clean energy that will be a major contributor to our economic prosperity. If we do not develop the policies that encourage the private sector to seize the opportunity, the United States will fall behind and increasingly become an importer of these new energy technologies.

We have already made the largest investment in clean energy in history, but there is much more to do to build on this foundation. We must continue to transform our energy economy, leveraging private capital to accelerate deployment of clean energy technologies that will cut greenhouse gas emissions, improve energy efficiency, increase use of renewable and nuclear power, reduce the dependence of vehicles on oil, and diversify energy sources and suppliers. We will invest in research and next-generation technology, modernize the way we distribute electricity,

and encourage the use of transitional fuels, while moving towards clean energy produced at home. (The White House, 2010, p. 30)

The president's vision established a national strategy based on a foundation of clean, efficient, renewable, domestically produced energy.

2. Blueprint for a Secure Energy Future

In 2011, President Obama further expanded his energy policy by publishing the *Blueprint for a Secure Energy Future* (The White House, 2011), in which he directly challenged Congress and members of his administration to create lasting energy policies. In *Blueprint for a Secure Energy Future* (The White House, 2011), he stated,

Every President since Richard Nixon has called for America's independence from oil, but Washington gridlock has prevented action again and again. If we want to create a more secure energy future, and protect consumers at the pump, that has to change. (p. 3)

President Obama's efforts towards lasting energy policies and independence from oil are a result of decreasing domestic oil production, increasing consumption, and increased importing of oil. U.S. petroleum consumption increased by 227% from 1949 to 2011. Domestic petroleum production has fallen by 42% from peak production in 1970, while imports have increased by 2,553% since 1949. Figure 1 shows U.S. petroleum consumption, production, and net imports from 1949 to 2011. Petroleum net imports increased at a greater rate than consumption from 1985 through 2005 (Callahan, 2011, p. 6).

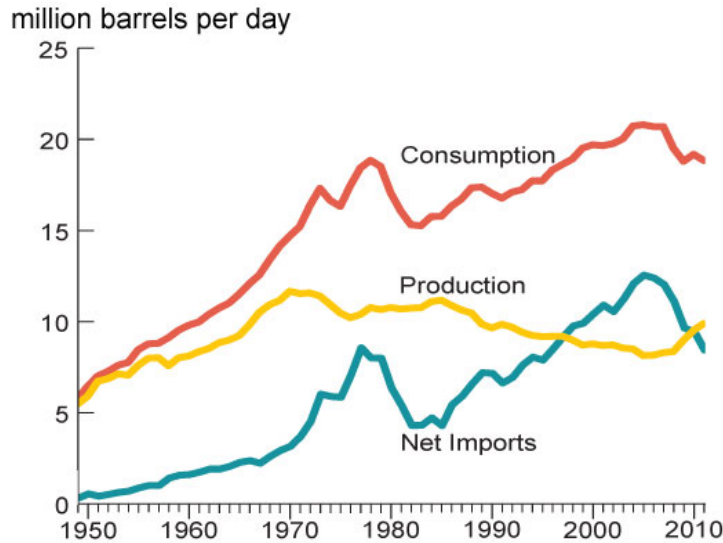


Figure 1. United States Petroleum Consumption, Production, and Imports, 1949–2011
(From Energy Information Administration [EIA], 2011)

To achieve U.S. independence from oil, the *Blueprint for a Secure Energy Future* (The White House, 2011) establishes a three-part strategy to achieve the president’s vision:

Develop and secure America’s energy supplies: We need to deploy American assets, innovation, and technology so that we can safely and responsibly develop more energy here and at home and be a leader in the global energy economy.

Provide consumers with choices to reduce costs and save energy: Volatile gasoline prices reinforce the need for innovation that will make it easier and more affordable for consumers to buy more advanced and fuel efficient vehicles, use alternative means of transportation, weatherize their homes and workplaces, and in doing so, save money and protect the environment. These measures help families’ pocketbooks, reduce our dependence on finite energy sources and help create jobs here in the United States.

Innovate our way to a clean energy future: Leading the world in clean energy is critical to strengthening the American economy and winning the future. We can get there by creating markets for innovative clean technologies that are ready to deploy, and by funding cutting edge research to produce the next generation of technologies. And as new, better, and more efficient technologies hit the market, the Federal government needs to put words into action and lead by example. (p. 4)

The *Blueprint for a Secure Energy Future* (The White House, 2011) demonstrated the president's commitment to the development of new energy technologies and his desire for the federal government to lead the innovation of new technologies in energy production, specifically in the development of alternatives to imported petroleum. But Congress holds the purse strings, so while the president guides the country's policy, Congress determines when and how that policy is funded.

B. LEGISLATIVE BRANCH

Article I of the United States Constitution gives Congress the power to control funding for the federal government. In the execution of this duty, Congress authorizes and appropriates funds for the operation of the government, including the Department of Defense (DoD).

1. Congressional Interest in DoD Petroleum Usage

The DoD is the largest government user of energy, accounting for 80% of government energy usage. Petroleum-based fuels represent 71% of all energy used by the DoD (Schwartz, Blakeley, & O'Rourke, 2012, p. 2).

In fiscal year (FY) 2011, the DoD consumed 117 million barrels of petroleum, down from 122 million barrels in FY2005. Spending on procurement of petroleum during the same time period increased from \$4.5 billion in FY2005 to \$17.3 billion in FY2011 (Schwartz et al., 2012, p. 2). Figure 2 shows the relationship between DoD petroleum usage and petroleum spending.

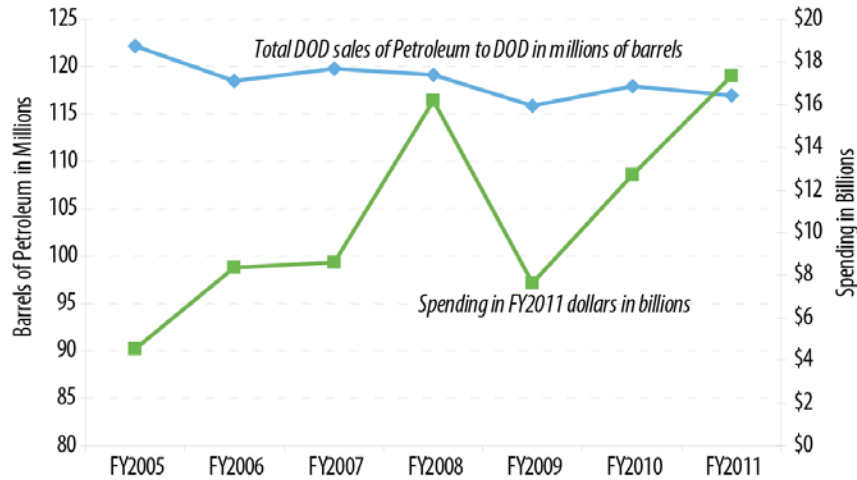


Figure 2. DoD Petroleum Spending and Consumption, FY2005–2011 (From Schwartz et al., 2012)

Between FY2005 and FY2011, the DoD experienced a 381%, or \$12.8 billion, increase in petroleum spending. Petroleum energy spending represents 2.5% of total DoD outlays for FY2011, compared to 1.1% of total DoD outlays for FY2005 (Schwartz, et al., 2012, p. 3).

2. Congressional Petroleum Energy Initiatives

Congressional interest in DoD petroleum spending is expected to remain high, throughout the foreseeable future, due to continually rising fuel prices. In response to rising petroleum costs, Congress passed several laws focused on reducing government energy use and encouraging the use of renewable energy. Congress defines *renewable energy* as energy coming from biomass, geothermal, wind, solar, and hydropower sources (EIA, 2008, p. iii).

a. Energy Policy Act of 2005

The Energy Policy Act (EPA) of 2005 mandates that future government purchases of energy include renewable energy at the rate of 3% between FY2007 and FY2009, 5% between FY2010 and FY2012, and 7% for FY2013 and beyond. The EPA does not include provisions on the type and use of renewable energy purchased, but does

include economic incentives including grants, income tax credits, subsidies, and loans to promote biofuel research.

b. Energy Independence and Security Act of 2007

The Energy Independence and Security Act (EISA) of 2007 further revises the requirements for government purchase of renewable energy. The EISA prohibits the purchase of renewable fuels, including biofuels, from sources that emit greenhouse gasses in excess of traditional petroleum production, except for research and development. Federal agencies must also reduce annual petroleum consumption by 20% and increase annual renewable fuel consumption by 10%, relative to the FY2005 baseline. The EISA also establishes the first biofuel production standards, requiring 9 million gallons of biofuel production by 2008 and 36 million gallons by 2022.

c. National Defense Authorization Act of 2007

The National Defense Authorization Act (NDAA) of 2007 was the first legislation passed applying to only the DoD. The 2007 NDAA requires the DoD to improve the fuel efficiency of weapons platforms in order to enhance performance, reduce the fuel logistics system, reduce the burden of high fuel consumption on agility, reduce operating costs, and dampen the financial impact of volatile oil prices. It also requires the Secretary of Defense (SECDEF) to conduct a study examining the feasibility of using renewable energy to provide electricity for expeditionary forces.

The 2007 NDAA does not directly require the DoD to adopt the usage of renewable fuels. It does demonstrate Congress's commitment to increased fuel efficiency and recognizes the impact oil prices have on the operation of the DoD.

d. National Defense Authorization Act of 2009

The 2009 NDAA requires the DoD to consider the requirements for, and vulnerability of, fuel logistics during force planning and analysis. It also requires the establishment of fuel efficiency key performance parameters (KPPs) in the development or modification of existing systems. Finally, it requires that life-cycle cost analysis for

new systems include calculation of the fully burdened cost of fuel and an analysis of alternative fuels during acquisition program design.

The 2009 NDAA reconfirms congressional desire for a more fuel-efficient DoD. The establishment of formal fuel efficiency KPPs, including for renewable fuels, is consistent with congressional and presidential interests.

e. National Defense Authorization Act of 2010

The NDAA of 2010 requires the DoD to produce or procure 25% or more of facility electricity from renewable energy no later than FY2025.

Congress authorized and established funding required for meeting the president's goals, but who is taking the lead in these endeavors? Although this is a DoD-wide initiative, the Navy, under Secretary Ray Mabus, is leading the effort.

C. DEPARTMENT OF THE NAVY

In 2009 the SECNAV, Ray Mabus, outlined a five-step vision for the U.S. Navy adoption of biofuels and alternative energy technology. His vision is a direct response to presidential and congressional mandates, and recognition of the strategic and tactical limitations of traditional petroleum. In a 2009 speech to the Naval Energy Forum, Secretary Mabus (2009) said the following about our strategic dependence on petroleum:

We know oil is a limited resource. We buy from volatile areas of the world. Over time, the price keeps going up. The use of oil creates harmful environmental effects. And to a certain extent we have ceded this to other nations who are allowed to exert disproportionate influence as a result. This creates an obvious vulnerability to our energy security, and to our national security, and to our future on this planet. (p. 2)

In the same speech, Secretary Mabus (2009) also commented on the tactical implications of petroleum use. He said,

Fossil fuel consumption has a deep impact upon our forces and our force structure, both in terms of the resources required to get fuel and to move it to the ships, tanks, aircraft, and equipment that need it, and in the Sailors and Marines whose duty it is to protect the ships or convoys moving the gas. We do not have operational independence and we are tied to a vulnerable logistics tail. (p. 2)

The DoN is the second largest user of petroleum within the DoD; the Air Force is the primary user. Figure 3 shows the percentage of DoD petroleum usage by Service.

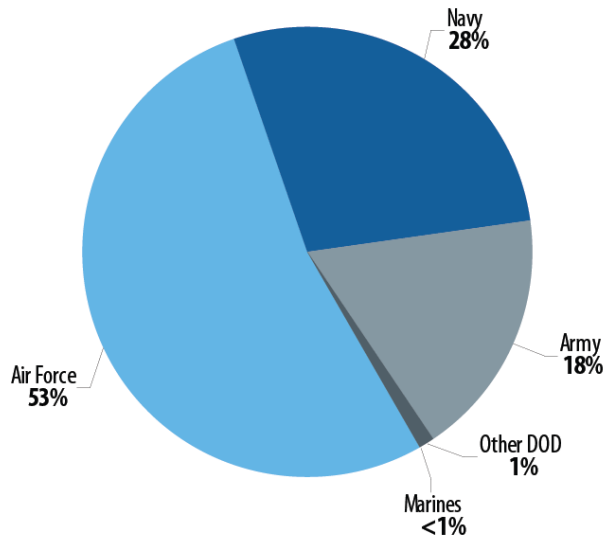


Figure 3. DoD Petroleum Usage by Service, FY2011 (From Schwartz et al., 2012)

DoN energy use differs from other the Services and the DoD. According to Schwartz et al. (2012),

The Department of the Navy is less dependent on petroleum than the Air Force and the Army for meeting its energy needs, in part because all of the Navy’s aircraft carriers and submarines are nuclear-powered. In FY2010, the Department of the Navy met 59% of its overall energy needs from petroleum, 22% from nuclear-powered ships, and 19% from electricity. Aircraft operations account for 54% of the Navy’s use of petroleum fuels, ships account for 43%, and non-tactical uses account for 3%.

Since FY2003, the DoN has reduced energy usage by 15.8%; most energy reduction occurred at the installation energy level (DoD, 2012, p. 19).

1. Leading Energy Change

In the same 2009 speech to the Naval Energy Forum, Secretary Mabus (2009) reminded the audience of the Navy’s role in leading change in the seagoing industry. He said,

Leading change is not new for the Department of the Navy. We have done so repeatedly in the adoption of new technologies to power our ships. And resistance to change is not new either. In the middle of the nineteenth century the Navy traded wind for steam and the ability to maneuver in any direction at will. Naysayers swore at that point the Navy was giving up a sure means of propulsion in favor of uncertain, dangerous, and probably infernal machines. The naysayers were wrong.

Forty years later, the liquid fuel board recommended that the Navy shift from coal to oil, which has twice as much thermal content and granted the ability to produce higher speeds in ships crewed by fewer sailors. Once again, traditionalists argued against adoption because the late-nineteenth century American Navy had already built a network of coaling stations around the world and established infrastructure built around coal. Again they were wrong. The Navy persevered. Oil created a tactical advantage; it allowed ships to stay at sea longer, replenish themselves underway from oilers rather than import from coal bunkers, and oil reduced the need for ships to maintain huge divisions of stokers. (p. 4)

Secretary Mabus (2009) clearly demonstrated his willingness to explore new renewable fuel technologies, including biofuel, despite resistance by members of Congress, industry, and the public. Establishing Navy renewable energy and biofuel is a primary concern of Secretary Mabus. To meet the presidential and congressional energy mandates, he established a five-step process. In his 2009 speech to the Naval Energy Forum he described the five steps:

- Change the way the Navy and Marine Corps award energy contracts to include lifetime energy costs of a system as a mandatory evaluation factor.
- Demonstrate by 2012 a Green Strike Group consisting of nuclear vessels and ships powered by biofuel.
- By 2015, reduce the petroleum use in the Navy commercial vehicle fleet by replacing vehicles with flex fuel, hybrid, and electric vehicles.
- By 2020, produce at least 50% of shore-based energy from alternative sources.
- By 2020, 50% of energy consumption for ships, aircraft, tanks, and tactical vehicle should come from alternative energy. (Mabus, 2009)

2. Alternative Operational Energy Progress

Meeting alternative energy requirements for operational units has presented a unique challenge for the Navy. In order to use biofuel in Naval aircraft and ships, the

Navy requires biofuel to be a 50/50 blend with either jet propulsion fuel five (JP-5) for aircraft or diesel fuel marine (F-76 or DFM) for ships, to demonstrate no noticeable difference in performance, and to require no changes to the existing fuel delivery and storage infrastructure (Naval Air Systems Command [NAVAIR], 2012).

a. *Naval Aviation Biofuel*

Naval Air Systems Command (NAVAIR) was the first naval organization to successfully test and demonstrate the viability of 50/50 biofuel mixes. Between 2010 and 2012, the following aircraft types were successfully flown on biofuel:

- F/A-18D Hornet
- F/A-18 E/F Super Hornet
- E/A-6B Prowler
- MH-60S Seahawk
- MV-22 Osprey
- AV-8B Harrier
- MQ-8B Fire Scout, and
- T-45 Goshawk (NAVAIR, 2012).

Further testing of biofuels in an operational environment occurred during the 2012 Rim of the Pacific (RIMPAC) exercise. Throughout the RIMPAC, Carrier Air Wing Eleven operated on a 50/50 biofuel mix for the first time.

b. *The Great Green Fleet*

Meeting the SECNAV's requirement to demonstrate the viability of biofuels in an operational environment occurred July 19 and 20, 2012. As part of the annual RIMPAC exercise, the Navy demonstrated the SECNAV's Great Green Fleet. The Great Green fleet consisted of

- USS *Nimitz* (CVN-68) and Carrier Air Wing Eleven,
- USS *Chaffee* (DDG-90),
- USS *Chung Hoon* (DDG-93),
- USS *Princeton* (CG-59), and
- USS *Henry J. Kaiser* (TAO 187; DoN, 2012).

In the demonstration, the USS *Nimitz* strike group burned 350,000 gallons of a 50/50 blended F-76 biofuel, while Carrier Air Wing Eleven burned 100,000 gallons of 50/50 blended JP-5 biofuel (DoN, 2012). The *Henry J. Kaiser* successfully demonstrated at-sea refueling by replenishing the strike group with both F-76 and JP-5 biofuel blends. The RIMPAC successfully evaluated biofuels in an operational environment, proving the feasibility of biofuels for military applications.

In this chapter, we discussed presidential interest and the strategic implications of biofuel for the United States. We explored U.S. law and congressional incentives for the development of commercial biofuels. Finally, we discussed the Navy's early acceptance and adoption of biofuels, including the Navy's biofuel adoption timeline. In the next chapter, we look at the history of biofuels, including the current production, cost, and output. Additionally, we discuss the difficulty the biofuel industry faces in moving from a viable production process to commercial viability before ending with the reasons why the U.S. government is interested in the commercial viability of biofuels.

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III. LITERATURE REVIEW

A. BIOFUELS

Biofuel energy is one of many options for non-carbon-producing energy currently under exploration to replace fossil fuels (Patil, Tran, & Giselrød, 2008). Industry divides biofuels into two types: first generation and second generation. In this chapter, we discuss the differences between first- and second-generation biofuels, the state of the biofuel industry, challenges to the commercialization of biofuel, and the benefits of biofuel development.

1. FIRST-GENERATION BIOFUELS

First-generation biofuel sources include traditional food items such as potatoes, corn, sugar, and various vegetable and seed oils. Commonly known, these fuels include ethanol, biodiesel, and pure plant oil (Havlik et al., 2011). These fuels, mixed with fossil fuels such as gasoline and used in everyday engines or in flex fuel vehicles or natural gas vehicles, are available commercially in limited quantities through the normal infrastructure (Naik, Goud, Rout, & Dalai, 2010). There are two major issues associated with first-generation biofuels. The use of food staples in production leads to increases in worldwide food prices, and the production of first-generation biofuel have a myriad of potential negative environmental impacts.

a. Rising Food Prices

Using crops in alternative fuel production means less food is available for sale on the market, increasing the price of food (Naik et al., 2010). In the *OECD-FAO Agricultural Outlook 2007–2016*, the Organization for Economic Cooperation (2007), in conjunction with the United Nation’s Food and Agriculture Organization, cited first-generation biofuels as a reason for long-term worldwide food price increases:

Currently strong world market prices for many agricultural commodities in international trade are, in large measure, due to factors of a temporary nature, such as drought related supply shortfalls, and low stocks. But, structural changes such as increased feedstock, demand for biofuel

production, and the reduction of surpluses due to past policy reforms, may keep prices above historic equilibrium levels during the next 10 years. (p. 10)

The report continues, addressing the effects on developing countries, urban populations, and livestock farmers:

Higher commodity prices are a particular concern for net food importing developing countries as well as the poor in urban populations, and will evoke on-going debate on the “food *versus* fuel” issue. Furthermore, while higher biofuel feedstock prices support incomes of producers of these products, they imply higher costs and lower incomes for producers that use the same feedstock in the form of animal feed. (Organization for Economic Cooperation, 2007, p. 10)

b. Environmental Effects

Environmental issues, specifically greenhouse gas emissions, are part of the push to develop first-generation biofuels. Ironically, this same development is leading to new ecological concerns. Changes in land use and concerns about rising greenhouse gases are the primary environmental issues arising from production of first-generation biofuel.

Land is a scarce resource. As demand for food crop biofuels increases, farmers worldwide are clearing and cultivating forests and grasslands previously left untouched (Fargione, Hill, Tilman, Polsky, & Hawthorne, 2008). Clearing these lands releases carbon stored in the vegetation. The carbon removal capacity of this vegetation is lost, effectively increasing carbon emissions into the atmosphere (Searchinger et al., 2008). Figure 4, from the article “Land Clearing and the Biofuel Carbon Debt” (Fargione et al., 2008), illustrates the time required to remove carbon emissions caused by this increased land use.

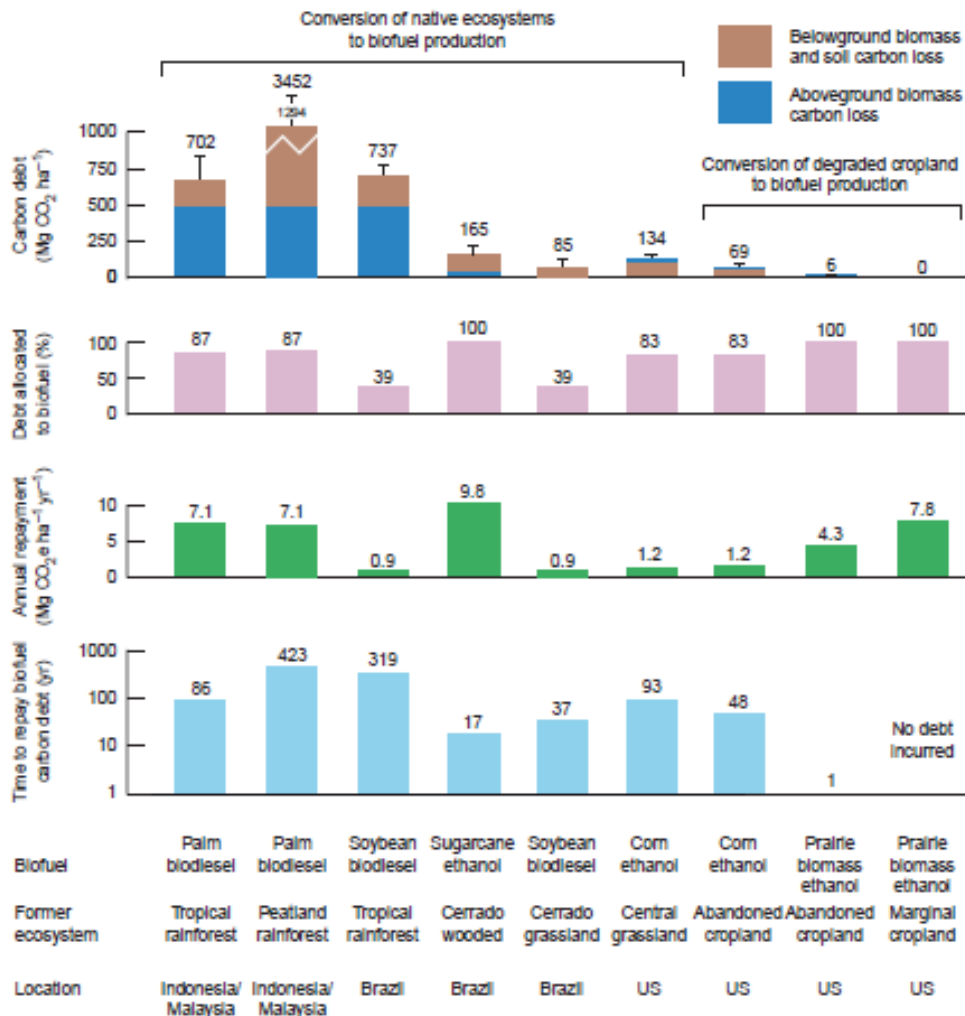


Figure 4. Carbon Debt, Biofuel Carbon Debt Allocation, Annual Carbon Repayment Rate, and Years to Repay Biofuel Carbon Debt for Nine Scenarios of Biofuel Production (From Fargione et al., 2008)

Carbon emissions are not the only greenhouse gases released during the production of biofuels. The use of chemical fertilizers to grow first-generation biofuel feedstock generates nitrous oxide (N₂O), which affects the ozone and has a global warming potential 296 times greater than that of carbon dioxide (CO₂; Crutzen, Mosier, Smith, & Winiwarter, 2008). N₂O released from fertilizer application during feedstock growth for biofuel production is three to five times greater than originally believed (Crutzen et al., 2008). Emissions of N₂O offset reductions in greenhouse gases experienced when switching between petroleum and biofuel (Crutzen et al., 2008).

2. SECOND-GENERATION BIOFUELS

Second-generation biofuels come from lignocellulosic feedstock, jatropha, and algae (Carrquiry, Du, & Timilsina, 2010). Second-generation biofuels do not compete for land because they are by-products or waste products. Those that do, such as jatropha and switch grass (a lignocellulosic feedstock), can be grown on marginal lands (Havlik et al., 2010).

a. Lignocellulosic Feedstock

Lignocellulosic feedstock comes from three sources: food crop by-products, forestry by-products, and grass or wood energy crops. Sugars from these become bioethanol through fermentation and processing (Carrquiry et al., 2011). Food crop by-products come from various crops including corn, rice, and sugarcane. Forestry by-products originate from logging, fuel wood removal, and wood processing mills. Grass crops include switch grass and alfalfa, while wood energy crops come from fast-growing trees such as poplar and eucalyptus (Carrquiry et al., 2010).

b. Jatropha

Jatropha is an oilseed-producing bush capable of growing in different climates and in good or poor soil. The bush is native to the Americas, but also grows in Asia and Africa (Carrquiry et al., 2011). Under the right conditions, jatropha produces large amounts of burnable oil with a high potential for use in biodiesel (Carrquiry et al., 2011).

c. Algae

Algae, and specifically micro-algae, are not a new source of biofuel. The National Renewable Energy Laboratory (NREL) experimented with algae from the late 1970s to the mid-1990s (Carrquiry et al., 2011). Algae are extremely efficient in biofuel production. They thrive on various types of water and land, making them very versatile (Carrquiry et al., 2011). High per acre productivity makes this an attractive source. Table 1 shows a comparison of fuel oil yields between two types of micro-algae and four different oilseeds.

Plant Source	Oil yield (L/ha/yr)
Soybeans	446
Rapeseeds/Canola	1,190
Jatropha	1,892
Palm	5,950
Algae ^a	12,000–98,500
Algae ^b	58,700–136,900

Table 1. Oil Yields of Algae and Other Seeds (From Carriquiry et al., 2011)

Note. ^a Range from 10 g/m²/d at 30% Triacylglycerids (TAG) to 50 g/m²/d at 50% TAG. ^b Range from 30% to 70% oil by weight in biomass.

B. ALGAE-BASED BIOFUEL INDUSTRY

The DoN’s use of 450,000 gallons of biofuels made from a combination of used cooking oils and algae as drop-in to create a 50/50 blend with petroleum signals the U.S. Navy’s continued commitment to meeting Secretary Mabus’ goal of deploying a Great Green Fleet in 2016 (NAVAIR, 2012). For this project, we focus on algae-based biofuel. Oil yields from algae, as shown in Table 1, are exponentially higher than yields from other second-generation feedstock. Higher oil yields from algae make it the preferred second-generation feedstock for the biofuel industry.

1. History

The idea to use algae as a fuel source originated at the Massachusetts Institute of Technology (MIT) in the 1950s (Climate Institute, 2012). The oil embargo of the 1970s served as the catalyst for the first serious investigation into the viability of algae as a source of energy (Department of Energy [DoE], 2010).

a. Aquatic Species Program (1978–1996)

The DoE’s Aquatic Species Program is one of the most thorough investigations into the use of algae as a fuel source (DoE, 2010). The program ran from 1978 to 1996. The program originally focused on using algae as a hydrogen source, but shifted to biodiesels in the early 1980s (Sheehan, Dunahay, Benemann, & Roessler, 1998). Over this 18-year period, the United States invested about \$25 million in the program (DoE, 2010). During this time, the program collected 3,000 types of microalgae.

The samples came from throughout the United States and varying environments. Researchers then narrowed the collection to a tenth of its original size, identifying the 300 algae types with oil production possibilities (DoE, 2010). The program also looked at various resources, including types of land, water, and power plants. It was determined that ample production resources existed to compete with petroleum use in the United States (DoE, 2010). The DoE shut down the Aquatic Species Program in 1995 due to funding cuts, but not before demonstrating that algae is a viable source of oil (DoE, 2010; Sheehan et al., 1998).

b. Post-Aquatic Species Program (1996–Present)

Government algal biofuel funding now originates in numerous governmental agencies. The DoD, Department of Agriculture (DoA), and DoE all provide funding for algal research (DoE, 2010). In 2002, the DoE started the biomass program with the aim to consolidate biofuel, bio-product, and bio-power research efforts (DoE, 2012). The DoE biomass program has four main goals:

- reduce dependence on foreign oil;
- promote the use of diverse, domestic, and sustainable energy resources;
- establish a domestic bioenergy industry; and
- reduce carbon emissions from energy production and consumption (DoE, 2012).

Additionally, the DoA and the DoE, in conjunction with the DoN, are working together to develop biofuels that can be used with petroleum after a challenge by President Obama to speed the process along (The White House, 2011). However, the government is not alone in this endeavor. Private companies are also pouring money into developing algal biofuels (DoE, 2010). Significant public and private investment lead one to ask the following question: With all of this money floating around, how developed is the algal biofuel industry base?

2. Current Production and Pricing

In the last section, we asked about the status of the algal biofuel industrial base. Figure 5 illustrates the stages of technology development. Currently, the advanced

biofuel industry is entering the latter half of the commercialization “valley of death,” Stage 4 (Solecki, Dougherty, & Epstein, 2012).

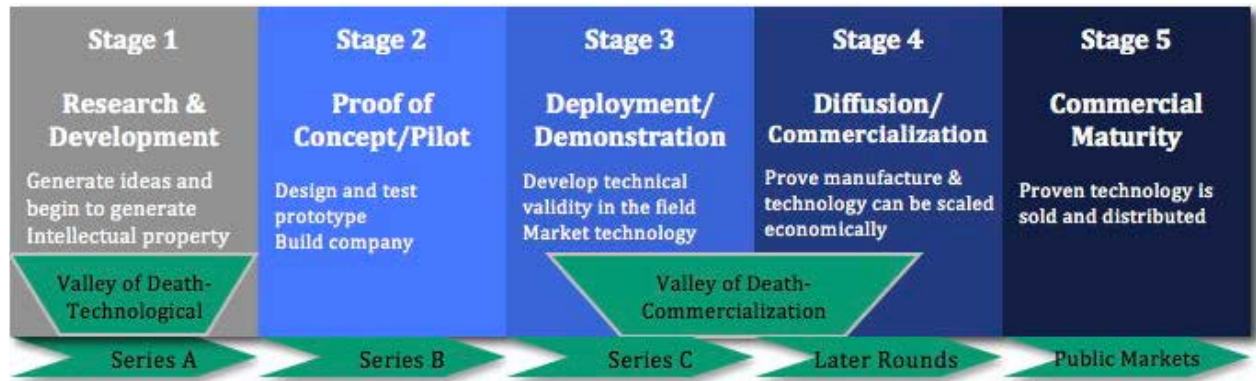


Figure 5. Stages of Technology Development (From Solecki et al., 2012)

So what is the commercialization “valley of death”? For advanced biofuels, the Bloomberg New Energy Finance (BNEF, 2010) report *Crossing the Valley of Death* defined it as the following:

In this phase, entrepreneurs face the dangerous convergence of high cash demands and a significant scarcity of capital. Without directly addressing this important market disconnect, clean energy deployment cannot move forward at the pace the climate challenge demands. (p. 5)

a. Production

The *Advanced Biofuel Market Report for 2012* (Yudken, 2012) lists 74 companies involved in producing high-end advanced biofuels; only seven list algae or algae oil as a feedstock. The 2012 combined capacity of these companies is 870 thousand gallons, or about 0.7% of the total of the 125.48 million gallons of high-end advanced biofuels. The report projects a total algae biofuel production of 186 million gallons by 2015, a nearly 214-fold increase in three years. That total makes up approximately 10% of the total advanced biofuels production for 2015 (Solecki et al., 2012).

b. Costs

In 2010, a gallon of algae-based drop-in biofuel cost \$455 per gallon (Universal Technology Corporation, 2010). In late 2011, the U.S. Navy paid \$26 per

gallon of algae-based drop-in biofuels (Solecki et al., 2012). Although this is 17.5 times cheaper than the previous year, it is still nearly 9.5 times higher than the \$2.75 per gallon cost for military-grade diesel (Andrews, Bracmort, Brown, & Else, 2012). What many fail to consider is the fact that the companies produced the drop-in biofuels for these cases in small quantities for testing purposes, not in the large quantities normally associated with petroleum use (Yudken, 2012). The basic cost structure for algal biofuels mimics the cost structure of traditional oil production. Algal biofuel production is dominated by high fixed costs and relatively low variable costs. Approximately two thirds of all costs associated with the production of algal biofuels are fixed costs (Davis, Aden, & Pienkos, 2011).

Current demand for algae-based drop-in biofuels is difficult to find. In late 2011, the U.S. Navy purchased 450,000 gallons of an algae and non-food-waste advanced biofuel for use in a Green Strike Group (Andrews et al., 2012). Current administration goals require 50% of the Navy’s fuel to be alternative fuels. Estimates place this at approximately 336 million gallons per year (DoD, 2011). Table 2 shows the projected DoD demand through 2020.

Projected demand	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Army	—	—	—	—	—	—	—	—	16.05	19.26	22.47
Air Force	0.40	0.40	0.40	0.40	129.43	258.47	387.50	387.50	387.50	387.50	387.50
Navy	0.19	0.32	0.45	0.45	0.56	1.12	1.68	84.00	168.00	252.00	336.00
Total DoD	0.59	0.72	0.85	0.85	129.99	259.59	389.18	471.50	571.55	658.76	745.97

Table 2. DoD Total Tactical Renewable Fuel Demand by Year (Million Gallons) (DoD, 2011)

3. Industry Challenges

The algae biofuel industry faces many challenges as companies try to jump start a fledgling industry. Lack of funding at critical junctures and a need to lower costs to compete with traditional petroleum coupled with the discovery of new oil sources and the potential for the United States to become a net exporter of oil create a condition ripe for this industry to fail. Here we discuss these issues and the threats they pose to the algae biofuel industry.

a. Valley of Death

Investopedia (Valley, 2012) defines the valley of death as “a slang phrase used in venture capital to refer to the period of time from when a startup firm receives an initial capital contribution to when it begins generating revenues.” This phrase describes the difficulties, created by a lack of capital, facing a new technology traversing from the product development phase to the commercial phase. Progress from the research phase to the commercial phase for a new technology is difficult because it must cross the so-called commercialization valley of death, a phenomenon mainly caused by a lack of capital investment (BNEF, 2010).

In March 2009, the Clean Energy Group (CEG) and Bloomberg New Energy Finance (BNEF) carried out a one-year study named *Crossing the Valley of Death: Solutions to the Next Generation Clean Energy Project Financing Gap* (BNEF, 2010) with two purposes:

- to survey and size the valley of death, and
- to examine potential financial or policy mechanisms that might allow companies to successfully negotiate it (BNEF, 2010).

This valley of death, situated between the pilot stage and the commercial stage, exists due to a lack of capital when the company or industry is experiencing a high demand for cash to purchase equipment, placing companies in an investment risk/reward category that is too risky for most banks and venture capitalists (BNEF, 2010).

Accordingly, the only potential investor with not only the capital, but also the responsibility to finance this type of endeavor is a government. Moreover, government involvement in the development of new technology is not unprecedented. Nuclear power is one of many industries nurtured through its early stages by the government (BNEF, 2010). However, financing is not and should not be the only support the government provides to an industry as it peers into the valley of death. Laws and commercial backing that show the government leading the way in the use of new technology help create and increase demand (BNEF, 2010).

The *Advanced Biofuel Market Report* (Solecki et al., 2012) discusses industry production and growth versus future demand for low carbon fuels, while

identifying stability as the primary hurdle to industry growth. Baseline stability can be established through government policy and funding programs. Government funding addresses the next barrier to industry growth, financing (Solecki et al., 2012).

The first major U.S. policy for biofuel stability was the renewable fuel standard (RFS) initially established by the Energy Policy Act of 2005, which led to the opening of multiple biofuel refineries in recent years (Solecki et al., 2012). The successor to this policy, RFS2, requires that 36 billion gallons of renewable fuel be blended with gasoline by 2022. The policy also divides the renewable fuels into four categories, capping some that may have an effect on food prices. These caps effectively create a demand for advanced biofuels (such as algae biofuels), thus helping to expand the market for advanced biofuels and removing some of the entry barriers and risks for potential investors (Solecki et al., 2012).

California's low carbon fuel standard (LCFS) is another important policy initiative (Solecki et al., 2012). The LCFS requires a 10% reduction in carbon intensity of California's transportation fuel by 2020. The program allows producers to determine the method they choose to meet the requirements, but also encourages producers to exceed the requirements by granting credits. Granting credits creates competition among producers, leading to industry advancement and expansion (Solecki et al., 2012).

The RFS2, LCFS, and similar policies strengthen the industry by providing a steady environment. Steady policies encourage banks and companies to provide the necessary capital to increase production and capacity (Solecki et al., 2012).

Encouragingly, some companies look to be successfully navigating the valley of death. Publicly traded Solazyme, a San Francisco-based company, recently secured \$120 million in funding to build a joint-venture algae biofuel plant with the Brazilian agriculture company Bunge (Fehrenbacher, 2013). Construction began in 2012 with initial production expected in the fourth quarter of 2013. Anticipated annual production levels start at 100,000 metric tons in 2014, with expected growth to 300,000 metric tons per year (Fehrenbacher, 2013). Solazyme is also nearing commercial scale in the United States. Solazyme and Archer Daniels Midland (ADM), an Illinois-based

agriculture company, expect to produce 20,000 metric tons in 2014 at a factory in Clinton, Iowa, with a future production goal of 100,000 metric tons annually (Fehrenbacher, 2013).

Two other companies expected to cross the valley of death are Sapphire Energy and Synthetic Genomics. Both companies use open-air ponds to grow algae (Fehrenbacher, 2013). Sapphire Energy's Columbus, New Mexico, site consists of 70 ponds and a refinery expected to produce 1.5 million gallons annually by 2014, with an expected daily production of 10,000 barrels by 2018 (Fehrenbacher, 2013). Synthetic Genomics, with \$600 million in funding from Exxon, will begin testing synthetic algae strains at its 81-acre site in Imperial Valley in California (Fehrenbacher, 2013).

b. Technological Barriers to Commercialization

In 2008, the DoE sponsored a workshop to discuss and study the technological barriers to biofuel commercialization. The end product of this workshop was the National Algal Biofuels Technology Roadmap (NABTR), which categorized the two main technological challenges facing algae biofuel (DoE, 2010) as follows:

- algae feedstock production and supply, and
- algae feedstock processing and conversion.

Building on the work of the NABTR, Gao, Gregor, Liang, Dawei and Tweed published a 2012 article titled "Algae Biofuel—A Feasibility Report" that confirmed the findings of the NABTR. Gao et al. (2012) also found that current production of algae biofuel is limited to small-scale production; therefore, the cost information associated with this level of production is not a reliable indicator of the true costs for commercial-scale production.

(1) Algae Feedstock Production and Supply

All algae have the potential to serve as biofuel feedstock; however, each type of algae has a unique set of requirements within the supply chain. The unique supply chain requirements of the algae types require significant investment in infrastructure and a commitment to a specific algae type (DoE, 2010). Among the algae species, *Botryococcus braunii* has shown the most promising results in small-scale

laboratory production; however, it has not been cultivated in large-scale production. Research into algae species and the associated oil production is not complete with many new algae species promising to deliver greater oil yields (Gao et al., 2012). With continued discovery and genetic enhancement of algae types, industry is reluctant to commit large amounts of capital to establish a unique and expensive supply chain for an algae type that may not be the best for use in commercial production (Gao et al., 2012). Until a standard algae type is found, investment in commercial algae production is expected to remain low.

Selection of an algae type is only the first step in the production process. Cultivation of algae for biofuel requires nutrients, water treatment, and water recycling. At the laboratory level, the cultivation of algae is relatively inexpensive (DOE, 2010); however, serious technical barriers exist when attempting to cultivate algae at a commercial scale. The costs associated with creating a dedicated algae cultivation system increase exponentially with capacity. Using the existing agriculture system to grow algae is possible and seems economically viable; however, algae are extremely sensitive to pathogens, chemical compounds, and heavy metals found in most commercial agriculture. Algae's largest advantage as a biofuel feedstock is the ability to grow it on land not dedicated to food production. Using the existing agricultural system removes this advantage. The alternative to using the existing agricultural system is the development and use of artificial algae ponds. At this time, the large-scale creation, use, and maintenance of algae ponds requires further study (DoE, 2010).

Two types of algae ponds exist, closed and open. In the closed-pond system, algae are completely isolated from the outside environment through the use of growth tanks. All nutrients and waste are introduced and removed from the closed pond in a very controlled manner, minimizing the possibility of outside contamination. Closed systems slightly improve algae yield, but do so at a very high capital cost. The open-pond system is not isolated from the outside environment. Nutrients and waste are controlled, but the possibility of contamination from the environment is high. Although open-pond systems have a lower algae yield compared to closed-pond systems, they also have significantly lower capital cost. It is generally accepted that open-pond systems are

the preferred algae cultivation method (Gao et al., 2012). In the rest of this section, we focus on the technological challenges associated with open-pond systems.

The NABTR identified two areas of cultivation that require technological improvement to facilitate the commercialization of algae biofuel: carbonation and mixing systems (DoE, 2010). Algae employ photosynthesis as their primary means of nutrient gathering. Photosynthesis is the process by which plants and algae absorb CO₂, convert it to energy, and release oxygen (O₂). In commercial-scale algae ponds, the immediately available CO₂ is insufficient to sustain algae growth, creating a requirement for additional carbon sources. This carbon supply is the largest source of operating costs for an open-pond algae system. Short of an outright reduction in the cost of carbon, very little can be done to reduce carbon costs. Approximately 40% of the carbon introduced into an open algae pond converts to CO₂ or dissolves in the water without providing nutrients for the algae (Gao et al., 2012). Research into carbon recycling includes capturing the carbon as it converts to CO₂ and extracting the carbon that has dissolved in water. Although recycling techniques have proven viable, they are not cost effective. Continued development and cost reduction is required before carbon recycling is a cost-effective way to reduce the amount of carbon required for cultivation.

Growing algae in an open pond requires mixing the pond to keep the algae's nutrients from settling, and prevent thermal stratification. There are two mixing methods in use: paddle-wheel systems and airlift systems (Gao et al., 2012). Paddle-wheel systems use physical paddles to stir and mix open algae ponds. This type of mixing requires a large capital expenditure to ensure that the entire algae pond is mixed. Large physical paddles are prone to breakdown and deterioration in the algae ponds. Airlift mixing systems use air jets to mix the water of open ponds. Airlift mixing has significantly reduced mixing costs in small-scale laboratory ponds, but has not been successfully demonstrated at the commercial level. Although sufficient cost data are not available to determine airlift mixing costs at the commercial level, several experts agree the costs are likely to be high (Gao et al., 2012).

(2) Algae Feedstock Processing and Conversion

Algae feedstock must go through processing and conversion before becoming a usable fuel. Processing of algae stock falls into two general steps: harvesting and extraction. The technology required to harvest and extract algae biomass depends on the exact type of algae being harvested and the location of the algae pond. Additionally, energy requirements increase exponentially as the amount of algae biomass being harvested increases (DoE, 2010).

The small-scale laboratory methods used to harvest algae are the centrifuge or skimming method. These methods are suitable for small-scale algae production, but are extremely inefficient as the size of algae growth increases. Centrifuge use is not practical for large-scale commercial algae production because the capital costs are high and the throughput of the centrifuge is low. Skimming is a relatively inexpensive process in itself, but it only utilizes the top layer of algae growth on the surface of an open pond, resulting in approximately 60% of available algae being left in the pond (Gao et al., 2012). Other harvesting technologies, such as gas floatation, micro-strainers, belt filters, and settling ponds, have proven successful in small-scale production. These methods provide greater cost efficiency and show potential for commercial-scale harvesting, but they still require large-scale testing (Gao et al., 2012).

Like all previous steps in algae biofuel production, the exact process of extracting oil from algae depends on the type of algae being used. The basic extraction process consists of two steps: drying and oil separation (DoE, 2010). Drying is a relatively straightforward process that is similar to many other commercial drying techniques used throughout various industries. The technological challenge comes during the actual oil separation step when the oil is separated from the dried algae biomass (Gao et al., 2012). The process of separating oil from biomass includes two steps: oil separation from biomass and trans esterification of oil. In commercial-scale algae production, oil is extracted from algae through physical grinding or sonically through a process called *sonication*. Both physical grinding and sonication agitate the algae biomass causing a breakdown of the organic structure of algae and release of the oil (Gao et al., 2012).

After the raw algae oil has been extracted, it must be converted into a usable form suitable for further refinement using traditional oil production techniques. This process is called *transesterification* and is the process by which algae oil is chemically converted into a usable form. Transesterification occurs in batch reactors that use large quantities of flammable organic solvents. After the transesterification process is complete the converted algae oil is separated from the organic solvents (Gao et al., 2012). In small-scale algae production, transesterification occurs through a manual process. Several designs for continuous-flow transesterification systems suitable for use at a commercial scale are in process; however, none have been tested, and the costs for operation are unknown (Gao et al., 2012).

The main barriers to growth of the algae biofuel industry are high capital, operations, and maintenance costs (Riberio & Da Silva, 2012). Capital and fixed operating costs can be reduced with improved technology, experience, and economies of scale. The success of the algae biofuel industry depends on government intervention to encourage the required technological innovation (Ribeiro & Da Silva, 2012).

c. Algae Biofuel's Relationship With Traditional Petroleum

In this section, we explore algae biofuel's relationship with traditional fuels. Many barriers exist to the commercialization of biofuels in comparison to traditional petroleum. Oil prices, new sources of oil, and advancements in drilling and refining technology affect the pricing, demand, and investment potential of biofuels.

The U.S. government first evaluated algae as a potential biofuel source during the 1970s' oil crisis and continued to evaluate it through the 1990s. Unable to compete with traditional petroleum's low price point, the algae biofuel program was abandoned by the DoE in 1996 (Yudken, 2012). In 2006, President Bush acknowledged America's oil dependency, spurring investment in algae biofuel research. A 2010 study conducted by the Lawrence Berkeley National Laboratory concluded that the cost of pond-cultivated algae biofuel is still nearly three to four times that of traditional fuel (Yudken, 2012).

Oil projections continue to discourage algae biofuel investment. Higher oil prices over the last decade increase the potential return on investment for most traditional oil projects, making more expensive oil extraction methods profitable. Higher oil prices, combined with increased oil exploration, increased global oil reserves by 8.3% in 2011. These oil reserves are enough to meet current demand for the next 54 years at existing production levels (Bergin, 2012). Table 3 illustrates the world-proven oil reserves by region in 2011 (BP, 2012).

Area	Proven Oil Reserves (millions of barrels)
North America	217,487
South and Central America	325,367
Europe and Eurasia	141,071
Middle East	794,980
Africa	132,438
Asia Pacific	41,269
Total Proven Oil Reserves	1,652,612

Table 3. Distribution of World-Proven Oil Reserves by Region in 2011 (From BP, 2012)

World oil consumption is rising, reaching 88 million barrels per day (BP, 2012). Consumption in Organization for Economic Cooperation and Development (OECD) countries dropped by 600,000 barrels per day, and non-OECD countries, led by China, experienced a surge in use of 1.2 million barrels per day (BP, 2012). Figure 6 illustrates the world oil production and consumption by region (BP, 2012).

In 2011, annual world oil production increased by 1.1 million barrels per day. The Organization of Petroleum-Exporting Countries (OPEC) has the highest net growth in world oil production, with Saudi Arabia, the United Arab Emirates (UAE), and Qatar leading production growth (BP, 2012). Outside of OPEC, the United States, Canada, Russia, and Colombia showed increased production levels. With an increase of 285,000 barrels per day in 2011, U.S. production reached its highest levels since 1998, leading all non-OPEC countries for the previous three years (BP, 2012). New technologies and drilling methods are having a positive impact on U.S. output.

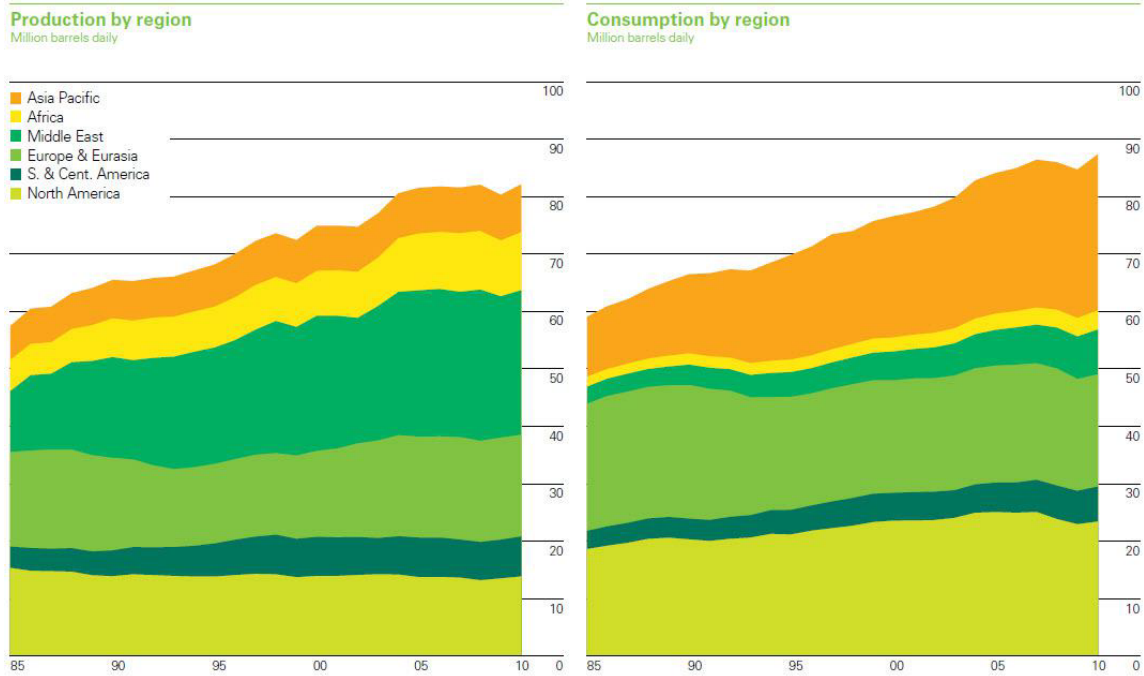


Figure 6. World Oil Production and Consumption by Region (From BP, 2012)

A major breakthrough in drilling techniques, known as *fracking*, is the primary driver behind the surge in U.S. production (Fahey, 2012). Continued U.S. production depends on the cost of drilling. Fracking is much more expensive than the types of drilling used in places such as Saudi Arabia. Although \$75 per barrel seems to be the cutoff for U.S. drillers, International Energy Agency projections place the lowest prices at \$89 per barrel over the next five years, certainly no threat to U.S. production (Fahey, 2012).

Production of U.S. crude oil and other liquid hydrocarbons, including biofuels, rose by 7% in 2012 to about 10.9 million barrels per day, marking a fourth straight year of rising production. 2012 also marked the highest annual increase since 1951 (Fahey, 2012). For 2013, the DoE projects U.S. production to reach 11.4 million barrels per day, near the daily production levels of Saudi Arabia. Predictions also place U.S. production levels at 13 to 15 million barrels per day by 2020, leading some to dub the United States the next “Middle East” (Fahey, 2012).

Where does this leave algae biofuel? Biochemist Dr. John Benemann answered by stating, “Algae biofuels cannot compete with fossil energy based on simple economics....The real issue is that an oil field will deplete eventually, while an algae pond would be sustainable indefinitely” (Gable, 2012, p. 1).

4. Why Government Intervention?

In Chapter II, we discussed the strategic importance of biofuels from the view of the U.S. government. Both the executive and legislative branches of our government believe developing and producing commercially viable biofuels in the United States gives the United States a strategic advantage. This advantage stems directly from the reduced importance of foreign oil, which gives the United States greater room to maneuver politically, militarily, and economically.

a. Political Impacts of Oil Dependency

A recent Council on Foreign Relations (CFR, 2006) report identified five ways that foreign oil dependency alters U.S. and worldwide foreign policy.

Oil-exporting countries have the flexibility and funding to adopt policies that oppose U.S. and worldwide interests. This flexibility is seen in the actions of countries such as Iran, Russia, and Venezuela. Iran funds much of its nuclear ambitions through the sale of petroleum despite economic sanctions imposed by the United Nations. Capital from petroleum sales raises the standard of living in Russia even while Moscow tightens control over the populace. Venezuela’s increasing influence and displacement of the United States in Latin America is driven by the monies from petroleum sales (CFR, 2006).

Countries such as China constrain the United States’ ability to form partnerships to achieve common objectives. Recent examples of political realignment include China’s shift in attitude toward the Middle East, Asia, and Africa. Despite different political and national interests, China has opened the door to cooperation with countries openly hostile to the United States in order to secure oil supplies. China’s move to secure oil in Asia directly challenges U.S. influence in countries such as Kazakhstan.

China's involvement with oil production in Sudan has resulted in the inability of the UN to manage the Darfur crisis. China continually threatens to use its veto power on the UN Security Council whenever the UN proposes action in Darfur (CFR, 2006).

High oil prices require importing countries to include political arrangements to guarantee oil supplies, circumventing the open-market system and guaranteeing oil sales to the country offering the most political benefits. These political deals often include infrastructure projects not related to oil production or exportation. Recent examples of Chinese oil investments in Africa have included deals to construct airports and telecommunication systems. These types of arrangements pose problems for the United States because they lead to political relationships that are difficult for the United States to reproduce and because they foster the idea that oil importers obtain access to oil through political favor versus a properly functioning global market (CFR, 2006).

Oil and gas revenue often undermines local governance, particularly in countries with less robust governments. Poorly governed and politically unstable countries struggle to properly manage the large revenue generated by national oil sales. National oil sales also entrench existing governments, even when they are opposed by the populace. Attempts by the United States to establish oil trade relationships with unpopular governments are perceived as tacit support for the totalitarian regime. Within the United States, popular opinion of the government suffers when it is forced to deal with unpopular regions such as the Middle East and Africa to secure adequate oil supplies (CFR, 2006).

During periods of oil price volatility or interruption, the United States and other oil-importing countries' foreign policy is adversely impacted. When disruptions to the U.S. oil supply occur, most ongoing foreign policy is put on hold while the country scrambles to normalize the oil supply. Often, foreign policy measures reached in order to stabilize oil supplies and prices run counter to planned U.S. foreign policy and may be counterproductive for long-term U.S. strategy (CFR, 2006).

Although the CFR report (2006) does not go so far as to say that biofuels are the answer to foreign oil dependency, it does recommend government involvement in alternative fuel research in an effort to reduce the political impacts of oil dependency.

b. Military Benefits of Biofuel

Biofuel commercialization benefits the U.S. military in a number of ways; however, all the benefits generally fall into two categories: shortening of supply lines and reduction in price volatility.

(1) Price Volatility

Economist Teresa Serra (2012) of the Center for Agricultural Economics in Spain defined price volatility as “generally characterized as a directionless variation in prices that cannot be predicted by market fundamentals, or, more intuitively, it is a measure of the extent to which prices jitter” (p. 2).

Serra (2012) described the ability of the U.S. biofuel industry to influence crude oil prices:

There are only a few studies that are able to provide a response to the issue of long-run causality links flowing from biofuel to crude oil price levels. Neither the Brazilian, nor the U.S. biofuels industries are found able of shaping crude oil prices. (Serra, 2012 p. 7)

In its current form the U.S. biofuel industry does not have the production volume required to influence and stabilize crude oil prices. President Obama seeks to stabilize fuel prices for the American consumer through the development of alternative fuels and energy technologies. In his *Blueprint for a Secure Energy Future* (The White House, 2011), he stated, “Volatile gasoline prices reinforce the need for innovation that will make it easier and more affordable for consumers” (p. 4).

The president’s statement demonstrated the link between energy security and the idea of petroleum price stabilization. Although President Obama speaks of stabilizing petroleum prices for the consumer, stabilizing petroleum prices also benefits the military. Understanding the impact of high prices on defense budgets

requires understanding the basic process by which the DoD receives and allocates funding.

Congress provides the DoD with funding each year through a series of appropriations bills. These bills grant the DoD budget authority to spend money in five basic categories: research, development, test and evaluation (RDT&E); procurement; military construction (MILCON); military personnel (MILPERS); and Operations and Maintenance (O&M; Jones, Candreva, DeVore, 2011). RDT&E, procurement, and MILCON are commonly referred to as investment accounts, while MILPERS and O&M are referred to as operations accounts. The investment accounts fund the development, procurement, and construction of future weapons systems and support infrastructure. These accounts buy future military capability. Operations accounts fund the day-to-day operation of the DoD, providing pay for military and civilian personnel and funds to purchase spare parts, fuel, and operating necessities. Operations accounts can be thought of as mandatory spending accounts, while investment accounts may be thought of as discretionary spending accounts.

In “The Impact of Cash Flow Volatility on Discretionary Investment and the Cost of Debt and Equity Financing,” Bernadette Minton and Catherine Scrhand (1999) said,

Higher cash flow volatility implies that a firm is more likely to have periods of internal cash flow shortfalls. Our analysis indicates that firms do not simply react to these shortfalls by changing the timing of discretionary investments to match cash flow shortfalls. Rather, firms forgo investments. Cash flow volatility is not the only reason that volatility affects investment decisions. Cash flow volatility is also positively related to a firm’s cost of accessing external capital. Firms with higher cash flow volatility will have higher capital costs. (p. 31)

The DoD acts in the same manner as business. When fuel prices, or other budgetary pressures, squeeze the O&M budget, the DoD initially seeks release from Congress through the form of additional appropriations; consider this as the corollary to a firm seeking external capital. The DoD faces a much higher price or capital cost when requesting this additional funding. This price is not in the form of higher interest rates, but rather congressional and public scrutiny of defense budgets and the requirement to

justify why the originally submitted budget is no longer adequate. If Congress does not grant additional budget authority, then the DoD looks inward to find savings to offset increased and volatile fuel costs. Figure 7 shows how the U.S. Navy plans to change its budget based on a reduction of \$58.1 billion between FY2012 and FY2013.

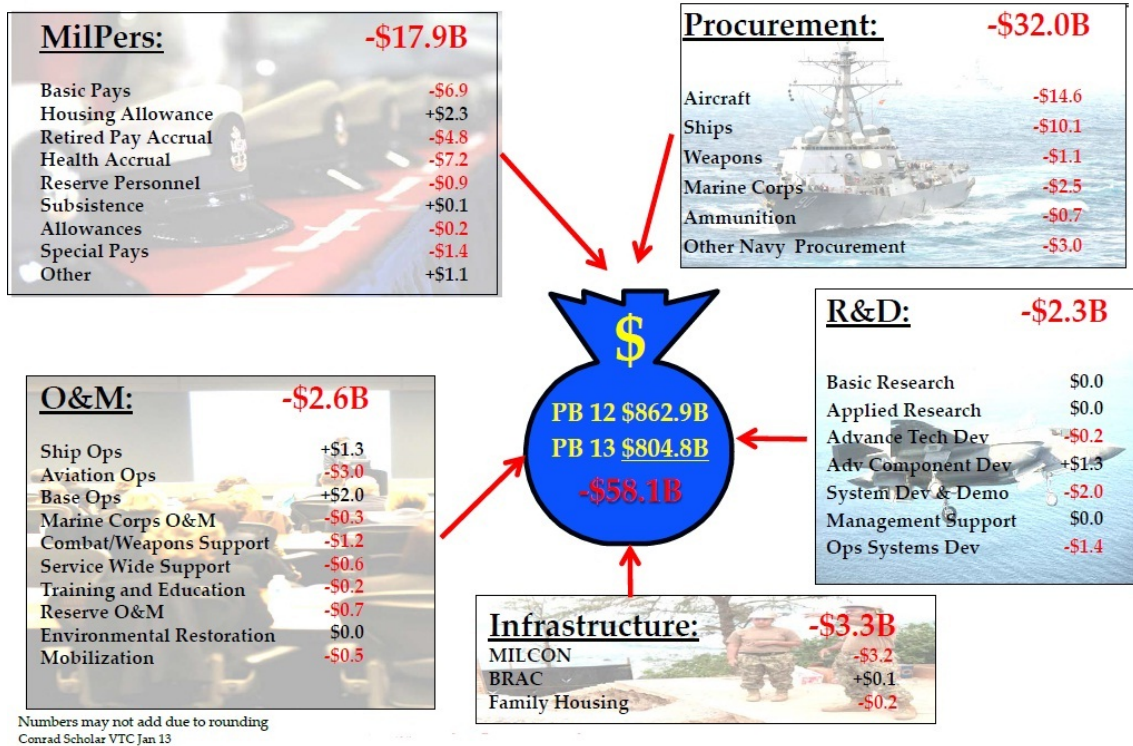


Figure 7. U.S. Navy Appropriation Changes From FY2012 to FY2013 President's Budget (From E. Cochrane, Associate Director Assistant Secretary of the Navy for Financial Management and Comptroller, personal communication, February 7, 2013)

Figure 7 shows a 55% reduction in procurement spending to meet the FY2013 budget. This reduction in procurement spending is analogous to a company deciding not to make capital investments. Firms that reduce R&D and capital procurement spending during periods of price volatility often face the difficult and costly task of doubling or tripling investment spending in the future when attempting to catch up on missed spending opportunities (Minton & Schrand, 1999). The DoD faces a similar “catch-up” spending problem when price volatility pushes out investment spending.

The desire to stabilize prices in the domestic and military fuels market could be assisted through the increased production of biofuels if the production quantity is sufficient to influence crude oil prices (Serra, 2012).

(2) Lines of Communication

Noted nineteenth-century military philosopher Carl Von Clausewitz (1832/1989) defined lines of communication, in his book *On War* as follows:

Routes that lead from an Army's position back to the main sources of supplies and replacements, and that are apt to be the ones the Army chooses in the event of a retreat, have two purposes. In the first instance they are the lines of communication serving to maintain the Army and in the second they are the lines of retreat.

They link the Army to its base, and must be considered its arteries. The roads are in constant use for all sorts of deliveries, for ammunition convoys, detachments moving back and forth, mail carriers and couriers, hospitals and depots, reserve munitions, and administrative personnel. All this together is vital to the Army

These arteries, then, must not be permanently cut, nor must they be too long or difficult to use. A long road always means a certain waste of strength, which tends to cripple the condition of the Army. (p. 364)

Clausewitz (1832/1989) identified lines of communication as vital links that connect front-line units to a support infrastructure providing needed supplies. These links are vital to the operation of front-line units and cutting them can be disastrous to a nation's military and to the nation itself. To understand the military benefits gained by reducing supply lines through the development of domestic biofuels, one must look at the sea lines of communication (SLOCs). Twentieth-century military philosopher Julian Corbett (1911) applied the concept of lines of communication to the world's oceans. In his book, *Some Principals of Naval Strategy*, he defined SLOCs as follows:

Sea lines of communication. This expression is used of three different things: (1) Lines of supply, running from the base of operations to the point which the operating force has reached. (2) Lines of lateral communication by which several forces engaged in one theatre of operations can communicate with each other and move to each other's support. (3) Lines of retreat, which are lines of supply reversed, i.e., leading back to the base.

Ashore lines of passage and communication are roads, railways, and waterways. At sea, they may be regarded as those waters over which passes the normal course of vessels proceeding from the base to the objective or the force to be supplied. They may also be regarded as trade routes, that is communications upon which depend the national resources and the supply of the main bases, as well as the “lateral” or connecting communications between various parts of a country’s possessions. (p. 176)

We continue to see the importance of trade routes today, as seen in the SLOCs of the Middle East depicted in Figure 8. Figure 8 shows the strategic passages and shipping lanes for the Middle East and provides an idea of the amount of conventional petroleum moved between the three choke points in the region.

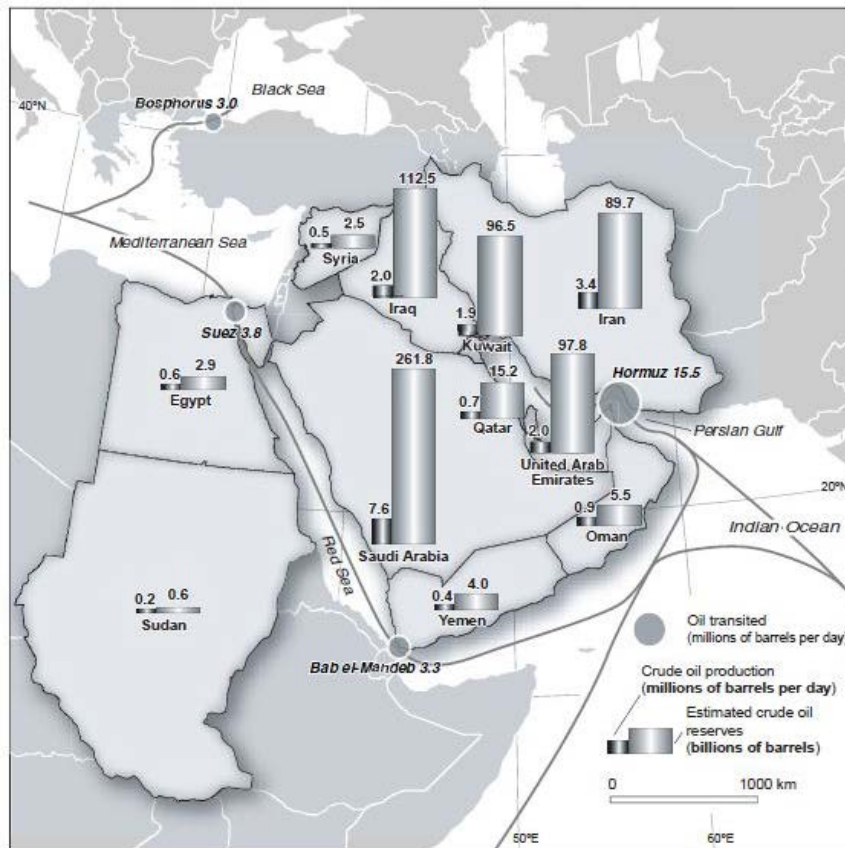


Figure 8. Shipping Lanes and Strategic Passages of the Middle East (From Rodrigue, 2004)

Although only 16% of the petroleum used by the United States moves through these shipping lanes, the majority of imported oil transits the seas (EIA,

2011). The Middle East SLOCs shown in Figure 8 represent the choke-point vulnerabilities found throughout the earth's oceans. These strategic choke points are vulnerabilities in the U.S. supply of imported oil and, thus, vulnerabilities for the U.S. military, which is heavily dependent on oil. The development of domestic biofuel can help reduce the dependency on foreign oil transported across vulnerable SLOCs by shortening the lines of communication. Instead of shipping crude oil to the United States for refining and returning refined oil to forward operating bases, domestic biofuel production could offset or eliminate the initial importation.

c. Economic Benefits

As an industry grows, new infrastructure is required to increase productivity to meet the increasing demand. Infrastructure growth can be observed in the expansion of the biofuel industry. Between now and 2020, 27 new algae biofuel plants are planned. These plants create direct and indirect economic benefits for the United States.

Direct economic benefits are defined as economic outputs generated by the DoD's purchase of drop-in biofuel to meet the 2020 fuel targets (Yudken, 2012). Algae biofuel refineries are expected to directly produce between \$9.6 billion and \$19.8 billion in economic activity from 2013 through 2020, and \$1.2 billion to \$2.4 billion in economic activity ever year after 2020 (Yudken, 2012). These direct economic benefits include the feedstock purchases, conversion of feedstock to biofuel, sales and distribution, and facility construction. Direct job creation estimates fall between a low of 96,600 and a high of 132,100 (Yudken, 2012).

Indirect economic benefits are defined as the change in economic activity resulting from subsequent rounds of production inputs purchased by industries affected by the planned DoD biofuel purchases along with changes in spending by workers whose earnings are affected by DoD biofuel purchases (Yudken, 2012). Indirect economic benefits are expected to add between \$19.2 billion and \$43.3 billion in economic activity between 2013 and 2020 with \$2.4 billion to \$5.4 billion in economic activity each year

after 2020. Indirect job creation estimates fall between a low of 160,500 and a high of 215,400.

In this chapter, we explored first- and second-generation biofuels, including the benefits of each type of feedstock. We examined the algae biofuel industry, discussing current production, costs, output, and the reasons algae biofuel is the preferred feedstock. Next we discussed the commercialization problem or why algae biofuel has not successfully crossed the valley of death. Finally, we discussed the reasons for government intervention into the biofuel market, including the benefits for the government and the United States.

IV. METHODOLOGY

One of the most important questions researchers must ask themselves before starting a research project is, “Will I use qualitative or quantitative analysis to answer my research question?” In this chapter, we describe why we used a qualitative approach to answer our research question and document the research methods used.

A. QUANTITATIVE VS. QUALITATIVE APPROACH

Originally, we planned to use a quantitative research approach to understand the government’s influence on commercialization of biofuels. Our initial research found limited data to support a quantitative approach to explain when biofuels could be commercialized. We looked into alternatives to quantitative research and were led to authors Miles and Huberman (1994). In their book *Qualitative Data Analysis: An Expanded Sourcebook*, Miles and Huberman (1994) described four considerations researchers should evaluate to determine whether qualitative research is appropriate. Those considerations are as follows:

- local grounding,
- richness and holism,
- sustained period and causality, and
- lived meanings (Miles & Huberman, 1994).

Local grounding refers to the study of specific organizations, participants, and processes because they hold intrinsic interest or because the organizational process can be understood only when the context is included in analysis. Technology systems, in particular those with national interest, are often subject to greater social and political influence (Patel & Pavitt, 1994). Thus, the complex nature of the biofuel industry cannot be studied without understanding the industry, including major players and the political and economic environments.

Richness and holism is the requirement for substantial depth in qualitative research. It is like asking the question, “Are you interested in more than numbers?” Initially, our plan for analyzing biofuel commercial viability appeared as a purely

economic question. However, as we discussed in Chapter III, biofuels are not commercially viable. In economic terms, the market alone will not create a biofuels industry; hence, our research becomes a question of strategic priorities and subjective assessments of value. A heated debate rages within the United States regarding the economic benefits of developing a technology with no clear economic future. Understanding why the United States continues to push for biofuel development requires understanding more than just economic numbers. It requires a holistic approach not available when using quantitative research methods.

Sustained period and causality is a method of observing an organization or process over a large period of time in order to develop casual inferences. Understanding the Navy's influence on biofuel commercialization requires long periods of observation and comparison to earlier commercialization attempts in industry. The relatively short-term quantitative information available on the cost, price, and economic willingness to pay for biofuels is insufficient to conduct a quantitative analysis. Organizations studying biofuels readily agree that several more years of cost and pricing data are required before accurate predictions about the biofuel industry are feasible. We do not have the time to observe personally the development of the biofuel industry and document the actions that successfully led to commercialization. By using a qualitative analysis, we compare purposively selected similar cases that do have a sufficient timespan and conduct a longitudinal analysis.

Lived meanings describes the perspectives of people and organizations and organizational structure. Lived meanings asks the question, "Are people's viewpoints, perceptions, assumptions, and organization structure important in understanding decision-making?" Taking a purely quantitative approach to biofuels excludes a large amount of data, namely the perspectives of the people and organizations making the investments. These perspectives are important in truly understanding the biofuel industry and how commercialization occurs.

Comparing our research to Miles and Huberman's (1994) four considerations, we determined that qualitative research is the best method to fully explore biofuels,

specifically biofuel commercialization. Deciding on a qualitative approach presented a new dilemma. What type of qualitative research best suits our research question?

B. GROUNDED THEORY

Grounded theory is a qualitative method originally proposed by Glaser and Strauss in 1967, and it was adopted widely across the social sciences. In their book titled *The Discovery of Grounded Theory: Strategies for Qualitative Research*, Glaser and Strauss (1967) defined a grounded approach as “the discovery of theory from data systematically obtained through social research.”

Glaser and Strauss (1967) stated that a grounded theory is the ideal methodology for uncovering basic social processes and is useful for understanding the underlying processes of a complex situation. Thomas Lee (1998) expanded grounded theory in his book, *Using Qualitative Methods in Organizational Research*. He said,

The main purpose of grounded theory studies is to generate new theory or conceptual propositions, and the main application of grounded theory techniques has been to the examination of phenomena that are not well understood. An underlying assumption in grounded theory is that social phenomena are complex. Correspondingly, the specific steps taken to study these complex social phenomena need to be flexible. Thus, there can be no hard-and-fast rules about how to conduct grounded theory research.
(p. 36)

We adopted a grounded approach to case analysis. That is, we did not conduct a grounded theory analysis and our aim was not to develop a new theory. Rather following recent developments in grounded theory methods (Corbin & Strauss, 2008), we applied a grounded theory approach to case analysis in order to explore a practical problem. As suggested by Glaser and Strauss (1967), we allowed our initial examination of the data to drive our subsequent analysis. We did not engage in line-by-line coding to generate theoretical concepts, but rather conducted a thematic analysis.

C. THE CASE STUDY APPROACH

In the article “Building Theories from Case Study Research,” Kathleen M. Eisenhardt (1989) developed a process for generating theory or propositions from case studies. Her process includes six steps with associated activities:

- define research questions,
- select cases and sources,
- craft instruments and protocols,
- analyze data,
- shape hypotheses, and
- compare literature.

In the remainder of this chapter, we discuss how we applied Eisenhardt’s (1989) six steps to our research.

1. Define Research Questions

Eisenhardt explained the purpose of defining a research question as, “The rationale for defining the research question is the same as it is in hypotheses testing research. Without a research focus, it is easy to become overwhelmed by the volume of data” (p. 3).

In Chapter III, we discussed the barriers facing commercialization of biofuels. We identified these barriers as cheap traditional petroleum and expensive biofuel production technology. Our initial research question asked, “Can the federal government influence commercialization of biofuel technology?” Intuitively, we suspected the answer was yes. The government can influence commercialization of technology, through myriad means such as direct or partnered research, purchasing of products, and grants. Since we know that an organization can influence technology, the more appropriate research question becomes, “Are the government biofuel initiatives likely to result in commercial viability?” Because of the complexity and early stage of biofuel development, to answer this question we explore how the government has influenced technological systems commercialization in the past and how the government is influencing biofuels today.

2. Select Cases and Sources

In any research, appropriate data selection is critical for success. Selection of appropriate and relevant data allows the researcher to generalize findings and indicate the range of result applicability (Eisenhardt, 1989). In quantitative research, most sampling of cases or data is done by random selection to ensure accurate and relevant statistical analysis. Emphasis is placed on ensuring the sample data are not biased or focused on a single area of a population. In qualitative research, sampling of cases or collection of data need not be random (Glaser & Strauss, 1967). Qualitative cases should be chosen to provide a basis for comparison, extend theory, fill theoretical categories, or provide examples of opposing viewpoints (Eisenhardt, 1989).

Case selection is usually a combination of purposeful selection and planned opportunism (Pettigrew, 1997). We selected cases containing information and data regarding successful technological commercialization endeavors involving the federal government that supported the U.S. Navy. Two of the best cases are nuclear power and nanotechnology. We defined *best* as cases containing successful commercialization with sufficient scope of available literature. These cases allow us to understand the structure and process that results in successful technological commercialization, and answer our first two research questions. We used a third case study, the ongoing biofuel case, to answer our final question. Ideally, we would select a failed case; however, due to the limited time available for our research, we did not analyze a failed case. We recognize this as a limitation to our research.

Source selection began with a simple Google Scholar search. We conducted searches for all sources using keywords appropriate to each case. The searches used these keywords: nuclear, power, commercialization, Navy, nanotechnology, and biofuels. This initial search led us to our first sources. After finding our first sources, we applied the snowball sampling method. Using snowball sampling, our first references led us to new sources. We gathered new sources until we reached data saturation.

3. Crafting Instruments and Protocols

When building a proposition, multiple data collection methods are usually employed. In qualitative data collection, the typical methods are interviews, observations, and archival sources. Although it is acceptable to use only one data collection method (Eisenhardt, 1989), we recognize that multiple data collection methods substantiate developed propositions. Due to limited research time, interviews and direct observations were not possible. Our research was limited to the use of archival sources describing the development of the nuclear power and nanotechnology programs. We recognize this as a limitation of our study.

Eisenhardt (1989) presented the idea of multiple investigators as a way to build confidence in findings and increase the likelihood of surprise findings. We used a variation of this technique. Project members divided the responsibilities for data review and analysis by case, with each team member analyzing a single case. The group then reviewed each case, allowing the group members who did not analyze the case to critically review the details, factors, and assumptions of the case. Group review generates discussion and brings varying, and possibly more objective, views to light (Eisenhardt, 1989).

4. Analyze Data

In qualitative research following a grounded approach, data analysis begins during the collection process. Combining data analysis and collection provides the flexibility to alter data collection methods in order to respond to the existing data and develop concepts and propositions. It also allows the researcher to begin sifting out and categorizing important data, but, more importantly, it allows researchers to structure the large volumes of data (Eisenhardt, 1989). We began our case study analysis drawing on the PESTEL framework. The PESTEL framework contains six factors that we believed had potential to influence the macro environment. Factors in the PESTEL model were dropped and added as necessary based on the findings of case reviews. Figure 9 shows the original PESTEL model and includes the standard factors that may influence innovation of technological systems.

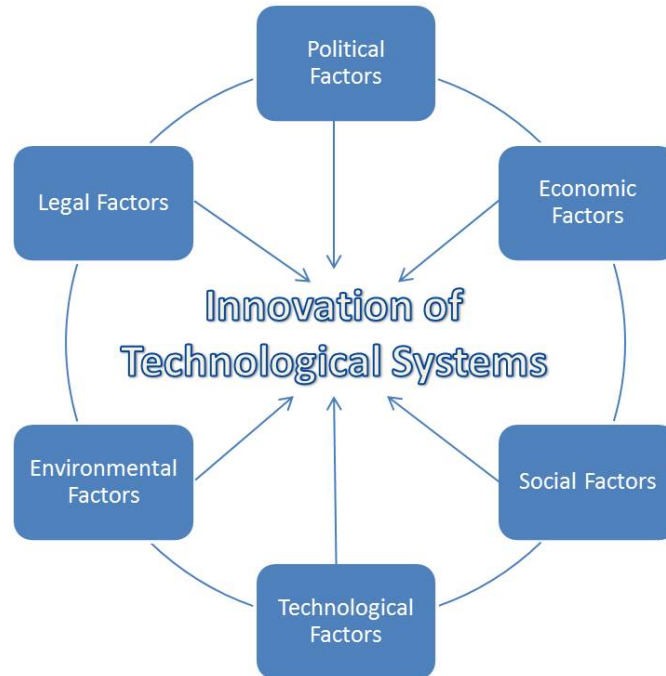


Figure 9. PESTEL Model, Describing Factors That May Influence Innovation of Technological Systems

The PESTEL framework was applied independently to each archival source for the three cases studies. Determining where case data fit within the framework was dependent upon the team member conducting the research. Assigning responsibility for one complete case to a single researcher helped maintain consistency throughout the categorizing process. Data analysis for each case was considered complete when new archival sources failed to introduce new information, or in other words we achieved data saturation (Eisenhardt, 1989). Upon completion, each source had a complete PESTEL analysis. When each PESTEL analysis was combined, it created a master case analysis.

A key part of data analysis is searching for patterns across cases. In our research, cross-case analysis involved three steps:

- comparison of nuclear power to nanotechnology,
- proposition development from nuclear power and nanotechnology, and
- application of propositions to biofuels.

There is a potential for bias when conducting cross-case analysis. People are poor processors of information and can reach premature and false conclusions as a result of

information-processing bias (Eisenhardt, 1989). In order to address information-processing bias, we employed two tactics. The first tactic to prevent information bias was information categorization using the PESTEL framework. This framework provides categories for comparison of data across numerous sources and cases. The use of categories assisted in drawing inferences between multiple sources and cases by standardizing the data collection and display. The second tactic to prevent information bias was comparison of similarities and differences between cases (Eisenhardt, 1989). In our research, we compared the successful commercialization of nuclear power against the successful commercialization of nanotechnology in order to define successful commercialization. We acknowledged similarities between the two cases as they provided reasons for common success. We also acknowledged differences between cases, allowing us to acknowledge the uniqueness of each case. The differences between cases also provided a way to demonstrate different solutions used to solve a common problem.

5. Shaping Hypothesis

Hypothesis generation in qualitative research does not follow traditional scientific theory. Hypotheses are often not generated before research is conducted in qualitative research. Instead the hypothesis often begins to present itself during the analysis process (Eisenhardt, 1989). In our research, we developed our proposition during our case analyses of nuclear power and nanotechnology. Each researcher began to see patterns emerge and began to infer relationships between the PESTEL factors and the outcome discussed in the source. Separate propositions were generated for the nuclear power and nanotechnology cases before the cross-case comparison was conducted. These independent propositions described successful commercialization for each case and were constantly updated as new sources were found and analyzed. When cross-case comparison was conducted, the two independent propositions were compared to develop a master proposition describing successful commercialization. The master hypothesis was tested against the nuclear power and nanotechnology cases to ensure proper fit.

6. Compare Literature

We compared the PESTEL factors of the master proposition to existing literature and looked for conflicting or complementing literature. Examining conflicting literature is important for two reasons. First, ignoring conflicting literature reduces the validity and confidence in our findings. By acknowledging conflicting literature, we prevented other readers from assuming our results are incorrect, or if correct, the results are recognized as specific to a given case (Eisenhardt, 1989). Second, acknowledging conflicting literature forced us to achieve deeper insight into our studies. We became familiar not only with our research, but also with the research of others whose results conflict with ours. Studying conflicting research resulted in deeper understanding of our cases and generated more creative thinking that refined our findings (Eisenhardt, 1989).

Understanding similar findings from other researchers is also important. Again we were forced to become familiar with others' research. The similarities between others' results and ours brought together processes and phenomena that initially appeared unrelated (Eisenhardt, 1989). Acknowledging similar research further refined and strengthened our proposition, adding validity and generalizability.

We used the idea of triangulation proposed by Todd Jick (1979) in his article "Mixing Qualitative and Quantitative Methods: Triangulation in Action." Jick defined triangulation as the combination of methodologies in the study of the same phenomenon in order to ensure that results represented the underlying structure and process of an issue and not the traits of the methodology used in analysis. The idea behind triangulation is that multiple independent measures of data collection provide a more certain portrayal of the issue being studied, if they reach the same conclusion (Jick, 1979).

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V. ANALYSIS

In this chapter, we draw on the PESTEL framework to identify and compare the factors that contributed to the development of nanotechnology and the nuclear industry. We highlight similarities and draw general conclusions about successful commercialization of technology systems. We identify and discuss conflicting literature and conclude the chapter with a comparison of our generalized findings to the biofuel case.

A. NUCLEAR POWER AND NANOTECHNOLOGY

We examined the early development of the nuclear power and nanotechnology industries independently drawing on the PESTEL framework. First, we identified the key element within each industry for each PESTEL factor. The key elements are displayed in Table 4. Next, we compared the PESTEL factors across the two cases to identify key drivers for each factor, shown in Table 5 at the end of this chapter. These generalized findings are the basis for our subsequent analysis and comparison with the biofuel case.

Factor	Nuclear Power	Nanotechnology
Political	Atomic Energy Commission	National Nanotechnology Initiative
Economic	Power Reactor Demonstration Program	Government Funding
Environmental/Social	Social Concerns with Pollution	Social Health and Environmental Concerns
Technology	Argonne National Laboratories	National Nanotechnology Initiative Network
Legal	Atomic Energy Act of 1954	Nanotechnology Patent Protection

Table 4. PESTEL Factors for Success in Commercialization of Nuclear Power and Nanotechnology

1. Political Factors

As discussed in this section, we determined that government involvement and coordination were key political factors affecting nuclear power and nanotechnology

development. These government programs assisted and guided R&D to serve national interests, and provided a catalyst for commercialization.

a. Political Factors and Nuclear Power

The Atomic Energy Act of 1946 created the Atomic Energy Council (AEC) and shifted responsibility for the development of U.S. atomic energy from the Army and the Manhattan District (Allen, 1977). The establishment of the AEC laid the groundwork for a national government initiative to develop and use atomic energy for “improving the public welfare, increasing the standard of living, strengthening free enterprise, and promoting world peace” (Allen, 1977).

Congress assigned the AEC five tasks intended to include the private sector in nuclear research and development. Those tasks were the following:

- support research and development in the private sector to achieve the highest amount of technical growth possible;
- distribute information related to atomic research in a controlled fashion, and control the manufacture and usage of uranium and plutonium;
- provide laboratories to research atomic energy whether or not there was any economic gain; and
- provide for the administration of the entire program while allowing dialogue with other nations concerning nuclear energy (Allen, 1977).

What effects, either positive or negative, did these tasks have on the early development of nuclear power? Congress intended the AEC tasks to encourage commercial industry participation in the development of the nuclear industry while maintaining national security. In the early years of the nuclear power program the power and weapons programs were a single entity. The early national security concerns limited commercial participation. Security measures required any company requesting nuclear information or technology to apply to the AEC. The AEC determined the potential security concerns of releasing the requested information (Allen, 1977). These restrictions hindered the program until the passage of the Atomic Energy Act of 1954 when the weapons and power programs were separated (Allen, 1977).

The early data controls interfered with the AEC's task of supporting private research through the contribution of industry (Allen, 1977). Competition among potential industry participants favored the few companies involved in nuclear programs during and shortly after World War II. These companies previously had access to restricted information and understood working with the AEC and its predecessors, thus giving them a unique advantage (Allen, 1977). The AEC recognized the need to include more companies in the development process and increase the availability of nuclear information to determine the viability of nuclear power in the generation of commercial power (Allen, 1977; Perry et al., 1977).

Despite the data release restrictions, one action by the AEC promoted participation by industry. Recognizing that utility and manufacturing companies would need to provide the funds necessary to commercialize the nuclear industry, the AEC developed the Industrial Participation Program (IPP; Allen, 1977). The purpose of the program was multi-faceted. The AEC needed to understand what phases of technology the new industry was in and how much further advancement would cost. The AEC needed to know what uses industry saw for nuclear power and how the AEC could encourage industry participation (Allen, 1977).

Initially only four groups participated in the IPP, with companies such as Dow Chemical, Pacific Gas and Electric, and Bechtel Corporation leading the way. At the conclusion of the IPP, 12 groups performed engineering and design studies, developed budgets for R&D, and developed timelines for production of commercial nuclear power plants (Allen, 1977). The most important results of the IPP were the identification of barriers to further commercial development of nuclear power (Allen, 1977). The IPP participants identified two major barriers to commercialization, both related to capital costs. AEC safety considerations required large isolation areas that were impractical for commercial use due to the cost of acquiring the land and the power lines to transmit the electricity to power grids (Allen, 1977). Further, the estimated capital costs of nuclear plant construction were cost prohibitive for industry. Industry leaders believed costs would decline as the nuclear industry matured, but none wanted to assume the costs of research and development (Allen, 1977). The results of the IPP contributed to

a reduction in the amount of land required to meet safety considerations and the establishment of the AEC's Power Reactor Demonstration Program (PRDP), designed to demonstrate the costs and benefits of a commercial power reactor.

The largest impact from the AEC is found in the mandate to conduct R&D and make available research laboratories unrestricted by the need to satisfy investors and unhindered by a need to show an immediate, real-world use (Allen, 1977). After assessing which issues were most important and could be handled by national labs, the AEC concentrated all design and engineering at the Argonne National Laboratory, one of the most important decisions in the technological development of the nuclear industry (Allen, 1977).

While the establishment and initial mandates of the AEC did not lead to a rapid growth in the nuclear industry, they laid the groundwork for some of the most important decisions and programs in the growth of nuclear power. Restriction of information due to national security concerns initially hampered efforts to include more companies in the nuclear industry, but it also accelerated the separation of the weapons and power programs. Most important was the establishment of two programs that we will discuss further in terms of their economic and technological factors: the PRDP and the Argonne National Laboratory. As we will discuss, the PRDP and Argonne National Laboratory led to a marriage of industry and government that was key in the difficult and expensive early years of nuclear power.

b. Political Factors and Nanotechnology

In 2001, the National Science and Technology Council (NSTC) created the National Nanotechnology Coordination Office and the National Nanotechnology Initiative (NNI; Roco, 2006). The NNI has led to synergistic, accelerated, and interdisciplinary development of nanotechnology while motivating academia and industry to jointly research and develop commercially viable nanotechnology and nanotechnology products (Roco, 2006). How did the NNI influence commercialization of nanotechnology?

The NSTC serves as a virtual agency with a member on the cabinet of the president of the United States. Before creating the NNI, the NSTC conducted core nanotechnology research to identify nanotechnology concepts that included most scientific disciplines. The NSTC defined nanotechnology and identified key research directions prior to commencing any actual research (Roco, 2006). In order to assemble fragmented scientific disciplines and generate support for the NNI, the NSTC conducted various working groups that led to collaboration of scientists across most disciplines and generated a bottom-up research plan for the initial implementation of the NNI. The NNI ultimately included 25 federal government agencies and thousands of academic, industry, state, and local institutions (Roco, 2006). Finally, the NSTC created a long-term research plan structured in the manner of a science project. This science project structure established research priorities and levels (national, agency, industry, and R&D). The early stages of R&D focused on fundamental or basic research relevant to multiple applications (Roco, 2006). This research was freely available to all participants including industry (National Nanotechnology Coordination Office [NNCO], 2005).

The NNI and the NNCO were formally established in 2001. The NNCO is responsible for coordinating research planning and budgeting between federal entities, private companies, and academic institutions (Miller, Serrato, & Represas-Cardenas, 2004). Appendix A lists all the federal NNI participants as of 2012. In 2001, the NNI also refined the long-term goals for the first stage of the NNI. The revised goals included the following:

- additional fundamental research goals driven by the outcomes of current research and the input of the organizations within the NNI;
- creation of centers and networks of excellence responsible for encouraging research networking and sharing of files;
- development of research infrastructure including funding for standardized metrology, instrumentation, and modeling and simulation equipment for all research facilities;
- workforce education and training to develop the new generation of nanotechnology workers; and
- the creation of grand challenges for nanotechnology (Miller et al., 2004).

The NNI also created grand challenges incorporating several national-level items of interest designed to encourage a national race for nanotechnology. These challenges included

- shrinking the entire contents of the Library of Congress into a device the size of a sugar cube;
- making materials from the bottom up, by building them from atoms and molecules;
- developing materials 10 times stronger than steel, yet lighter, suitable for use in land, sea, air, and space vehicles;
- using gene and drug delivery to deter cancerous cells by nanoengineered MRI contrast agents;
- removing the finest contaminants from water and air; and
- doubling the energy efficiency of solar cells (Miller et al., 2004).

In 2006, Dr. Roco, a member of the NNI, discussed the successes of the NNI between 2001 and 2005. He stated,

What are the major outcomes after five year [FY2001 to FY2005] of the NNI? The R&D landscape for nanotechnology R&D has changed, advancing from fragmented fields and questions such as “what is nanotechnology?” and “could it ever be developed?” to a highly competitive domain where the main question is “how industry and medicine can take advantage of it faster?” In only five years, nanoscience and nanotechnology have opened an era of integration of fundamental research and engineering, increased technological innovation and enabled a base for improving human health. For this reason government and industry investments worldwide have increased five-fold in five years, reaching about \$4.1 billion in 2005 from about \$825 million in 2000, and all Fortune 500 companies working in materials, electronics, and pharmaceuticals have made investment in nanotechnology. The NNI fuels these developments. By creating a “power house” of discoveries and innovations, the NNI has been the major driver for nanoscience and nanotechnology developments and applications within the United States and the world. In 2005, NNI supported over 4,000 projects and 60 new centers of excellence for networks and user facilities in the United States. Over \$8 billion is now invested worldwide by governments and industry for nanotechnology R&D. The vision of a decade ago has taken place. (p. 15)

In 2006 the NNI shifted focus from purely basic research and began to include some applied research (Roco, 2006). The focus became the vertical integration with industry in order to align research efforts with societal needs and aspirations.

The NNI's coordination of nanotechnology R&D profoundly impacted the growth of the nanotechnology industry. The NNI focused R&D efforts by creating specific goals and challenges for the government, private industry, and academia. The NNI created a clearing house for information developed during the early stages of nanotechnology under the NSTC, and made it accessible to any entity involved in nanotechnology development. Focus and information sharing were key to the rapid growth of nanotechnology investment over a five-year period and a shift to applied research geared toward use of nanotechnology in society.

c. Generalized Findings

Nuclear power and nanotechnology are products of very different political environments that both achieved commercial success. We found both programs were in essence national organizations leading commercialization efforts. The nuclear power program was spearheaded by the AEC, while the nanotechnology program was led by the NNI. The activities undertaken by the AEC and the NNI can be represented by four common elements:

- established long-term goals based on national-level items of interest;
- incorporated government, industry, and academia into a national research group;
- shared information freely among participants; and
- established policy regarding research and use of developed technology.

These factors are representative of a National Innovation System (NIS). The NIS concept was first proposed more than 20 years ago by Christopher Freeman (1981) while he studied Japan's post-WWII rise to an economic superpower. Freeman (1981) was the first to use the idea of an NIS; however, there is no agreed-upon definition of an NIS. Building upon Freeman's NIS concept, we defined an NIS as a framework

established at the national level to encourage and promote innovation and commercial development of technology to support national goals.

It is impossible to say if nuclear power and nanotechnology could have reached commercialization without an NIS. However, we believe that without an NIS the development of commercial nuclear power and nanotechnology would have faced greater opportunities for failure, taken longer to develop, and resulted in a fragmented industry.

2. Economic Factors

Research and development of new or highly innovative technology require large amounts of capital. Private industry must show that a new technology has a sustainable, practical use to convince investors to contribute large amounts of capital towards research and development. Governments are not always constrained by this need to show an immediate practical use and are not controlled by a need to turn a profit. Therefore, government and industry partnerships develop to accelerate the growth of an industry.

a. Economic Factors and Nuclear Power

Capital cost was the key financial issue that limited industry interest and participation in the early development of nuclear power. Industry leaders believed building a nuclear power plant was too expensive for privately held firms to support (Allen, 1977). Industry leaders believed only the government had the necessary funds to construction a nuclear power plant. Congress provided the groundwork for nuclear cooperation between the government and private industry in the 1954 Atomic Energy Act. The Atomic Energy Act stated,

Many technological problems remain to be solved before widespread atomic power, at competitive prices, is a reality. It is clear to us that continued Government research and development, using Government funds, will be indispensable to a speedy and resolute attack on these problems. It is equally clear to us, however, that the goal of atomic power at competitive prices will be reached more quickly if private enterprise, using private funds, is now encouraged to play a far larger role in the development of atomic power than is permitted under existing legislation. In particular, we do not believe that any developmental program carried out solely under government auspices, no matter how efficient it may be,

can substitute for the cost-cutting and other incentives of free and competitive enterprise. (p. 751)

In response to industry concerns about the capital costs of nuclear power, the AEC established the Power Reactor Demonstration Program (PRDP; Allen, 1977).

The PRDP began in January of 1955 and was broken into four phases. Phases One and Two ran concurrently with Phase One involving large corporations and Phase Two involving small public companies. Phase Three limited participants to demonstrable nuclear technology. The fourth phase required industry to submit designs capable of producing 400MWe of power using a light water reactor design. The goal of the PRDP was “to bring private resources into the development of engineering information on the performance of nuclear reactors and to advance the time when nuclear power will become economically viable” (Perry et al., 1977).

To encourage industry participation in the PRDP, the AEC recognized the need to offset industry R&D costs. To accomplish this, the AEC

- waived nuclear fuel use charges,
- conducted R&D on behalf of industry using government labs and research equipment free of charge,
- required companies to openly share research information in benefit of the nuclear program,
- paid for reactor construction for small utility companies in Phase Two, and,
- in Phase Four, focused industry on the light water reactor (Allen, 1977).

The PRDP encouraged industry development of nuclear power by reducing capital costs associated with the research, design, and production of nuclear power and focused industry on the proven design of the light water reactor. Focusing on the light water reactor further reduced development costs by reducing the number of outstanding reactor designs from six to one.

b. Economic Factors and Nanotechnology

Federal government spending for nanotechnology was \$14.9 billion between FY1997 and FY2012 (American Association for the Advancement of Science [ROCO], 2009; Miller et al., 2004). Large federal government spending administered through a national innovation system such as the NNI has provided funding for basic and applied R&D critical for the development of commercial nanotechnological products. The importance of government funding can be seen in the words of Mr. William P. Moffitt, CEO, Nanosphere, Inc., and Dr. Mark Melliar-Smith, CEO of Molecular Imprints. Both testified before Congress on March 11, 2008 (U.S. House, Subcommittee on Science and Technology, 2008), about the vital importance government research played in the development of their respective nanotechnology-based products. Moffitt said,

Nanosphere was founded in 2000, based upon nanotechnology discoveries made by Northwestern University in Evanston, Illinois. We have taken basic science, funded by the NIH and NSF [part of the NNI] out of the university research setting and translated it into a diagnostics platform that delivers three distinct economic values. First, the ability to move complex genetic testing into mainstream medicine; second, early detection of diseases, such as cardiovascular disease, cancer, and neurodegenerative diseases, as nanoparticle probes improve detection sensitivity by orders of magnitude; third, the potential to test for disease where no tests exist today. Moreover, while we are focused on medical diagnostics, this same technology platform is applicable to biosecurity, agriculture, food safety testing, and industrial contamination control. Nanotechnology has a potential to shift markets on a global economy and replace or greatly modify existing leadership positions. (p. 41)

Moffitt's statement shows the impact NNI basic research played in Nanosphere's growth and the recognition of nanotechnology's potential to generate new economically viable products. Recognition of the potential economic benefits associated with nanotechnological production demonstrated the willingness of individual businesses to incorporate nanotechnology in order to generate income. The idea that basic research conducted under the early stage of the NNI provided the initial idea of nanotechnology based products is further supported by the words of Mellinar-Smith (U.S. House, 2008). While speaking about his company, Molecular Imprints, he said,

We have also received extensive help from government-funded facilities. Recently, especially useful has been our access to state-of-the-art electron beam tools at the molecular foundry at Lawrence-Berkley National Laboratory in California. Government funding has been supplemented by over \$60 million of venture capital and industry investment, and in fact, in my experience, I found no dichotomy between the two sources of funding. They seem to be synergistic and collaborative. We are grateful for all of this support. (p. 50)

Mellinar-Smith's comments again show the importance of government funding toward the initial commercialization of nanotechnology. In this case, Mellinar-Smith highlights that funding need not be in the form of direct investment. Instead, funding in the form of assistance from national laboratories and agencies provided the catalyst for initial commercial success.

The purpose of this March 11, 2008, Congressional hearing was to understand ongoing challenges for commercialization of nanotechnology and, ultimately, to understand how the government could assist industry in commercialization of nanotechnology (U.S. House, 2008). When asked by Congress, "What are the hurdles to commercialization of nanotechnology?" Moffitt said,

First and foremost the lack of early stage capital for cutting-edge, translational research. Much of the government's direct spending in nanotechnology has been on scientific discovery. It takes extensive capital to translate nanoscience discoveries into platform technologies and demonstrate the potential and commercial viability in order to attract capital required for commercialization. For example, at Nanosphere, up to the point of first commercial product launch, we invested over \$100 million in converting nanoscience to scalable product technology. Many great nonscientific discoveries fail to attract the extensive capital required for commercialization, and for this reason, the gap between the research lab and the product prototype is often referred to as the Valley of Death. There is a great need to balance spending on basic research and translational work or goal-oriented development programs and to focus such programs on specific areas with the greatest promise to benefit the national interest. (p. 42)

Moffitt's statement demonstrated the idea that government funding should include basic and applied research. Shortly after his testimony, the NNI increased its

spending on applied nanotechnology research programs (ROCO, 2009). Since 2009, nanotechnology applied research has resulted in

- 1,000+ consumer products utilizing nanotechnology at the end of 2011,
- 54% of all new nanotechnology originating within the United States,
- 18,000 nanotechnology patents being issued to U.S. companies between 2009 and 2011, and
- 5,400 U.S. companies actively developing products based on nanotechnology (Shapira, Youtie, & Kay, 2011).

Government funding was vital to early nanotechnology development. Basic research funded by the government and conducted by NNI partners laid the foundation for expansive applied research. Further investment and focus by the government in applied nanotechnology research helped defray costs that may have kept industry from investing in nanotechnology research. This led to explosive growth over a short period of time, making the U.S. a leader in nanotechnology.

c. Generalized Findings

The common economic thread found in the development of nuclear power and nanotechnology is an industry leader reluctance to fund research and development, especially applied research. The reluctance to invest in research can be traced to private industry's responsibility to investors. Private firms need to show investors that a practical use exists for any new technology the company wants to develop in order to secure funding. Without a practical use, investors may be hesitant to fund developing technologies. The PRDP helped industry realize the practical application of the nuclear reactor by offsetting the development of various reactor designs, ultimately developing the light water reactor that proved economically viable. Government investment into basic and applied R&D by the NNI removed industry burden to invest in an unproven technology. Basic research in nanotechnology structures and manipulation provided the foundation for industry development of commercial nanotechnology products by reducing capital costs.

3. Technological Factors

Private industry guards its research and development in ways similar to countries guarding state secrets. Without sharing of information, the potential for duplicate research and effort can waste resources and time, slowing the development of new technology, increasing costs and time to commercialization.

a. Technological Factors and Nuclear Power

When the AEC was established in 1946, research into nuclear energy for civilian use was still in its infancy. Numerous technical questions required answers. Fuel behavior, safety concerns, moderator types, and nuclear theory were still in development (Allen, 1977). To answer these questions, the AEC was tasked with determining

- what to study and fund,
- where to conduct research, and
- how to coordinate research (Allen, 1977).

To accomplish these tasks, the AEC centralized nuclear design and engineering at the Argonne National Laboratory (Allen, 1977).

The Argonne National Laboratory supervised all federal atomic energy at various sites around the country. This included the Materials Test Reactor (MTR) and Experimental Breeder Reactor, both located in Idaho, and the intermediate power breeder located at GE's site in Schenectady, NY (Allen, 1977). The MTR was used to test materials, fuels, and coolant in an operational reactor and provided familiarity with light water reactors while the Experimental Breeder Reactor led to new components, materials, and maintenance practices (Allen, 1977).

Centralizing the control of information and projects meant that projects working in different areas of the country were not disjointed, allowing for more efficient research. This was key during the development of the submarine reactor for the Navy. While GE and Westinghouse were competing with different designs to use on submarines, they both had access to the pool of research and information at Argonne (Allen, 1977). Because of this, the programs had similar beginning points in the basics of

nuclear energy and could spend less time on R&D. The light water reactor designed for the submarine program became the basis for all commercial reactors in the U.S.

Centralization of nuclear R&D at the Argonne National Laboratory was key to early nuclear power development. Research was focused and shared, leading to cheaper initial development costs for industry. Centralized information also allowed companies to move to practical applications sooner. The early knowledge and experience gained with the light water reactor established the reactor as a stable design, a key in the final PRDP phase towards commercialization.

b. Technological Factors and Nanotechnology

Nanotechnology development was slowed by a lack of processes and technologies to facilitate collaboration across diverse fields. Additionally, the supply of standard lab equipment was insufficient for the rapid increase of nanotechnology research and the ever-changing laboratory equipment needs (Roco, 2006). To facilitate collaboration among the various entities involved in nanotechnology research, the NNI established the National Nanotechnology Initiative Network (NNIN; Roco, 2006). The self-described mission of the NNIN is the following:

The National Nanotechnology Initiative Network is an integrated networked partnership of user facilities, supported by the National Science Foundation, serving the needs of nanoscale science, engineering and technology.

The mission of NNIN is to enable rapid advancements in science, engineering and technology at the nano-scale by efficient access to Nanotechnology infrastructure. We provide shared open, geographically distributed laboratories, each with specific areas of technical excellence, and provide fabrication, synthesis, characterization, and integration resources to build structures, devices, and systems from atomic to complex large-scales. Our users belong to diverse areas: astronomy, plant pathology, materials science, physics, chemistry, life-sciences, various branches of engineering, etc., and come from academe, national laboratories, and industry. Projects may be short term or long term, from Academic or Industry, and range from pure research to prototype product development. Users can perform research on-site using facility equipment, training and staff support. For many tasks, remote usage is also feasible. External users typically spend a week or two, or commute, to complete

their work although longer visits are possible. We help users succeed by providing strong pre-visit technical interaction, mechanisms that let users protect their intellectual property, and strong training and knowledge support. (NNI, 2012)

The NNIN provides a network of research centers specializing in various technical aspects of nanotechnology. Each center contains fully equipped laboratories that can be used by any organization conducting nanotechnological research. Development of the NNIN has evolved as collaboration technology has involved. The ubiquity of the Internet has increased the availability of the NNIN resources.

Outdated equipment and lack of cooperation hampered early nanotechnology growth. The NNIN laboratories provided NNI organizations with modern equipment and a cooperative research environment that encouraged the open sharing of information among participants.

c. Generalized Findings

When the nuclear power and nanotechnology industries were in the early stages of development, duplicate research and lack of communication slowed both programs. This was addressed by the establishment of centralized infrastructures for the development of the two industries. The Argonne National Laboratory served as a control center for the early development of nuclear power while the NNIN established a network of specialized research centers. These centralization allowed different companies and research sites to access information and technology from other sites. This collaboration minimized time lost when issues arose because the issues could be simultaneously addressed from multiple angles while also reducing costs to individual firms because much of the information they needed was easily accessed.

4. Environmental and Social Factors

We combined the environmental and social factors and addressed them together. The idea that environmental factors are a concern arises from societal concern about the environment. Therefore, environmental and social factors are closely interwoven and worthy of discussion as one unit.

How an industry will impact the environment is generally unknown at the beginning of technology development and often slows social acceptance of the new technology. Conversely, if an older, related industry is viewed in a positive fashion, the new industry may experience social acceptance before environmental concerns are addressed. Addressing environmental and social concerns or misgivings early and often helps new industries reach social acceptance.

a. Environmental/Social Factors and Nuclear Power

Today, many associate the environmental effects of nuclear power with the Three Mile Island incident of 1979, the Chernobyl meltdown of 1986, and the Fukushima disaster of 2011. In the early years of nuclear power, most people did not know or think about the environmental and social issues of nuclear power. Most looked at nuclear power as “clean” energy, especially compared to coal-powered plants (Ga’ndara, 1977). The government, recognizing the unknown risks involved in the commercialization of nuclear power, included public safety in the mandate for the AEC (Rolph, 1977).

Immaturity of early reactor technology meant establishing consistent standards for location, construction, and operation. The measures established were not objective but subjective to the plant being built and were designed to ensure public safety and confidence in nuclear power (Rolph, 1977). Small reactors, containment vessels, and distance from population centers would serve to minimize the effects of a nuclear incident, not prevent one. The public did not pay much attention to the regulations put forth by the AEC (Rolph, 1977) regarding nuclear safety. The public noted the immediate difference on the environment between nuclear power and coal-powered plants. Coal plants visibly polluted the air and needed fuel storage and transportation facilities, while mining for coal was also coming under scrutiny, making nuclear power more appealing to companies (Ga’ndara, 1977).

Early nuclear power development was not hampered by modern-day societal concerns of radiation release and disposal. Still, the AEC recognized potential issues and incorporated basic safety concerns into licensing requirements. Of more

concern to the general public was the growing recognition of pollution from coal-powered plants. The concerns about coal plants led to a greater public acceptance of nuclear power, encouraging companies to build nuclear reactors.

b. Environmental/Social Factors and Nanotechnology

In 2003 and 2004, society accepted a future in which nanotechnology is used to produce consumer products; however, there was recognition that potential occupational and health hazards associated with nanotechnology exist. The lack of information describing the health and environmental risks of manufactured nanoparticles and nanomaterials was an area requiring further study (Dreher, 2004). The nanotechnology industry had two options for dealing with societal concerns about the potential environmental and health implications of nanotechnology. In 2004, two toxicology studies of nanoparticles found that nanoparticles produced lung lesions and pulmonary granulomas in laboratory mice. Further studies demonstrated that existing OSHA exposure standards did not provide adequate protection from nanoparticles (Dreher, 2004). These examples of the potential health concerns regarding nanoparticles came to light in 2003 and 2004. In response, the NNI had two possible actions regarding societal concerns. First, they could ignore society's concerns and continue with nanotechnology research. Second, they could accept the concerns and integrate environmental and health impacts of nanotechnology into the research structure (Brumfiel, 2003).

The NNI realized that ignoring societal concerns was not a viable method to ensure the continued research and commercialization of nanotechnology. The NNI cited the example of transgenic crops (Brumfiel, 2003). Transgenic crops were introduced in 1982 and almost immediately came under fire from the public. Producers of transgenic crops in the early years chose to insist that the crops were safe and not to conduct additional research into the long-term impacts of genetically modified crops (Brumfiel, 2003). The result was a public who shunned transgenic crops, ultimately delaying the advancement and commercialization of the industry (Brumfiel, 2003). In response to societal concerns about nanotechnology, the EPA, NIH, National Toxicology

Program, and the National Institute of Environmental Health (NIEH) identified five nanotechnological environmental and health areas requiring further study, which were incorporated into the NNI research plan:

- exposure risks to manufactured nanoparticles;
- toxicology of manufactured nanoparticles;
- extrapolation of nanoparticle toxicity using existing nanoparticle data;
- environmental and biological fate, transport, persistence, and transformation of nanoparticles; and
- recyclability and sustainability of manufactured nanomaterials (Dreher, 2004).

The NNI also established the annual Nanotechnology Environmental and Health Implications (NEHI) working group that brought government and academic research together with industry. The outcome of these annual NEHI meetings was as follows:

- research emphasis on addressing unexpected consequences of nanotechnology by anticipation and corrective actions;
- programs designed to increase public awareness of nanotechnology and the results of environmental and health studies;
- integration of social scientists, economists, and the public into integrated teams working with researchers; and
- commencement of nanotechnological projects exploring the social implications of nanotechnology. Appendix B lists the social problems and nanotechnology contributions (Roco & Bainbridge, 2005).

The NNI recognized potential societal and environmental concerns early in nanotechnology development. Instead of ignoring these concerns, the NNI established specific environmental and social research areas. It also established an annual workgroup to address potential consequences of nanotechnology growth. These increased public acceptance of nanotechnology by accepting and mitigating society's concerns about the impacts of nanotechnology.

c. Generalized Findings

Society generally decides when an environmental issue becomes a decision factor in industry. We have seen this recently in the rise of green technologies such as electric and hybrid automobiles as more people become concerned with their carbon footprint. Likewise, nuclear power enjoyed early social acceptance because of environmental effects caused by coal-fired power plants.

More importantly, though, we see proactive steps taken by the government to address potential concerns or issues. The addition of the five factors requiring further study in the NNI research plan addressed the concerns of the public, while early licensing requirements for nuclear power plants took into account the relative unknown dangers of nuclear power by reviewing requests based on size, location, and containment. While the actions taken for these two programs may not provide protection for the public, they helped alleviate concerns, reducing resistance and accelerating social acceptance.

5. Legal Factors

One of the most important legal factors in business is ownership. Ownership of technology or equipment gives a company the freedom to determine how they will use the technology with little or no interference from the government or outside companies. In nuclear power and nanotechnology, we continue to see ownership play a key role in encouraging industry participation.

a. Legal Factors and Nuclear Power

When originally established by the 1946 Atomic Energy Act, the AEC had cognizance over military and civilian atomic energy uses. The overriding task assigned to the AEC was to ensure information pertaining to nuclear energy was released only if such information would not jeopardize national security (Perry et al., 1977). Information security was a hindrance to industry because the application process was arduous (Allen, 1977). Industry was not permitted to use or own material required to make nuclear fuel, known as fissionable material, or own and operate nuclear reactors (Allen, 1977). The

AEC informed Congress that these policies negatively affected industry interest, leading to the Atomic Energy Act of 1954.

The Atomic Energy Act of 1954 was intended to encourage industry to take a greater role in early development of nuclear power. The Atomic Energy Act of 1954 allowed industry to own reactors and use (but not own) nuclear materials, enabled easier access to information, eased patenting requirements, and authorized the AEC to provide financial and research assistance (Allen, 1977). The AEC was also prohibited from building reactors for the generation of commercial electricity (Allen, 1977). While these changes did not lead to a rush of industry participation in nuclear power, they established the groundwork for the PRDP, as discussed in the Economic Factors and Nuclear Power section.

Government control and ownership of nuclear materials and reactors acted as deterrents to private industry investment in early nuclear power development. Relaxing these requirements in the Atomic Energy Act of 1954 laid the groundwork for the PRDP and legalized private ownership of a nuclear reactor.

b. Legal Factors and Nanotechnology

Industry is reluctant to spend money, time, and effort developing nanotechnology when ownership of intellectual property is unclear. Nanotechnology's legal challenges concerned the ownership of nanotechnology, specifically, the ownership of research by industries receiving funding from the federal government and technology spun off from academic institutions (Newberger, 2003). Nanotechnology also experienced conflicts with the idea of academic early disclosure. Industry faced a similar disclosure issue. Often the nanotechnology industry needed additional capital to exploit research gains. This capital required disclosure of research results, often times before patents were filed (Newberger, 2003). Before nanotechnology research could be expected to return commercializable results, the following ownership questions had to be answered:

- explain the relationship between government funding and ownership of intellectual property,

- understand how to protect industry intellectual property and allow industry to seek additional capital, and
- define nanotechnology in regards to patent application (Newberger, 2003; O'Neill, Hermann, Klein, Landes, & Bawa, 2007).

The passage of the Bayh-Dole amendments (Patent Act, 1980) to the Patent Act, 35 U.S.C. § 200–212, allows business entities and non-profit organizations to retain intellectual property ownership rights for federal government-sponsored research. The passage of the Bayh-Dole amendments (Patent Act, 1980) effectively solved the ownership issues arising from government-sponsored research.

Industry continually faces pressure to disclose intellectual property found during nanotechnology research in order to receive outside capital to continue development (Newberger, 2003). One such method is the use of provisional patent applications. Provisional patent applications allow the filing of an early patent purely to protect the “art” or the idea of the patent from later filing. Provisional patents are not true patents; they serve only to protect the intellectual property for 12 months while a full patent application is submitted. Provisional patents allow industry to file for patent protection in order to disclose a discovery or research finding in order to seek capital. At the end of the 12-month period, a full patent application must have been received by the U.S. Patent and Trademark Office (USPTO) or the provisional patent expires (USPTO, 2013).

The granting of nanotechnology patents, provisional or otherwise, was compounded by the number of patents filed for demonstration purposes, and a lack of standard nanotechnology terminology leading to vague and overlapping patents (O'Neill et al., 2007). Many companies found their nanotechnology patents effectively worthless due to the vagueness of early nanotechnology patent vocabulary. To solve this problem, the USPTO partnered with industry, academia, and government nanotechnology experts to help solve the patent problem (O'Neill et al., 2007). The USPTO also partnered with the Institute of Nanotechnology to develop standard terminology. In 2007, the USPTO created a unique patent class for nanotechnology. These nanotechnology standards prevented companies from using and patenting ideas such as nanoparticle and

nanostructure, items considered basic knowledge within the nanotechnology industry. Training of USPTO patent examiners in nanotechnology vocabulary further reduced the granting of vague and overlapping patents (O’Neill et al., 2007).

Intellectual property is in some cases more important to industry than physical property. The ability for a company to claim a product or advancement as its own is essential to obtaining funds. Companies were slow to receive private investment due to a fear of being unable to receive economic gain from nanotechnology. The government recognized these concerns and took action. Through legislation and changes to patent laws, the intellectual property rights of new discoveries and government-funded research were protected to encourage industry participants to continue nanotechnology development.

c. Generalized Findings

No matter the field, industry needs assurance that the results of resources spent developing new technology will belong to the company. Potential competition, especially from the government, can keep companies from investing in research and development. In both Nuclear Power and Nanotechnology, ownership concerns were addressed through Congressional action or new regulations. The Atomic Energy Act of 1954 prevents the AEC from owning reactors to sell electricity, removing government as a potential competitor. The Bayh-Dole amendments (Patent Act, 1980) provide industry ownership of technology developed using federal dollars. Intellectual property was protected in the private and academic sectors by changes made in the patenting process. These government actions encouraged industry investment in nuclear power and nanotechnology.

6. Summary of Generalized Findings

Through our PESTEL analysis of nuclear power and nanotechnology, we identified the key elements of each PESTEL factor for each industry. We determined the similarities between the factors of each case, and identified generalized findings for comparison to biofuels. The generalized findings are summarized in Table 5.

Factor	Generalized Findings
Political	National innovation system
Economic	Practical application and sufficient R&D funding
Environmental/Social	Social acceptance
Technology	Centralized research infrastructure
Legal	Ownership

Table 5. Generalized Commercialization Factors From Nuclear Power and Nanotechnology

A National Innovation System such as the Atomic Energy Commission or the National Nanotechnology Initiative encourages industry participation in programs of national interest. This encouragement can be in the form of funding, research assistance, or sharing of information, and is designed to streamline a new technology's development. This NIS may provide sufficient R&D funding and help identify a practical application for a new technology earlier than if industry was developing the technology alone. Additionally, a centralized research infrastructure such as the Argonne National Laboratory and the NNIN, intended to focus R&D and prevent overlap and repeat work, may be put in place by the NIS. These infrastructures lend themselves to more rapid growth of a new technology because they encourage sharing of ideas, new equipment, and potential problems among participants. Environmental issues are driven by societal concerns. This leads to the idea that social acceptance of a new industry, the industry's potential effects, and the steps taken by the government and industry to address and mitigate these effects is paramount to successful commercialization. Finally, legal ownership of property, both physical and intellectual, encourages companies to enter early into a new technology.

While two of these findings (practical application and sufficient R&D funding, and centralized research infrastructure) can be identified as having been spawned from another of the findings (national innovation system), all are important to commercialization of an industry. Each appeals to a different concern for private industry involvement. Both nuclear power and nanotechnology were in the early stages of development when the government became involved. These factors contributed in some way to the development of both of these technologies.

B. COMPARISON TO OTHER LITERATURE

In Chapter III, we discussed the use of triangulation to confirm our research findings. In this section we apply the idea of triangulation to our research results as highlighted in Table 5. We compared our research results to those found in five studies on commercialization success factors. The five studies chosen were the following:

- “Technology Commercialization: Have We Learned Anything?” (Allen, 2012),
- “The Government’s Role in the Commercialization of New Technologies: Lessons for Space Policy” (Rose, 1986),
- “Key Success Factors for R&D Project Commercialization” (Astebo, 2003),
- “An Integrative Model to Explain the Ability to Commercialize Innovations: Linking Networks, Absorptive Capacity, Ambidexterity and Environmental Factors” (Datta, 2011), and
- “Innovation and Commercialization of Emerging Technology” (Office of Technology Assessment [OTA], 1995).

These sources complement our triangulation strategy by providing alternate views to our research. Allen (2012), Rose (1986), and Datta (2011) present qualitative analysis of commercialization using frameworks that differ from the PESTEL framework. Astebo (2003) seeks to understand commercialization factors by using a statistical approach, thus bringing quantitative comparisons to our qualitative research. Finally, the OTA article presents a government take on commercialization. The varying research methods selected for comparison broadened the horizon for understanding commercialization. This method is known as convergent triangulation (Jick, 1979).

Our findings for the environmental/social, technology, and legal factors were supported by these five sources, despite that fact that we used different terminology and analysis methods. In the remainder of this section, we discuss the political and economic factors influencing commercialization and present alternative suppositions as presented by the authors.

1. Political Factors

We identified a national innovation system as the single most important political factor influencing commercialization of technology. A part of a national innovation system is a country's academic institutions and their associated research.

In her article "Technology Commercialization: Have We Learned Anything?," Kathleen Allen discussed the role of universities in the commercialization of new technology. She presents the idea that academic inclusion in a national innovation system can actually reduce the rate of commercialization of new technologies (Allen, 2012). Allen cites the Bayh-Dole Act (Patent Act, 1980), which allows academic institutions to own the research findings of federal-funded programs, as the cause of brain drain at the university level (Allen, 2012). She attributed this brain drain to a desire by researchers to commercialize their research, which can only occur from within industry (Allen, 2012). She found this phenomenon occurred within all industries and academic research environments, but particularly those in high-tech fields such as biotechnology (Allen, 2012). Moreover, she concludes that researchers who choose to remain within the academic environment are shifting from basic research to applied research, possibly undercutting the basic research required to make the next great technological advance (Allen, 2012).

Nancy Rose presented an alternative view to the importance of national innovation systems in her article "The Government's Role in the Commercialization of New Technologies: Lessons for Space Policy." Rose directly challenges the idea of government involvement in commercialization. She said, "Government policies to hasten commercialization of a technology typically are quite costly relative to their accomplishments, and frequently are counter-productive to their objective" (p. 114).

Her first argument against government involvement in commercialization rejects the idea that market failures result in commercially viable projects failing to commercialize. She cited her case study of 24 federally funded demonstration projects including the Super Sonic Transport (SST), Clinch River breeder reactor, and a variety of Synfuel projects that failed to produce commercially viable products. Her study found

that the percentage of non-governmental investment was a key indicator in determining which projects would ultimately be successful (Rose, 1986). She attributed the willingness of industry to invest in a project as a direct correlation to the project's potential for commercial success and said, "Industry reluctance to provide capital for commercial development is therefore a signal of the project's discouraging economics rather than a market failure" (p. 114).

Rose's second argument against government involvement in commercialization questions the true economic benefits of accelerated technology development. While early adoption of new technology may provide political benefits, it may not be the best path to ensure commercialization (Rose, 1986). She supported her argument by looking at the aircraft industry at the end of the 1940s. Germany and Britain both produced an operational jet fighter by 1944. However, the United States may have realized second-mover advantages by following and not producing an operational jet fighter until 1945/46 (Rose, 1986). Specifically, the U.S. began production with an understanding of jet propulsion, including efficiency and structural fatigue not available to Germany or the United Kingdom. Providing another example, she said, "Perhaps the strongest example of potential second-mover advantages is Japan's success in high technology commercial enterprise, even though that nation rarely has been at the forefront of technology invention and innovation" (p. 114).

The alternate ideas proposed by Allen and Rose in their studies conflict with our research findings by suggesting that government involvement does not accelerate commercialization. Rather than choosing to disregard our work, or disregard the work of Allen and Rose, we accept their findings as an indication that the political environment is complex. Often times, political actions have negative externalities such as the academic brain drain presented by Allen. Sometimes the achievement of a grand scientific accomplishment, such as those proposed by the AEC or the NNI, has benefits that outweigh the purely economic analysis presented by Rose.

2. Economic Factors

We concluded that the most important economic factor in the successful commercialization of new technology is recognition of practical application and sufficient funding to continue development. Thomas Astebro disagrees.

In his article, “Key Success Factors for R&D Project Commercialization,” he uses statistical regression to determine which factors influence technology commercialization. His model suggests that 80.9% of commercialization behavior can be explained by the factors of expected profitability (practical application), technological opportunity (capital availability), legal protection (ownership), and development risk (Astebro, 2003). Development risk is not an economic factor represented in our PESTEL analysis and is worthy of discussion. Astebro defined development risk as the inherent risk of developing a new and untested technology expressed in economic terms (Astebro, 2003).

In “An Integrative Model to Explain the Ability to Commercialize Innovations: Linking Networks, Absorptive Capacity, Ambidexterity and Environmental Factors,” Avimanyu Datta (2011) provides an alternate explanation for economic factors influencing commercialization of technology. Datta (2011) suggests that the type of economic market plays a large role in the potential success of commercialization. Type of market refers to either an existing technology market or a new market created by a new technology (Datta, 2011). Regardless of the technology being commercialized, Datta suggested that entering an existing market is more difficult than creating a new market and those firms creating a new market are more likely to successfully commercialize a product (Datta, 2011).

The ideas proposed by Astebro and Datta complement our research. We simplified our research and selected the most important economic factor based on our cases. Astebro and Datta’s research indicates that the economics of commercialization are complex. When compared with our research, their research identifies additional economic variables that should be included when attempting to understand successful commercialization.

C. BIOFUEL COMMERCIALIZATION

1. Political Factors and Biofuel

Efforts to commercialize the biofuel industry were initiated by the federal government in a manner similar to nuclear power and nanotechnology. The DoE and the DoA are the lead government agencies responsible for the current biofuel effort. In Chapter II, we discussed the Aquatic Species Program which ran from 1970 to 1996, and the current biomass program administered by the DoE Office of Energy Efficiency and Renewable Energy (EERE; DoE, 2012).

Annually, the DoA and DoE host the Biomass Research and Development Initiative, where the Biomass Research and Development Technical Advisory Committee (TAC) hold public workshops designed to promote the development of biomass-based products. The TAC charter lists three official functions of the committee:

- advise the Secretary of Energy and the Secretary of Agriculture on the technical focus and direction of requests and proposals issued under the biomass initiative;
- facilitate consultations and partnerships among federal and state agencies, agricultural producers, industry, consumers, the research community, and other interested groups to carry out activities related to the biomass initiative; and
- evaluate and perform strategic planning for initiative activities (DoE, 2012).

The joint DoE and DoA biomass industry development efforts have several elements in common with our definition of an NIS; however, they differ in several ways. First, the biomass program does not focus solely on the development of biofuels. Biofuels are a relatively minor subset of the biomass industry and are not the primary focus of the biomass program. Second, no single government organization is responsible for the development and commercialization of biofuels. The combined DoE and DoA program often leads to confusion among various agencies in academia, government, and industry, regarding research priorities and specific agency roles (DoE, 2012). The fragmented nature of the biofuel research effort leads us to believe that it is less likely to result in commercially viable products within the desired timeframe.

2. Economic Factors and Biofuel

Our research found that practical application and sufficient R&D investment were the key economic factors for commercialization of technology systems. Neither factor appears to be present in the biofuel case.

Total federal funding for biofuel programs from 1997 to 2012 (15 years) was \$4 billion (DoE, 2012). Nanotechnology, in contrast, has received \$14.9 billion in federal funding during the same time frame. This demonstrates a lack of sufficient R&D capital needed to quickly commercialize the biofuel industry.

The relatively low price of fossil fuels continues to be a major hurdle for the development of biofuels. In late 2011, the U.S. Navy paid \$26 per gallon for biofuel. During the same time, the price of military-grade diesel was \$2.75 per gallon. Industry is unlikely to invest heavily in new technologies that do not provide practical application and clear economic benefit. In Chapter II, we discussed the growth in petroleum production throughout the world, driven by new technology in petroleum extraction. The ability to economically extract new sources of oil keeps the cost of petroleum low and is expected to continue into the foreseeable future. Low oil prices and proven oil extraction technology continue to discourage investment in biofuels and challenge the idea that biofuels are a practical and economically viable technology. Petroleum is a commodity and petroleum prices are set by worldwide supply and demand. Biofuels are a substitute to petroleum; however, they remain subject to worldwide supply and demand. While worldwide petroleum production is increasing, industry has no incentive to spend large amounts of time and money on an unproven product with questionable economic return. The lack of practical application of biofuels and limited federal investment in R&D appear to be hindering the commercialization of biofuels.

3. Environmental/Social Factors

Biofuel faces several environmental and social challenges to commercialization. As the population of the United States continues to become socially aware, it demands products and services that meet social responsibilities. In Chapter II, we discussed the

negative externalities of first-generation biofuel feedstocks such as corn and sugarcane.

Those externalities are

- long-term worldwide food price increases,
- reduction of available land for growth of food supplies, and
- increased carbon footprint due to clearing of land and reduction of carbon removal capacity.

In our research, we expressed the idea that for commercialization to succeed government and industry must identify and incorporate environmental and social concerns in the research and development process. We see this incorporation of social concerns within the biofuel commercialization effort. In Chapter I, we introduced the Energy Policy Act of 2005. Under this act, the federal government requires biofuels to generate less life-cycle greenhouse gas than the traditional petroleum it replaces and caps the maximum production of biofuels based on first-generation feedstocks in order to reduce the impact on food prices. The limitations on first-generation feedstocks found in the Energy Policy Act of 2005 effectively create a demand for second-generation biofuels based on byproducts, feedstock capable of growing on marginal lands, and algae. The joint DoE and DoA TAC also includes an interagency workgroup responsible for identifying and mitigating the environmental and social impacts of biofuels (Biomass Research and Development Board [BRDB], 2012). The TAC environmental and social working group is responsible for promoting research activities designed to reduce biofuel life-cycle carbon emission and the human health impacts of biofuel (BRDB, 2012).

The efforts described previously are a demonstration of the federal government's acceptance of the need to address social concerns about biofuels. The subsequent laws and working groups promoting environmental and social awareness meet our definition of successful social factors likely to positively influence commercialization of biofuel.

4. Technological Factors

The biofuel industry does not operate under the umbrella of a single coordinating government entity. As discussed in Section C, Paragraph 1, of this chapter, the biofuel industry is loosely led by agreements between the DoE and DoA. While both

organizations desire to promote the open sharing of biofuel technology, we do not see the level of collaboration between industry seen in the nuclear power and nanotechnology cases. Without a strong cooperative influence, a system of collaboration for sharing of information and resources within the biofuel industry has not been created. No organization similar to the Argonne National Laboratory or the NNIN exists for the biofuel industry; thus sharing of technology and information depends mostly on the extent that industry chooses to create partnerships.

The lack of collaborative technology does not mean the biofuel industry will not end with a commercialized product. However, it is likely that the process for commercialization is slowed as each company spends resources on basic and applied research, without gaining the efficiencies found in collaboration.

5. Legal Factors

Our key legal factor of ownership, or the ability to own the product created through research and development, is present in the biofuel industry. We see the idea of ownership in the 2,796 biofuel patents issued between 2002 and 2008. In 2006 and 2007, the number of patents issued in the biofuel industry increased by 150% per year. In 2007, the number of biofuel patents issued was 25% greater than the combined total of solar- and wind-power patents awarded (Ronald & Mandar, 2008). Biofuel industry intellectual property ownership is protected and benefits from the same laws as nuclear power and nanotechnology discussed in Section A, Paragraphs 5a and 5b, of this chapter.

Clearly defined ownership of intellectual property associated with research and development spending is a key factor that leads to commercialization of a technology. Companies that successfully patent ideas in emerging technology markets such as biofuels establish industry standards, giving the company a high probability of emerging as a dominant player in the field (Wolek, 2011). In the case of biofuels, it is likely that the legal protection offered by U.S. patent laws, specifically laws such as the Bayh-Dole amendment (Patent Act, 1980), are encouraging commercialization of biofuel technologies by providing industry assurance of intellectual property ownership.

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VI. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

In Chapter V, we applied the PESTEL model to the nuclear power and nanotechnology industries to deduce the factors that lead to successful commercialization. We determined the following factors contributed to commercialization:

- existence of a national innovation system,
- practical application for new technology and sufficient R&D investment,
- acceptance of social concerns about new technology,
- existence of a collaborative technology for open sharing of research information and infrastructure, and
- ownership rights for intellectual property.

We compared these factors to the current state of the biofuel industry and found several areas where there is opportunity to improve the U.S. biofuel commercialization effort. The remainder of this chapter discusses our recommendations for improving the biofuel commercialization effort, the limitations of our study, and our recommended areas of further study.

A. RECOMMENDATIONS

The following recommendations are based on our research regarding commercialization of nuclear power, nanotechnology, and biofuel. They are structured using the PESTEL framework which we used for our analysis.

1. Political Recommendations

Designate the DoE as the lead government organization responsible for commercialization of biofuels. The current partnership between the DoE and the DoA creates confusion among participants in government biofuel programs. The DoA plays a vital role in biofuel development due to the agricultural nature of biofuel; however, it does not have the background in energy policy. The DoA should remain involved in biofuel development, but as an advisor to the DoE. The biofuel working group should be separated from the annual biomass working group. Participants in the biofuel working

group should form the basis for the permanent DoE-led biofuel initiative. A separate biofuel working group (initiative) would be free from the limitations and agendas of the parent group. These changes would result in a unified biofuel innovation system that meets our definition of an innovation system introduced in Chapter V.

2. Economic Recommendations

Biofuels face stiff competition from traditional petroleum. As previously discussed, advances in petroleum extraction continue to result in adequate petroleum reserves to meet worldwide demand for the foreseeable future. Sufficient supply keeps worldwide petroleum prices relatively low, hindering biofuel's ability to compete. Short of increasing taxes on oil or subsidizing biofuel, there is little the government can do to show a practical economic need for biofuel. We recommend that the government continue current subsidies for feedstocks deemed desirable to avoid wasting money and effort developing feedstocks causing negative externalities. Additionally, the government should shift biofuel spending from procurement to direct R&D spending. The current government model provides the majority of government investment through the purchase of usable biofuels. The purpose of this policy is to support emerging companies while they refine and develop production techniques required to produce commercially viable biofuel. The government believes these companies will be able to lower costs, either through economies of scale or through advancements in production technology. However, we believe that requiring companies to provide a useful end product the government actual retards the commercialization of biofuels by directing spending toward production instead of R&D. One promising biofuel feedstock is algae; however, current algae production is not economically viable due to the cost of production and the amount of oil produced by the algae. Rather than requiring algae producers to provide a usable end product, the government should directly fund the R&D of new algae production technologies and the genetic alteration of algae to produce more oil. This direct spending is more likely to result in commercialization of algae biofuel because it addresses why algae is not commercially viable. Direct government R&D spending does not require companies to invest in capital-intensive production facilities that may or may not be usable as production technology matures.

Government investment in biofuels is insufficient to generate rapid progress in commercialization. As discussed in Chapter V, \$14.9 billion were spent on the development of nanotechnology between 1997 and 2012. Only \$4 billion were spent on biofuels during the same period. Today we have a multitude of commercially viable nanotechnology products, while all biofuel products rely on some form of government (federal, state, or local) subsidy. The government should make a sizeable increase in the amount invested into biofuels, but only after implementing the organizational and policy changes recommended in the political and economic section of this thesis.

3. Environmental/Social Recommendations

The government must create a policy regarding identifying biofuel feedstocks allowed for use within the United States. Selection of feedstocks that minimize negative externalities is vital to the commercialization of biofuel. We recommend the DoE discourage biofuel research that uses first-generation feedstock such as corn, sugarcane, and other food-based feedstocks. These feedstocks compete directly with food supplies for resources, including land, and indirectly increase the cost of food. This negative effect has been seen in numerous studies in many countries. Use of food waste to generate biofuels should not be limited under this policy. Second- and third-generation feedstocks such as algae and jatropha do not increase food prices and can be grown on marginal lands, thus not competing for scarce agricultural resources.

4. Technology Recommendations

Create a centralized collaboration technology similar to the NNIN for sharing biofuel research and resources. This recommendation requires the implementation of the recommendations found in the political and economic sections. Once a preferred feedstock type is selected and government spending is focused on research versus procurement of biofuel a centralized collaboration structure is needed.

5. Legal Recommendations

Current intellectual property laws provide protection for companies and assurance that resources spent will result in ownership. It is up to the USPTO to recognize any

differences that may arise within the biofuel industry that require specific intervention to clarify and protect ownership, similar to the nanotechnology case.

6. Summary

In this paper we identified factors that influence commercialization of technology systems and applied them to the government biofuel effort. We used the PESTEL framework and a grounded theory case study methodology to analyze previous government commercialization endeavors. Using nuclear power and nanotechnology examples we identified key success factors and compared them to the biofuel effort. Finally, we recommended changes to improve the government biofuel effort. Table 6 summarizes the lessons learned from nuclear power and nanotechnology as well as the recommendations for government biofuel program.

Factor	Lessons Learned from Nuclear Power and Nanotechnology	Recommendations for Biofuel
Political	National innovation system	(1) Designate DoE as government lead (2) Separate biofuel working group from biomass working group
Economic	Practical application and sufficient R&D funding	(1) Shift biofuel spending from procurement to dedicated R&D (2) Increase federal biofuel R&D spending
Environmental/Social	Social acceptance	Select feedstock with fewest negative externalities (algae, jatropha, etc.) to focus R&D efforts
Technological	Centralized research infrastructure	Create centralized collaboration technology to share basic biofuel research
Legal	Ownership	None, current patent laws sufficient

Table 6. Summary and Recommendations for Biofuel.

B. LIMITATIONS OF STUDY

This section presents a consolidated list of the assumptions and limitations of this work. This section acknowledges these assumptions and limitations, and provides the reader with a list of additional topics for review.

1. Assumptions

The following assumptions were made during the course of this study:

- biofuels are important to national security and are a national priority worthy of study;
- government investment is required to commercialize the biofuel industry;
- the biofuel industry is not currently operating in a commercially viable state; and
- nuclear power and nanotechnology are examples of successful government-aided commercialization.

2. Limitations

We acknowledge the following limitations of our study:

- our discussion of second-generation biofuel feedstock in Chapter II focuses primarily on algae,
- our selection of successful commercialization cases was limited to nuclear power and nanotechnology,
- no unsuccessful commercialization cases were reviewed,
- application of only the PESTEL framework may not identify all relevant factors to commercialization, and
- the identification of a single factor for each part of the PESTEL framework may not explain all commercialization behavior.

C. AREAS FOR FURTHER STUDY

Notable areas of study that are not included in this project but could have an impact on the commercialization of biofuel are listed, and should be considered for further study:

- impact of government feedstock subsidies on the choice of feedstock research and development;

- the impact of oil prices on biofuel commercialization, including determination of the oil price that would make current biofuel production methods commercially viable;
- the likely response of oil-exporting nations to the development of commercially viable biofuels within the United States and other nations;
- under current pricing and cost models, what production capacity is required for various biofuel feedstock and production methods to be commercially viable; and
- a comparison of energy output between various biofuel feedstocks.

APPENDIX

A. FEDERAL GOVERNMENT ORGANIZATIONS PARTICIPATING IN THE NATIONAL NANOTECHNOLOGY INITIATIVE

Agricultural Research Service (ARS)
Bureau of Industry and Security, Department of Commerce (BIS/DOC)
Consumer Product Safety Commission (CPSC)
Department of Defense (DoD)
Department of Education (DoEd)
Department of Energy (DoE)
Department of Homeland Security (DHS)
Department of Justice/National Institute of Justice (DOJ/NIJ)
Department of State (DoS)
Department of Transportation/Federal Highway Administration (DoT/FHWA)
Department of Treasury (DoTreas)
Department of Labor/Occupational Safety and Health Administration (DOL/OSHA)
Environmental Protection Agency (EPA)
Food and Drug Administration (FDA)
National Aeronautics and Space Administration (NASA)
National Cancer Institute
National Institute for Occupational Safety and Health (NIOSH)
National Institute of Standards and Technology (NIST)
National Institutes of Health (NIH)
National Science Foundation (NSF)
Nuclear Regulatory Commission (NRC)
U.S. Department of Agriculture, Forest Service (USDA/FS)
U.S. Department of Agriculture, National Institute of Food and Agriculture (USDA/NIFA)
U.S. Geological Survey (USGS)
U.S. Intelligence Community
U.S. Patent and Trade Office (USPTO)
United States International Trade Commission (USITC)

B. SOCIAL TRENDS AND POTENTIAL NANOTECHNOLOGICAL SOLUTIONS

Social Problem	Nanotechnological contribution to solution
Healthcare and working capacity of aging population	Convergence of nanotechnology with biotechnology; neurotechnology would address chronic illness, loss of sensorial capacity, and maintenance of work capability
Collapse of birth rate in most advanced nations, below level required for population	Convergence of nanotechnology with biotechnology to overcome infertility
Poverty and inequality in under developed nations	Economic progress, fueled by technological developments requiring systematic control of nanoscale process and materials
Loss of jobs in advanced nations as work goes to nations with lower wages, weaker worker benefits, and worse workplace safety	Progress in nanoscience will allow industrial nations to maintain quality of life, generate new domestic industries with high-quality jobs, even as poor nations benefit from globalization
Threatened exhaustion of natural resources	Nano-enabled technologies for improved efficiency in use of non-renewable resources, including energy production, water filtration, and invention of many high-quality nano-fabricated substitute materials
Environmental degradation, including global warming	Reduced pollution from more efficient use of materials; specific new pollution remediation nanotechnologies; improved environmental monitoring by means of nano-enabled sensor nets
World political instability threatens the gains achieved by newly democratic nations	Stability requires technology that can offer abundance to a majority of people in all societies with existing natural resources; nanotechnology enables greater resource efficiency
Security issues within industrial nations	Numerous specific nanotechnology-based solutions, such as sensors to detect bioterrorism substances; inexpensive “smart labels” to deter theft of valuable goods; armor and vehicle components from nano-structure materials
Cultural chaos in a post-industrial, post-modern pluralist society	Nanotechnology will permit rapid progress in technologies of computation, communication, and creativity to sustain a culture of connectivity, equal access to information, and myriad subcultures simultaneously

Social Problem	Nanotechnological contribution to solution
In medicine, diminishing returns from research; rising cost of healthcare	Fresh approaches to disease diagnoses and treatment from nanotechnology; prevention of disease from better nutrition and from quick detection and treatment of conditions predisposing people to disease
Possible slowing of progress in many fields of science and engineering (e.g., aviation and space, nuclear power, computers)	Fresh ideas, research methods, and design approaches generated by convergence and combination of many fields, made possible by the nanoscale science and technology platforms. It will support rapid advancements in biotechnology and information technology

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