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Managing R&D Risk in Renewable Energy

Gordon Rausser and Maya Papineau[1]

Introduction

As crude oil prices move in the direction of $120 per barrel or higher, incentives for the U.S. economy to adjust by substituting renewable energy for fossil-based energy have intensified. In this process, governmental bodies will be pulled and pushed in the direction of subsidization support for emerging technologies. Moreover, now that corn prices have moved above $6 per bushel, another round of adjustments, substituting one source of feedstocks for another, will accelerate, including the possibility of eliminating tariffs on sugarcane-based ethanol. In the face of these dramatic market movements, public support for emerging clean energy technologies is a cornerstone of federal energy policy, whether implemented by the Department of Energy (DOE) or Department of Agriculture (USDA). Federal funds to promote clean energy are allocated on an annual basis across the spectrum of renewable energy technologies, utilizing a wide array of policy instruments, including R&D subsidization, demonstration projects, knowledge networks, education and awareness programs, tax credits, as well as direct subsidies. Moreover, given the size of market opportunities generated by the price of fossil-based energy sources, the private sector has begun to respond with material increases in renewable energy investment.

As their exposure in renewable energy technologies increases, private investors will inevitably seek public support from the government to protect the downside risk that might arise from future declines in fossil fuel prices. These technologies include, *inter alia*, cellulosic ethanol, biodiesel, sugar ethanol, corn ethanol, methanol, solar (including artificial organisms that convert sunlight into biofuel), a host of other feedstocks with genetic engineering modifications of plants, microbials, animal fats, animal waste and forest waste. State and federal governments will be drawn into support and subsidization for such potential innovations, whether the result of "learning by doing" or new discoveries. From the standpoint of societal welfare, the extent of such support is fundamentally a problem of ex-ante portfolio analysis under risk and uncertainty.

The historical experience of substitutable fossil sources of energy has revealed to all participants engaged in the development of renewable energy technologies that the prices of crude oil and natural gas will determine their economic viability. In the late 1970's the rapid expansion in the development of solar energy sources was brought to a screeching halt in the mid-1980's when crude oil prices plummeted to slightly over $10 per barrel. As a result, agents supporting each potential alternative renewable energy source will be actively engaged in lobbying to eliminate the downside risk that could well emerge (Rausser and Goodhue, 2002). For example, the coal industry has been estimated to have spent $7 million on federal lobbying in 2007 (www.politicalmoneyline.com). The framework emerging from this lobbying effort is the design of a subsidization program conditioned upon crude oil prices; if oil prices fall below $40 per barrel, the federal government would subsidize coal based liquid fuel plants, while if oil prices climbed above $80, liquefied coal companies would return to the government a surcharge. Similar structured risk swaps will be pursued by special interests investing in alternative technologies that are necessarily exposed to the risk of volatility in crude oil and natural gas prices. The implementation of such risk swaps in the commercialization of renewable energy technologies can be expected to be driven by a number of sustainable but uncertain forces, viz: global warming; geo-political risk; terrorism; the promise of genetic engineering and synthetic biology; other sources of environmental pollution; crude oil and natural gas prices; willingness of U.S. consumers to pay a premium for green energy; and U. S. rural development.

Governmental subsidization of corn and gasoline containing ethanol has been far less effective than Brazilian subsidization of sugar-based ethanol. Regardless, failure to perform an ex ante, objective analysis will likely lead state and federal governments to engage in the subsidization of selected

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technologies based on the effectiveness of lobbying efforts. Through the course of history, governments have failed badly in the design and implementation of industrialization policies. As demonstrated time and again, capital markets are far more agile than governments responding to market and commercial signals. Nevertheless, governmental support for renewable energy technologies, if properly designed, could well serve the public interest. The hope is, of course, that creating and/or supporting demand for clean energy and the cost for delivering such energy could well result in permanent and sustainable decreases in prices over the long run.

If major adjustments take place over the next decade, both public sector and private investment in renewable energy R&D will be crucial. Historically, private spending has contributed, on average, about one half of domestic R&D efforts; however, data up to 2003 suggest U.S. companies have cut their R&D spending by more than half (Kammen and Nemet, 2005). This downward trend is consistent with two well-known and related facts related to energy R&D. First, the criterion for determining the market value of R&D is the subsequent profitability of any breakthroughs, and to the extent that profitability understates the social benefits of breakthroughs, private R&D spending will tend to be under-provided by the private sector (Spence, 1984). Second, the existence of environmental externalities leads to incomplete markets and therefore under-priced or unpriced environmental goods, a second market failure that magnifies the R&D spillover effect by mitigating the profitability of new low-carbon technologies (Cropper and Oates, 1992). A combination of these factors and recent spending declines in aggregate energy R&D has led some researchers to call for increased public sector energy spending (Davis and Owens, 2003; Schock *et al.*, 1999), some at a scale equivalent to the Apollo Project of the 1960s (Nemet and Kammen, 2007).

Tempering such proposals, however, is the evidence that increased government spending "crowds out" private sector spending (Payne, 2001), and that new energy R&D crowds out other forms of R&D. This latter form of crowding out has been conjectured to affect estimates of social benefits accruing from public R&D spending (Popp, 2006). The crowding out phenomenon can also occur in the other direction, when reduced government spending is accompanied by greater levels of private spending (Heutel, 2007). This possibility is consistent with the fact that the recent downturn in company-level R&D funding has been accompanied by an almost tenfold increase in alternative energy venture capital investments between 2001 and 2007 (VentureOne, 2008). This paper presents the components of an ex-ante portfolio analysis of R&D risks in renewable energy.

Current R&D Renewable Energy Landscape

A key element in the innovation process that leads to productivity improvement is investment in building an economy's knowledge base through R&D. Both the federal government and the private sector are major players as well as stakeholders in this process, and both have an interest in successfully generating the path-breaking innovations that lead to enhanced productivity. Innovations in the renewable energy sector can create a double benefit by contributing to a nation's productivity growth while decreasing the impact of negative environmental externalities.

Public Sector

Renewable energy milestones promulgated by the Department of Energy are presented in Table 1. Ostensibly, these milestones suggest the federal government places a positive probability on path-breaking breakthroughs in cellulosic ethanol, hydrogen, solar and wind energy. Federal renewable energy R&D spending is intended, at least in part, to achieve these goals. Over the past twenty years, spending on energy R&D has remained more or less constant, whereas the share of renewable energy R&D has increased over the past ten years, as shown in Table 2.

Tables 3 and 4 present a more detailed breakdown of federal renewable energy R&D between 2001 and 2007. Both the DOE and USDA have bioenergy R&D programs. At the USDA, bioenergy R&D between 2002 and 2007 was carried out under the auspices of the Biomass Research and Development Act of 2000, which mandated that up to $14 million of Commodity Credit Corporation funds from the Farm Bill be allocated to R&D leading to the production of biobased

Table 1. DOE Renewable Energy Milestones

Cellulosic Ethanol	Cellulosic Ethanol Cost Competitive with Conventional Ethanol by 2012 Replace 30 Percent of Today's Gasoline in 2030 with Biofuels
Hydrogen	Industry Commercialization Possible by 2012 Fuel Cell Vehicles in the Showroom and Hydrogen at Fueling Stations by 2020
Solar	Reduce Solar Costs to Grid Parity in all U.S. Markets by 2015
Wind	Reduce Cost of Energy from Large Systems to 3 cents/kWh by 2010 Greatly Expand Demployment of Distributed Wind Energy by 2016 Large-Scale Offshore Wind and Hydrogen Production from Wind by 2020

Table 2. Federal Energy R&D

Year	Total Energy	Renewable	Share of Total
	($ millions)		
1987	3,142	482	0.15
1988	3,139	416	0.13
1989	3,428	404	0.12
1990	4,047	381	0.09
1991	3,844	482	0.13
1992	3,940	558	0.14
1993	3,316	613	0.18
1994	3,475	719	0.21
1995	3,355	770	0.23
1996	2,908	644	0.22
1997	2,638	627	0.24
1998	2,810	699	0.25
1999	3,111	763	0.25
2000	3,036	746	0.25
2001	3,401	800	0.24
2002	3,580	825	0.23
2003	3,425	779	0.23
2004	3,418	712	0.21
2005	3,361	693	0.21

Source: Nemet and Kammen, 2007

industrial products. At the DOE, spending on the Biomass and Biorefinery Systems R&D program has been increasing steadily since 2004 in an attempt to reach the Program's goal of making cellulosic ethanol cost competitive by 2012. In addition, DOE's 2009 budget request proposes spending $75 million for the creation of three multidisciplinary Bioenergy Research Centers focused on generating scientific breakthroughs in cost-competitive biofuels production (USDOE, 2008b).

In contrast to recent bioenergy spending trends, Table 3 suggests federal renewable energy R&D spending in solar, wind, geothermal and energy storage technologies has declined somewhat over the past three years. DOE's 2008 budget increases funding for hydrogen technologies and biomass, but cuts wind funding by $4 million and leaves solar funding constant (USDOE, 2007a).

Federal funds also support renewable energy through channels other than R&D. The Energy Independence and Security Act, signed in December 2007, amends the Renewable Fuels Standard to require 36 billion gallons of renewable fuels production in the U.S. by 2022, up from 9 billion gallons in 2008. The Act also authorizes $500 million annually from 2008-2015 for the production of advanced biofuels that yield at least an 80 percent reduction in lifecycle green-house gas (GHG) emissions relative to current fuels (RFA, 2008a). This includes funds for small-scale 'biorefinery' demonstration projects that will produce 2.5 million gallons of cellulosic ethanol per year (USDOE, 2008a). More recently, the new Farm Bill has approved a $1.01 per gallon credit for cellulosic biofuels, whereas the $0.51 per gallon subsidy for conventional ethanol producers has been reduced somewhat to $0.45 per gallon. Facilities producing energy from wind, solar, geothermal or certain types of biomass are also eligible for a 1.5 cent per kWh tax credit for the first ten years of operation. The ethanol industry also benefits from the government's ad valorem tariff of 2.5 percent on ethanol imports, on top of a 54 cent per gallon import charge (RFA, 2008b).

Private Sector

Increasing levels of public sector spending have contributed to a favorable environment for new biofuels investments. Optimism about cellulosic biofuels has even led Vinod Khosla, head of Khosla Ventures, a prominent venture capital firm, to predict oil dropping to $35 a barrel by 2030 due to substitution of biofuels (San Francisco Chronicle, 2008). Biofuels are not the only clean energy technology to have generated increasing investor interest. Barely a week goes by without the popular media reporting on the latest company

Table 3. Federal Renewable Energy R&D, Selected Technologies

	Hydrogen	Fuel Cells	Energy Storage	Solar	Wind	Geothermal
			($ million)			
2001	n/a	n/a	7	105	45	30
2002	n/a	n/a	78	100	43	30
2003	n/a	n/a	93	90	45	31
2004	85	73	9	86	42	26
2005	96	76	4	87	42	26
2006	80	75	3	83	39	23

n/a - not available
Source: IEA, 2007

Table 4. DOE and USDA Biomass R&D

Year	DOE	USDA
	($ million)	
2002	92	5
2003	86	14
2004	69	14
2005	89	14
2006	90	12
2007	150	12

Source: USDOE & USDA FY Budget Summaries

to invest in a renewable energy project, and firms are hedging their bets by pursuing a variety of options. British Petroleum (BP) and General Motors have both recently stated they foresee hydrogen as the likely 'fuel of the future' (Hargreaves, 2008), even though both are also investing significant sums in cellulosic ethanol (Baker, 2008; Sanders, 2007). Chevron has invested in multiple solar energy projects, a hybrid solar/fuel cell power plant, stationary fuel cell power plants and a biodiesel power plant (Chevron Energy Solutions, 2008). Shell's renewable energy segment is investing in a global network of hydrogen refueling stations, next-generation thin-film photovoltaic cells, and an algal biodiesel demonstration project (Shell, 2008a and b; Fortson, 2007).

Universities, the federal government, and some of the 'Big 5' fossil fuel companies have also recently come together in several high-profile public-private partnerships. BP has partnered with UC Berkeley, the University of Illinois, and Lawrence Berkeley National Laboratory, offering $500 million over ten years for research leading principally to breakthroughs in cellulosic ethanol; Chevron has offered UC Davis up to $25 million over five years for biofuels research; and Conoco-Phillips has partnered with Iowa State University and the Department of Energy in an eight-year, $22.5 million project to construct a biomass gasification system that produces synthetic diesel fuel.

Venture capital (VC) investment in biofuels, solar energy and batteries has mirrored this exuberance, as shown in Table 5 and Figure 1. Biofuels VC has witnessed a 10-fold increase between 2004 and 2007, and a 100-fold increase between 2001 and 2007; solar VC has increased from $5 million in 2001 to more than $700 million in 2007; and battery technology VC has quadrupled over the same period. To be sure, VC investments are inherently risky. The long-term value of any given renewable energy investment is dependent on both fossil-fuel prices and on the eventual technology 'winner' in the race to profitably supply a significant portion of energy services for transportation and/or electricity and heat generation. The recent Bear Stearns bailout is a reminder that in many cases, firms are rewarded with profits when they succeed, but government provides insurance against large downside risks. This 'socialized risk' structure is built into the U.S. Farm Bills, for example, and more broadly it has important implications for government energy policy. As the private sector increases its exposure in renewable energy markets, government will be increasingly be pulled in the direction of insuring against the downside risks of clean energy investments.

Technologies

In 2006, combustion technologies in the electricity and transportation sectors, respectively, generated approximately 33 percent and 28 percent of U.S. green-house gases (GHGs) (USDOE-EIA, 2007). Non-electricity uses of fossil fuels in the industrial, commercial and residential sectors generated approximately 22 percent, whereas methane and nitrous oxide from landfills and animal waste contributed another 4 percent. Altogether, these sectors are responsible for 87 percent of U.S. GHGs. Multiple renewable energy technologies have the potential to replace a significant portion of these energy services, including biofuels, hydrogen and fuel cells, electric vehicles, solar energy, wind energy, and electricity from biomass.

Table 5. U.S. Alternative Energy Venture Capital

Year	Biofuels	Batteries	Fuel Cells	Geothermal	Hydrogen	Solar	Wind
				($ million)			
2001	2.5	4.0	7.8	7.2	9.3	4.7	0.0
2002	3.0	0.0	16.5	0.0	12.8	31.0	0.0
2003	2.5	4.8	44.8	0.0	5.0	0.7	0.0
2004	28.0	14.0	210.0	0.0	10.0	54.8	0.8
2005	56.0	7.3	91.8	0.0	8.0	107.7	0.8
2006	546.7	61.0	34.5	0.0	11.6	291.3	8.0
2007	297.7	101.7	98.5	4.0	0.0	718.7	33.8

Source: VentureOne Inc., 2008

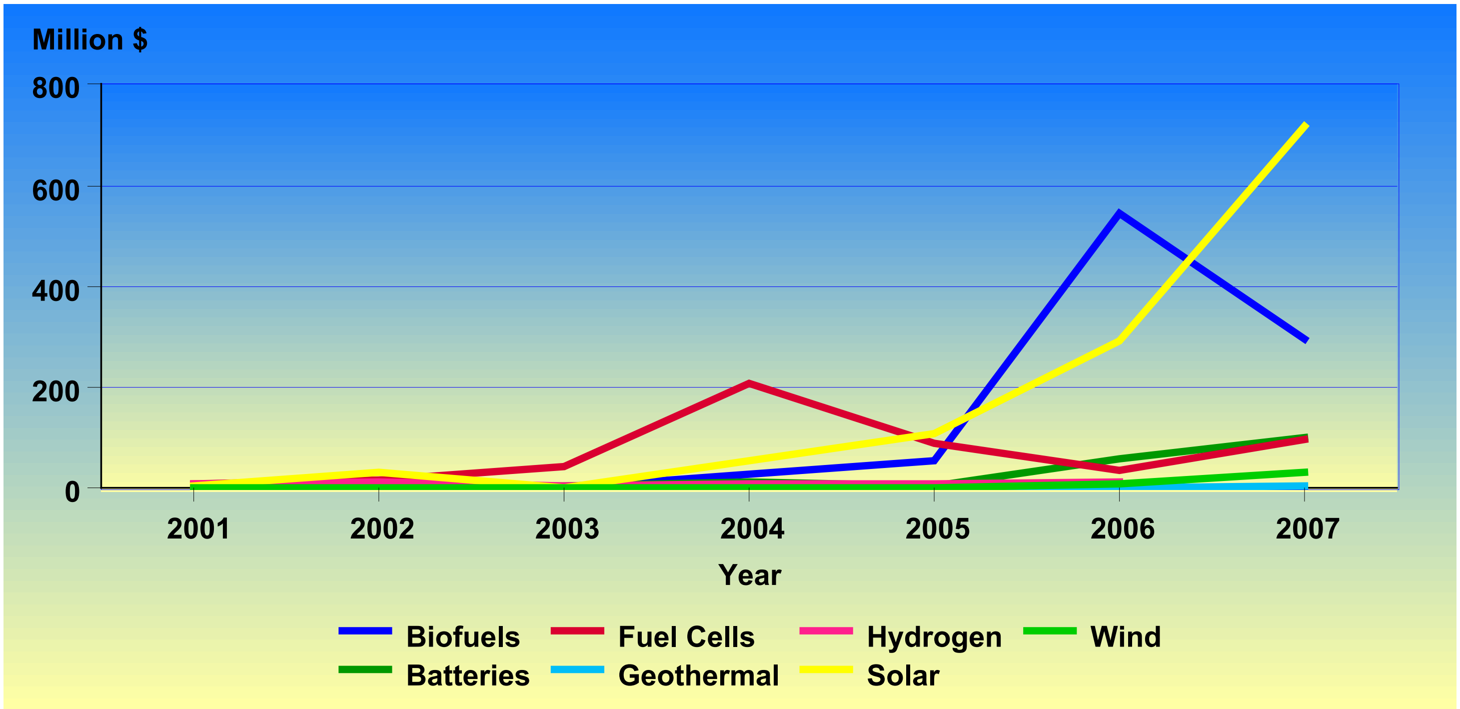

Figure 1. Clean Energy Venture Capital (US)

Ethanol and Biodiesel

Ethanol can be produced through two channels: biochemical and thermochemical conversion, as illustrated in Figure 2. In both of these processes, biomass feedstock is transformed into ethanol and other valuable coproducts. At present, ethanol is produced principally through the biochemical channel – this approach is outlined in Figure 3. Conventional ethanol production (ethanol produced from corn, sugarcane and sorghum) follows the "starch process" outlined in the top half of Figure 3. In this process, microorganisms such as yeast

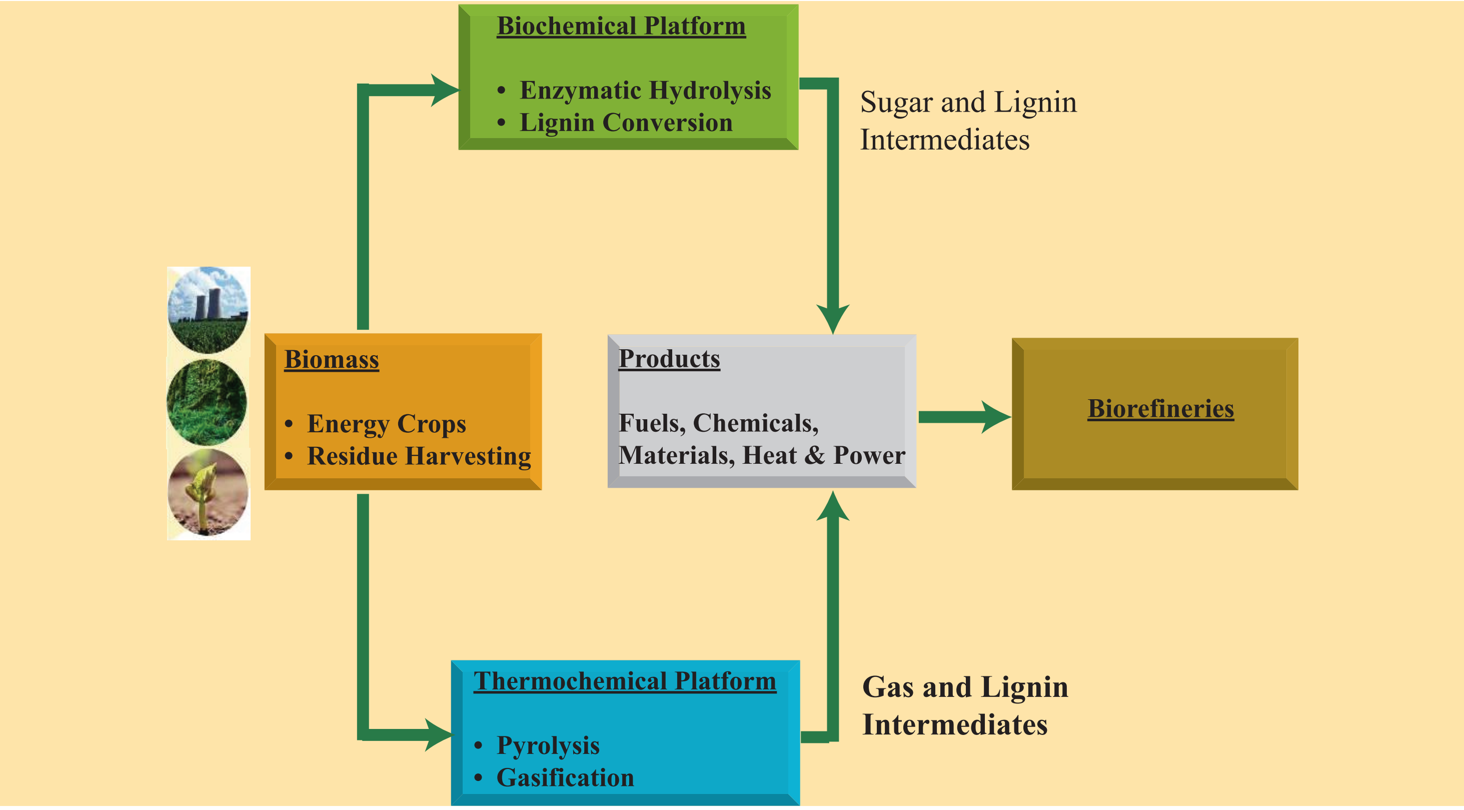

Figure 2. Alternative Paths to Ethanol Production

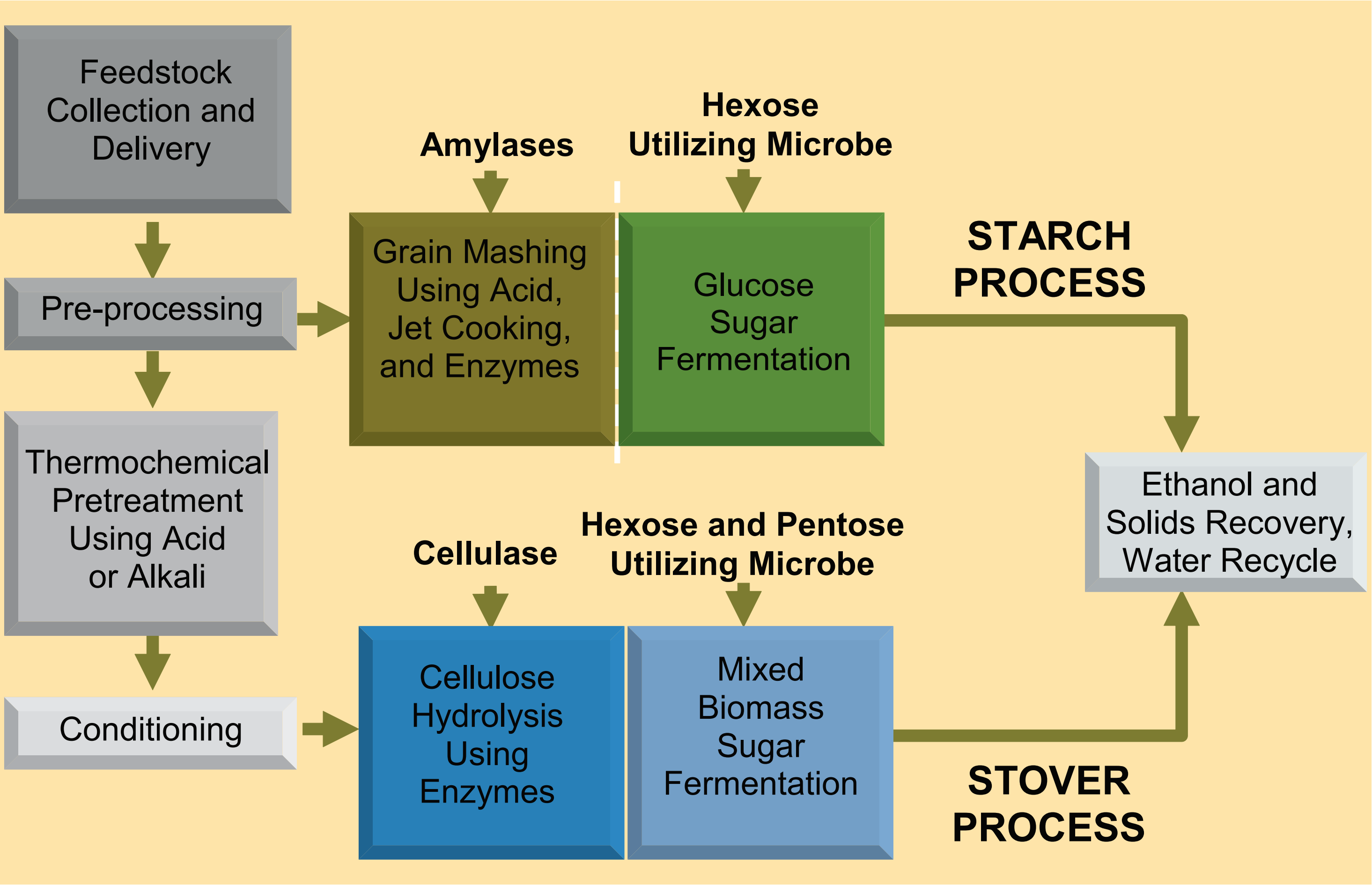

Figure 3. The Ethanol Production Process

and bacteria ferment sugar from starch and sugar crops into ethanol. Biochemical conversion can also make use of more abundant "cellulosic" biomass sources such as grasses, wood chips, and agricultural residues. Cellulosic ethanol production, as shown in the bottom half of Figure 3, involves the application of heat, pressure, chemicals, and enzymes to unlock the sugars in cellulosic biomass, followed by the application of microbes, potentially genetically engineered, to ferment the sugars into ethanol.

Biofuels can also be produced through thermochemical processes, as shown in the bottom half of Figure 2. Pyrolysis decomposes lignocellulosic biomass by heating it in the absence of air. In gasification, biomass is heated with a limited amount of oxygen to convert biomass into a hot 'syngas'. This can be combusted and used to produce electricity in a gas turbine or converted to hydrocarbons.

Conventional ethanol is currently a commercially proven fuel technology. In 2007, the industry produced a record 6.5 billion gallons, more than double that produced in 2003 (RFA, 2007). Prospects for enhanced conventional ethanol production per unit of energy input are in the area of genetic engineering. This includes the development of corn seed genetics for enhanced crop yields and the development of high-fermentable corn: corn hybrids that improve refinery yield by producing more ethanol per bushel of corn than conventional feed corn does (Rendleman and Shapouri, 2007). Potential also exists for productivity improvements through the development of thermo-tolerant yeast and new enzymes to hydrolize starch at low temperatures, and increasing the value of byproducts (NSF, 2007).

Cellulosic ethanol has not been commercially demonstrated; however, the promise of cost-competitive cellulosic ethanol has been characterized as being mostly comprised of "process improvement" (Sommerville, 2007). Potential breakthroughs in cellulosic ethanol can be separated in four broad categories. Two of these are devoted to developing low-cost hydrolysis, a key step in ethanol production whereby heat, chemicals and enzymes are applied to separate the sugars in cellulosic feedstocks. One possibility is the identification of new classes of lignin precursors that would enable production of compounds that are more easily hyrolizable. Plant products with large amounts of cellulose are held together by lignin, which current enzymes find difficult to break down, resulting in higher production costs. This leads to the second research focus: identification and large-scale replication of new catalysts that can more effectively decompose cellulose in the hydrolysis process (DellaPenna and Last, 2008; Kintisch, 2008).

Another area of focus in cellulosic ethanol is microbial genetic engineering to enhance the productivity of the fermentation process that converts plant sugars to ethanol. Current microbes used in ethanol production ferment only a subset of the available sugars, mostly glucose and xylose. Microbes that can ferment hexoses and pentoses are already known, but have not been adapted to large-scale industrial fermentation (Service, 2007). A long-term research goal rests on the possibility of developing a fermentation process for direct conversion of biomass to biofuels, rather than undergoing the intermediate hydrolysis step. This would require identification of acid-resistant thermophile organisms (Sommerville, 2007).

Researchers are also working on the potential for enhanced biodiesel production. Conventional biodiesel is a commercially proven technology, albeit at a small scale (USDOE-NREL, 2006a). These biodiesel facilities use vegetable oils, seed oils, or animal fats to react them with methanol or ethanol in the presence of a catalyst. Some researchers have stated that the potential for large scale increases in conventional biodiesel production is limited (Somerville, 2007). Nevertheless, work is ongoing to increase the value of coproducts in biodiesel production, and improve catalytic systems in biodiesel production (NSF, 2007). Genetic engineering work has also produced algae with a high lipid content that can be used as another source of biodiesel. Several projects and private start-ups in algal biodiesel production are currently underway (NSF, 2007; Fortson, 2007). Scientists have also expressed interest in algal biodiesel production for jet fuel production. Ethanol and conventional biodiesel do not have sufficient energy density to supply jet fuel, whereas ‘hydroprocessing’ of algal biodiesel shows promise in producing a fuel very similar to petroleum-derived commercial and military jet fuels (USDOE-NREL, 2006b).

Other Renewable Technologies

In addition to biofuels, breakthroughs in hydrogen production and fuel cell technology, electric vehicle technology, biomass, solar and wind energy may lead to one or more of these technologies supplying an increasing share of energy services in the transportation and electricity and heat generation sectors.

Hydrogen

Although the Department of Energy estimates it will take at least 30 years before mass-market use of hydrogen fuel cells produce significant carbon reductions (Plotkin, 2007), fuel cell vehicles and low-cost hydrogen production may eventually displace at least a portion of conventional gasoline vehicles. Current research in this field is focused on two hurdles to large-scale adoption of fuel cell vehicles and the required fueling infrastructure: hydrogen fueling and storage capacity enabling vehicles to travel up to 300 miles before refueling, and low-carbon, large-scale hydrogen fuel production.

In the former category, scientists are focusing on the identification of compounds that would enable hydrogen to be stored at much higher densities; condensing hydrogen gas into a usable solid fuel; compact hydrogen storage using carbon nanotubes; and reducing hydrogen vehicle weights. Low-carbon hydrogen production is being pursued through research on electrolysis; photo-electrochemical splitting; producing hydrogen from algae and bacteria that produce hydrogen naturally; and hydrogen production from biomass using anaerobic digestion or fermentative microorganisms.

In the latter category, scientists are currently investigating the fermentation of sugars and pretreated cellulosic biomass to produce hydrogen. Current work is focused on identifying microbial cultures that can directly ferment cellulosic biomass into hydrogen (NSF, 2007). Microorganisms, like green algae and cyanobacteria, can produce hydrogen by splitting water through a process called "biophotolysis" or "photobiological hydrogen production”. This photosynthetic pathway produces renewable fuels without producing greenhouse gases. The scientific challenge associated with the approach is that the enzyme that actually releases the hydrogen is sensitive to oxygen. The process of photosynthesis produces oxygen and this normally stops hydrogen production very quickly in green algae. To overcome this problem, scientists are generating oxygen- and hydrogen-tolerant producing mutants from photosynthetic microorganisms by various genetic approaches (NSF, 2007).

Electric Vehicles

The Department of Energy is supporting the development of hybrid vehicles and electric propulsion technologies, and several startups are working on breakthroughs in battery technology in electric vehicle applications. The major research focus in this field is enhanced battery energy density. Current lithium-ion batteries have so far failed to compete with the energy-per-kilogram in gasoline: conventional liquid fuels hold 80 times more energy per kilogram than current electric vehicle batteries. However, several firms are working on ‘next-generation’ lithium-ion batteries and others are experimenting with new compounds such as barium-titanate powders that may lead to large improvements in energy density (Hamilton, 2008).

Biomass for Electricity Production

Biopower (biomass-to-electricity power generation) is a proven electricity-generating option. However, large-scale increases in biomass electricity generation may eventually compete with the biomass supply in biofuels production. With about 10 Gigawatts (GW) of installed capacity, biopower is the single largest source of non-hydro renewable electricity in the United States (USDOE, 2008c). This installed capacity consists of about 7 GW derived from forest-product-industry and agricultural-industry residues, about 2.5 GW of municipal solid waste (MSW) generating capacity, and 0.5 GW of other capacity such as landfill gas-based production. The 7 GW of traditional biomass capacity represents about 1 percent of total electricity generating capacity and about 8 percent of all non-utility generating capacity.

The majority of the capacity is produced in Combined Heat and Power (CHP) facilities in the industrial sector, primarily in pulp and paper mills and paperboard manufacturers. All of today's capacity is based on mature, direct-combustion boiler/steam turbine technology. The nearest term low-cost option for greater use of biomass in electricity production is co-firing with coal in existing boilers.

Another electricity generation option is gasification. Gasification for power production involves the devolatilization and conversion of biomass in an atmosphere of steam or air to produce a medium-or low-calorific gas. The resulting biogas is then used as fuel in a combined cycle power generation plant that includes a gas turbine topping cycle and a steam turbine bottoming cycle. Advanced biomass power systems based on gasification benefit from the substantial investments made in coal-based gasification combined cycle (GCC). The first generation of biomass GCC systems could have efficiencies nearly double that of direct-combustion systems (e.g., 37 percent versus 20 percent). In cogeneration applications, total plant efficiencies could exceed 80 percent (ODOE, 2007).

Solar Breakthroughs

Thin film photovoltaic (PV) cells and PV concentrators are likely candidates for building-integrated solar construction and utility-scale solar electricity generation, respectively, in the medium term. Recent advances in chemistry, materials science, and solid state physics can potentially lead to solar cells with nearly double the efficiency of traditional silicon-based solar cells and of plastic versions that cost just a fraction of today's photovoltaics (PVs). However, most of these novel solar cell technologies are not yet close to commercialization (Service, 2008).

Thin-Film PV

Three types of thin films have demonstrated good potential for large-scale PV: amorphous silicon, copper indium diselenide, and cadmium telluride. Others are at somewhat earlier levels of maturity (film silicon and dye-sensitized cells). Commercial interest exists in scaling-up production of thin films; as they are produced in larger quantity, and as they achieve expected performance gains, they will become more economical for large-scale commercial applications. However, to meet the economic goals needed for large-scale use, much more technical development is required. Important technology development must be carried out to (1) transfer very high thin film PV cell-level efficiencies (up to 18 percent) to larger-area modules; (2) optimize processes and manufacturing to achieve high yields and improved materials use; and (3) assure long-term outdoor reliability. Today's technology base suggests that (with adequate resources) all of these goals can be achieved, but each will be challenging (USDOE, 2008d).

PV Concentrators

Photovoltaic concentrator systems use optical concentrators to focus direct sunlight onto solar cells for conversion to electricity. The modules are mounted on a support structure and, during daylight hours, are oriented to face (or track) the sun using motors, gears, and a controller. The solar cells in today's concentrators are predominantly silicon, although solar cells utilizing materials such as gallium arsenide or cadmium telluride may be used in the future because of their high-conversion efficiencies. By using optical concentrators to focus direct sunlight onto solar cells, the cell area, and consequently cell cost, can be reduced by a factor of up to one thousand (a 1,000x concentration factor). However, large-scale utility application of PV concentrators still requires advances in higher-efficiency cells, better optics, more-robust modules, and reliable sun-tracking arrays (USDOE, 2008d).

Over the longer-term, several possible breakthroughs in solar could bring about significant productivity improvements, and therefore lower costs. These include development of inorganic semiconductor nanocrystals with the potential to improve cell efficiencies from 33.7 percent to 44.4 percent via multiple exciton generation (Service, 2008); development of materials for tandem thin film cells to push 20 percent efficiency, in which several light-absorbing materials are layered to capture different portions of the solar spectrum; high-efficiency hybrid organic-inorganic photovoltaic cells (USDOE, 2007b); and breakthroughs in the emerging field of plasmonics to increase light absorption and therefore PV cell performance (USDOE, 2007b).

Wind Energy

Electricity from wind is currently supplied on a commercial scale, and continued improvements in cost and performance of wind turbines are likely in the future. Turbine design improvements that will continue to reduce costs are projected to continue in the coming decades: lightweight, increased capacity turbines with higher turbine diameter and hub height are expected to reduce units costs up to the 2030 timeframe. Technical improvements in the form of eliminating hydraulic systems, “smart rotor” development, and flexible turbine systems driven with interactive controls are also expected (USDOE, 2007c; NSF, 2007).

Table 6. Renewable Energy Costs, Transportation Fuels

	($/MJ)
Gasoline Benchmark	0.012
Biofuels:	
Corn Ethanol	0.018
Corn Stover	0.024
Switchgrass	0.035
Miscanthus	0.024
Sugar Cane (Brazil)	0.010
Sugar Cane Bagasse	0.056
Biodiesel Algae	n/a
Biodiesel Waste	0.010-0.016
Biodiesel Vegetable Oil	0.016-0.020

Sources: Khanna, 2007; USDOE-EIA, 2007; and ODOE, 2007. Conversions to $/MJ completed by authors. One megawatt-hour contains 3600 megajoules.

Table 7. Renewable Energy Costs, Electricity

	($/MJ)
Coal Benchmark	0.011-0.014
Biomass:	
Biomass Electricity (No Cogen)	0.014-0.019
Landfill Gas Electricity	0.008-0.010
Anaerobic Digestion Electricity	0.010-0.015
Hydrogen from Wind	0.028-0.039
Solar	0.083-0.110
Wind	0.009-0.014

Sources: Khanna, 2007; USDOE-EIA, 2007; and ODOE, 2007. Conversions to $/MJ completed by authors. One megawatt-hour contains 3600 megajoules.

Current Costs

Current estimated costs of renewable energy production of potential transportation and electricity fuels are presented in Tables 6 and 7 respectively. Costs of energy from gasoline and coal are also listed as a benchmark. Estimates have been converted to dollars per megajoule (MJ) to enable a consistent comparison across technologies. Corn ethanol is currently about 30 percent more expensive than gasoline, though recent record corn prices have dramatically increased the cost of corn ethanol since the reported value is based on 2007 data.

Data presented in Table 6 indicate costs of cellulosic ethanol will have to be reduced by more than half to become competitive with gasoline. Note, however, ethanol produced from Brazilian sugar cane is already cost-competitive with gasoline – though the reported value does not include import tariffs. Electricity production from biomass is almost cost-competitive with pulverized coal, as is electricity produced from anaerobic digestion. Landfill gas electricity is already cost-competitive with pulverized coal, though this source is evidently limited in supply. Under the most favorable weather conditions, wind electricity is also cost-competitive with coal, but the variability of wind electricity costs is quite high.

Costs presented in Table 6 can be considered initial conditions in a dynamic process of productivity improvement, or equivalently, cost reduction. Production cost reductions in renewable energy technologies are expected to occur as a result of R&D investment and learning-by-doing (Papineau, 2006). Since most of the emerging renewable energy industries are still operating at a very small scale, cost reductions as a result of dynamic economies are expected to be of a much higher magnitude compared to the decline in fossil energy production costs.

Analytical Framework

The optimal allocation of R&D among the various renewable energy technologies, in both the public and private sector, is dependent upon the potential for productivity increases or cost reductions in each technology. In order to model the process of cost reduction, each technology must be represented in a common framework.

Production and Cost Representations

Each technology can be represented in a production function framework, where feedstock inputs are transformed into valuable outputs and a carbon byproduct in accordance with

$$m_{it} = r_{it} + a_i tF_{it}(L_{it}, K_{it}, m_{it}), \qquad (1)$$

where m_{it} = feedstock input for technology i at time t, F_{it} (•) = multi-output correspondence for technology i at time t, r_{it} = carbon byproduct, a_{it} = productive efficiency parameter for technology i at time t, and L_{it}, K_{it}, = labor and capital inputs, respectively, for technology i at time t.

This production process is consistent with the materials-balance principle, which explicitly accounts for pollution byproducts as inevitable parts of the production process (Ayres and Kneese, 1969). Materials balance implies that modern production processes yield at least two outputs and require at least two inputs: the use of energy to transform matter into economically valuable outputs (e.g. ethanol and animal feed produced as coproduct) will also produce an undesirable pollution byproduct (Ethridge, 1973). Thus, every process of modern production is necessarily joint production. As explained by Pethig (2006), incorporating the materials-balance principle in theoretical analyses adds significantly more computational complexity, and environmental economists have been reluctant to explicitly incorporate it in their analyses. This means much of the production processes in present models are at variance with the law of the conservation of mass; the literature has rarely produced non-linear production models that satisfy the mass balance principle (van den Bergh, 1999).

Technical improvements can be represented as an increase in a_{it}, implying that more output can be produced from the same inputs and a constant quantity of carbon output. Given the duality between production and costs, such productivity improvements are equivalent to downward shifts in costs, or, in term of Table 6, lower costs per MJ of energy service, holding carbon output constant. In terms of initial conditions, there is a mapping between the productive efficiency of technology i at time t, or a_{it}, and the initial cost parameter b_{it}, where $b_{it}C_i$ is the unit cost of the *i*-th technology at time t.

Decision Theory

The optimal allocation of renewable energy R&D investment across the various technologies is a complex problem of decision-analytic modeling; fundamentally the problem must be structured to eliminate any of the biases often inherent in the decision-making process. Future productivity improvements among the renewable technologies, in other words increases in a_{it} or reductions in b_{it}, are an important determinant of the optimal ex-ante allocation of R&D. To estimate the growth rate of a_{it} and/or the reductions in b_{it}, expert opinion will be used to elicit the prior multivariate probability distribution around future costs or productivity measures (O'Hagan, 1998; Raiffa and Schlaifer, 1961). If $b_{it}C_i$ is the unit cost of the *i*-th technology at time t, then the quantity of principal interest is the rate of decrease of b_{it} as a function of the R&D investment in each technology. The variable C_i is an exogenously determined initial condition: in our application these are the costs per MJ from Table 6. The problem is to elicit expert opinions about the multiple b_{it}'s . Elicitation of the complete joint prior distribution is a highly complex task involving multiple parameters, however in practice it is often simplified by adopting Bayes linear methods that only require the elicitation of prior means, variances and covariances of the parameters (Goldstein, 1988).

The assessment of potential productivity and cost evolution for the various technologies must be complemented by future trajectories in the external forces mentioned in the introduction. Without determining the role of these external forces, it is not possible to evaluate the value proposition for the adoption and diffusion of any technological advancements that might take place. The market value of major discoveries and/or continued learning-by-doing (Rausser, 1999) will be determined by future political and economic conditions. The potential probability distribution trajectories for all of the external forces except for future crude oil and natural gas prices will be assessed through expert panels for a 20-year horizon. In the case of crude oil and natural gas prices, both futures markets data and available econometric models will be combined to generate composite probability distributions over the same horizon. The results of the expert panel assessments will be designed as a Bayesian structured updating process to separate those technologies that remain viable from those whose support should be terminated (Rausser and Small, 2000). The portfolio model will be constructed as a Monte Carlo simulation analysis, quantifying the updated conditional probability distribution for two categories of choice variables (i) the R&D investment in specific technologies; and (ii) policy instruments set by the government to incentivize private sector investment in renewable R&D across the various technologies.

Determination of the Optimal Portfolio

Determining the allocation of R&D investment across the technologies described in Section 2 depends on the presumed governance structure and decision-making process. In our analysis, we will draw a sharp distinction between basic and applied research and the feedback loops between each of these two categories of research (Rausser, 1999; Rausser, Simon, and Stevens, 2008). Three alternative formulations are considered, each with a different criterion function and constraint structure. In each case, the focal decision space is the allocation of R&D investment across the specified technologies, updated each period in accordance with a Bayesian learning model characterizing the underlying probability distributions on costs and/or productivity measures as well as the external forces.

Social Welfare

For this formulation, the distinction between the public sector and private sector is collapsed into a social planning framework. In this framework, a social planner is presumed to control the allocation of R&D investment based on initial conditions and ex-ante multivariate probability distributions for all renewable energy technologies and external forces. The resulting portfolio model will determine the optimal ex-ante strategy across promising technologies, isolating the scope of investment (subsidization) that services the public interest. The solution for this formulation will set the first-best outcome or benchmark for more realistic specifications.

Private Sector Conditional On Public Sector Actions

In this formulation our focus is private sector investment in renewable technologies. Initially, we shall disaggregate these investments across the venture capital community, the large oil companies, and all other sources. The behavior of private sector will be presumed to be driven by the same Bayesian learning model characterizing the underlying probability distributions on costs and/or productivity measures as well as external forces but now only with respect to applied research (Rausser, 1999). In addition, however, the private sector can be expected to take into account the R&D efforts of public sector, both basic and applied, including ongoing university and public-private research. Moreover, incentives resulting from a number of governmental policy instruments such as price subsidization, biofuels mandates, tax subsidies, credit subsidies, risk swaps, input subsidies, and trade protection will increase the amount of private sector R&D investment that would otherwise take place. The existence of such policy instruments, however, can also be expected to result in organized interest groups to be formed who will lobby the government to maintain and expand such subsidization support (Rausser and Goodhue, 2002). In other words, resources will be allocated not only to R&D investment in potential commercial technologies but also to lobbying the government to redistribute any resulting market surplus in their favor.

Public Sector Decision-Making

Due to the active intervention of the government in R&D investment and the subsidization of the private sector commercial developments, we recognize that the actual public sector decision-making will dictate a political economic analysis. A governing criterion function must be specified which incorporates both the "public interest" as well as the "specialized interest" of the private sector, or more specifically the recipients of governmental transfers (Rausser and Goodhue, 2002).

The maximization of this criterion function will be subject to the constraints represented by the private sector investment in renewable technology R&D as well as the portfolio of probabilistic assessments for potential technological advancements and the external forces. This formulation will allow an evaluation of vested-interest group formation (e.g. corn ethanol plant investors), which may emerge around the design and implementation of subsidization policy instruments. Also, in the context of this formulation, the effectiveness of the design and implementation of alternative policy instruments will be assessed in terms of incidence, i.e. who wins and who loses, along with the political economic forces. The quantification of the political economic forces will be the basis for determining which subsidization instruments will fade away versus those that will face significant exit barriers due to political power and influence.

Conclusions

A number of potential uses of our risk modeling framework can be identified. First, the public sector can determine a portfolio risk-adjusted allocation of R&D resources to renewable energy technologies. Second, with some minor modifications the private sector can do the same. Third, the framework can also be employed to evaluate grant proposals not only in terms of their potential separable impact but also their overall effect on the entire portfolio of renewable energy technology R&D efforts.

The ultimate purpose of our analysis is to explicitly recognize that the public sector will be pulled and pushed in the direction of subsidization support for emerging technologies. In essence, the government has become engaged in an industrialization policy effort that will only intensify over the next decade. We must be mindful of the fact that governments have failed badly in the design and implementation of such policies. As demonstrated time and again, capital markets are far more agile than governments at responding to market and commercial signals. Nevertheless, governmental support for renewable energy technologies, if properly designed, could well serve the public interest. The hope is, of course, that creating and/or supporting demand for clean energy and the cost for delivering such energy could well result in permanent and sustainable decreases in prices over the long run. Regardless, caution must be exercised to avoid the permanent subsidization of the private sector engaged in the commercial development of renewable energy technologies. Our proposed ex-ante portfolio analysis under risk and uncertainty is structured to temper the typical government failure that arises from "infant industry" analysis of "picking winners". The proposed analysis is the basis for generating a performance-dependent mixed strategy across alternative renewable energy technologies with exit clauses for terminating policy instruments that generate rents and subsidies to the private sector.

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