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Managing R&D Risk in Renewable Energy: Biofuels vs. Alternate Technologies

Gordon Rausser, Reid Stevens, and Kiran Torani
University of California, Berkeley

The government's use of upstream R&D investments and downstream incentives for renewable energy is intended to achieve commercial breakthroughs in biofuels, batteries, fuel cells, hydrogen, solar, and wind energy. The private sector has reacted to these policy instruments with significant increases in renewable energy R&D and commercial investment. As the private sector exposure in renewable energy markets increases, the public sector will increasingly be pulled by special interests in the direction of insuring against the downside risks of clean energy investments. A central question arises in this context: what is the optimal ex-ante allocation of renewable-energy public R&D investment in combination with downstream policy instruments across the emerging technologies? From the standpoint of societal welfare, the optimal allocation of such support is fundamentally a problem of ex-ante portfolio analysis under risk and uncertainty. This article presents an ex-ante portfolio analysis of public and private R&D and commercialization risks in renewable energy based on expert elicitation.

Key words: biofuels, portfolio analysis, R&D risk, renewable energy technologies.

Introduction

Reaching the US federal government's renewable energy milestones (Table 1) will require efficient coordination of public and private investments. Three sets of governmental policy instruments are used to encourage private investment in renewable energy: upstream research and development (R&D) investments, downstream market incentives, and downstream non-market incentives. Upstream investments in renewable energy R&D actively involve the government in the research process with the private sector. Downstream market incentives (i.e., mandates, subsidies, tax credits) are expected to lead to additional commercial developments. Downstream non-market instruments (carbon taxes) create incentives for renewable energy production by pricing externalities resulting from the utilization of exhaustible resources. Each of these policy instruments is designed to alter the incentives for the use of renewable energy by making it more competitive with exhaustible sources of energy.

Historically, the economic viability of renewable energy has been determined by the prices of crude oil and natural gas. It is useful to recall Santayana's maxim "those who cannot remember the past are condemned to repeat it" when considering the rapid expansion in the late 1970s of solar energy, which was brought to a halt when crude oil prices plummeted to slightly over $10 per barrel in the mid-1980s. To eliminate this downside risk, private investors in renewable energy have actively engaged in lobbying for public funds (Rausser & Goodhue, 2002). For example, the coal industry spent millions in recent years in a lobbying effort for a subsidization program conditioned upon crude oil prices with the following framework: if oil prices fall below $40 per barrel, the federal government would subsidize coal-based liquid fuel plants, while liquefied coal companies would return a surcharge to the government if oil prices climbed above $80 per barrel.

It is unlikely that the government will be able to coordinate renewable energy investments efficiently in the face of these political economic efforts without a clear, ex-ante investment plan. To date, the government lacks coordinated support of renewable energy technologies across upstream R&D investments and downstream (market and non-market) policy instruments. Each government agency's approach to promoting renewable energy is compartmentalized. The US Department of Energy (DOE) and the US Department of Agriculture (USDA) both use upstream R&D investments, while much of the federal government legislation focuses on downstream market incentives. The problem is not unique to the United States; the other major players in renewable energy (Brazil, China, and the European Union) find themselves with similar uncoordinated strategies.

Without an objective, ex-ante guide for renewable energy investment, governments are likely to promote

Table 1. DOE renewable energy milestones.

Cellulosic ethanol	Cellulosic ethanol cost competitive with conventional ethanol by 2012
	Replace 30% of today's gasoline in 2030 with biofuels
Hydrogen	Industry commercialization possible by 2015
	Fuel cell vehicles in the showroom and hydrogen at fueling stations by 2020
Solar	Reduce solar costs to grid parity in all US markets by 2015
Wind	Reduce cost of energy from large systems to $0.03/kWh by 2010
	Greatly expanded deployment of distributed wind energy by 2016
	Large-scale offshore wind and hydrogen production from wind by 2020

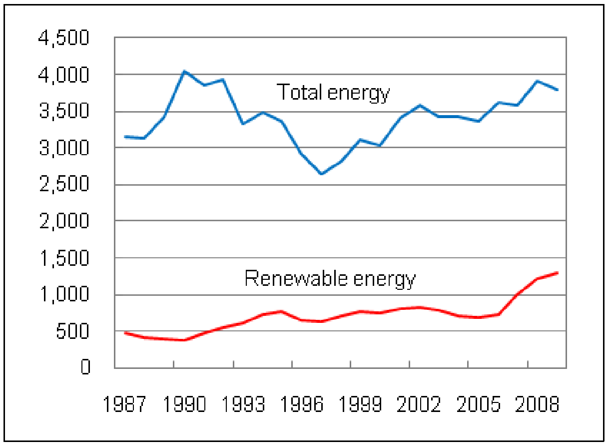

Figure 1. Federal energy R&D ($ millions).
Source: Departmental budget summaries.

technologies based on the effectiveness of political economic efforts. This article will provide an analysis of renewable energy technologies using portfolio analysis under risk and uncertainty. Though we restrict our analysis to the US renewable energy market, our findings are applicable to any countries that are using similar approaches to R&D investment and downstream incentives.

Current R&D Renewable Energy Landscape

R&D funding drives innovation in renewable energy. Both the federal government and the private sector are stakeholders in this process and both have an interest in successfully generating innovations that lead to enhanced productivity while decreasing damage to the environment.

Table 2. DOE and USDA biomass R&D ($ million).

	USDA	DOE
2002	5	92
2003	14	86
2004	14	69
2005	14	89
2006	12	90
2007	12	150
2008	2	198
2009	20	214
2010	28	220

Source: Departmental budget summaries

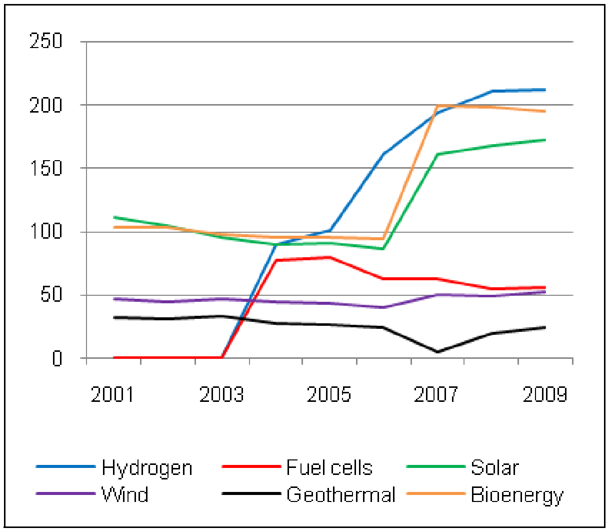

Figure 2. Federal renewable energy R&D, selected technologies ($m).
Source: International Energy Agency (IEA) R&D database.

Public Sector

The DOE's renewable energy milestones (Table 1) suggest that the federal government places a positive probability on breakthroughs in renewable energy technologies. Over the past 20 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 10 years (Figure 1).

Figure 2 and Table 2 present a more detailed breakdown of federal renewable energy R&D. Both the DOE and USDA have bioenergy R&D programs. 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.

Federal funds also support renewable energy through channels other than R&D. The Energy Indepen-

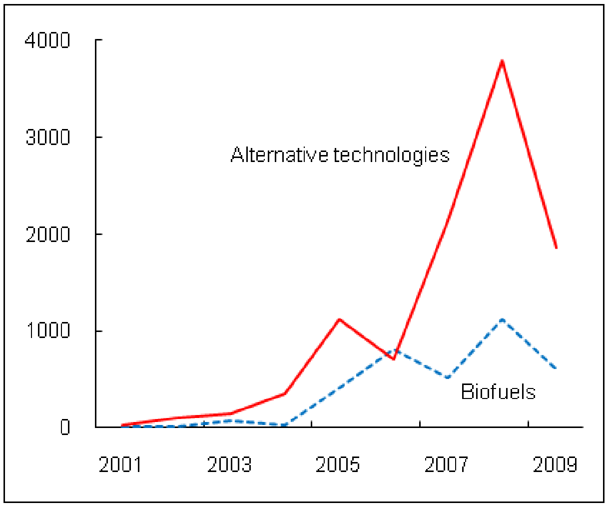

Figure 3. Biofuels vs. alternative technologies VC ($m).
Source: VentureOne, Inc. (2008).

dence and Security Act of 2007 amends the Renewable Fuels Standard to require 36 billion gallons of renewable fuels consumption in the United States 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% reduction in lifecycle greenhouse gas (GHG) emissions (Renewable Fuels Association [RFA], 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 $0.015 per kWh tax credit for the first 10 years of operation. The ethanol industry also benefits from the government's ad valorem tariff of 2.5% on ethanol imports, on top of a $0.54 per gallon import charge (RFA, 2008b).

Private Sector

Increasing levels of public-sector spending have contributed to a favorable environment for new biofuels investments and downstream incentives. Oil companies are among the biggest investors in biofuels. British Petroleum has stated that they foresee hydrogen as the likely 'fuel of the future' (Hargreaves, 2008), even though they are also investing significant sums in cellulosic ethanol with DuPont and in public-private R&D efforts. 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, 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 (Fortson, 2007). In mid-2009, Exxon Mobil announced a $600 million investment in algae-based biofuels with Synthetic Genomics.

Table 3. Renewable energy costs, transportation fuels ($/MJ).

Fossil fuel benchmark	Gasoline	0.0120
Biofuels	Corn ethanol	0.0180
	Corn stover	0.0236
	Switchgrass	0.0354
	Miscanthus	0.0242
	Sugar cane (Brazil)	0.0101
	Sugar cane bagasse	0.0560
	Biodiesel algae	n/a
	Biodiesel waste	0.0103-0.0158
	Biodiesel vegetable oil	0.0159-0.0203

Table 4. Renewable energy costs, electricity ($/MJ).

Fossil fuel benchmark	Pulverized coal	0.0110-0.0140
Biomass	Biomass electricity (no cogen)	0.0140-0.0190
	Landfill gas electricity	0.0080-0.0100
	Anaerobic digestion electricity	0.0100-0.0150
	Hydrogen from wind	0.0280-0.0390
Other renewable	Solar	0.0830-0.1100
	Wind	0.0090-0.0136

Venture capital (VC) investment in renewable energy (Figure 3) has mirrored this exuberance. Though there was a pronounced spike in solar funding—which, at its peak, received more VC funding than all other technologies combined—funding for biofuels, solar, and wind technologies has begun to converge. In contrast, VC funding of battery, fuel cell, geothermal, and hydrogen technologies remains relatively low.

Current Costs

Current estimated costs of renewable energy production of potential transportation fuels and electricity generation are presented in Tables 3 and 4, respectively. Costs of energy from gasoline and coal are also listed as a benchmark.

Table 3 shows that the cost of cellulosic ethanol will have to be reduced by more than half to become competitive with gasoline. However, ethanol produced from Brazilian sugar cane is already cost-competitive with gasoline, although 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.

Analytical Framework

The government's choice of upstream R&D investments and downstream policy instruments will determine private sector investment in renewable energy technologies. The government's policies should depend on the technology's probability distribution of cost breakthroughs for each technology and on the environmental impact. Our goal is to develop a portfolio analysis of R&D investments in renewable energy technologies through a computable portfolio model with a Bayesian-structured updating process and generation of a time- and performance-dependent optimal mixed strategy across renewable technologies. To model the cost-reduction process, we evaluate each technology in a multiple-output production function framework.

Multiple-Output Production Function Framework

Each renewable energy technology can be represented in a multiple-output production function framework with two outputs: an economic output and a carbon output. The production process includes a productivity parameter with three inputs: labor, capital, and feedstock. Given the duality between production and costs, increases in the productivity parameter are equivalent to downward shifts in costs, or lower costs per megajoule (MJ) of energy.

This production process is consistent with the materials-balance principle, which explicitly accounts for pollution by-products as inevitable parts of the production process (Ayres & Kneese, 1969).[1] Life Cycle Analysis (LCA) has been used to evaluate the material balance of inputs and outputs in renewable energy production in terms of environmental emissions and marketable outputs. Though LCA has a broad scope, incorporating the total amount of extractive resources and polluting resources over the course of production, the analysis assumes coefficients are fixed rather than functions of government policies and market forces (Rajagopal & Zilberman, 2008). Until general equilibrium effects are carefully modeled, LCA will not be able to reliably estimate the net environmental impact of biofuels.

Table 5. Expert population.

	Total	University	Govt	VC
Batteries	72	27	22	23
Biofuels	200	75	19	106
H & FC	198	87	37	74
Solar	205	108	30	67
Wind	31	9	16	6
Total	706			

Determination of the Optimal Portfolio

Determining the optimal combination of upstream and downstream policy instruments across the technologies depends on the presumed governance structure and decision-making process. The focal decision space is the combination of policy instruments across renewable energy technologies, updated each period in accordance with a Bayesian learning model characterizing the underlying probability distributions on costs and/or productivity measures.

We acknowledge the institutional structure by explicitly modeling the private sector reaction function to government policy. The government acts as a "Stackelberg leader" maximizing its own objective function, given the private sector's reaction function, by setting a combination of upstream R&D investments and downstream market and non-market incentives. The public sector's upstream R&D investments include both basic and applied research conducted by governmental agencies, universities, and public-private research partnerships. The public sector's downstream market incentives include price subsidization, renewable energy mandates, tax subsidies, credit subsidies, risk swaps, input subsidies, and trade distortions. The downstream non-market incentives are designed to attach prices to the production of non-market goods (like carbon) through taxes or trading schemes. Each of these policy instruments is designed to increase private sector R&D

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[1] *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).*

Table 6. Battery data summary.

	The cost ($/kWh) of a 35kW lithium-ion battery pack for a passenger vehicle					
Batteries	**Lower bound mean**	**Std dev.**	**Median mean**	**Std dev.**	**Upper bound mean**	**Std dev.**
2 yrs status quo	$594.25	115.18	$618.25	79.78	$670.75	47.84
5 yrs status quo	$504.25	137.57	$556.25	105.31	$611.75	75.71
10 yrs status quo	$418.00	149.41	$472.50	140.33	$533.00	128.46
2 yrs incr funding	$534.25	112.51	$596.25	71.34	$638.25	51.56
5 yrs incr funding	$405.25	148.58	$451.00	137.95	$518.75	112.43
10 yrs incr funding	$302.75	187.48	$347.25	175.01	$428.75	165.15

n=4

The current cost of a 35kW lithium-ion battery pack is estimated at $706/kWh.

investments. The private sector reacts by investing in R&D, commercialization, and political economic efforts to maintain and expand favorable R&D investments and incentives (Rausser & Goodhue, 2002).

A governing criterion function must be specified that incorporates both the "public interest" as well as the "specialized interest" of the private sector—or, more specifically, the recipients of governmental transfers (Rausser, Simon, & Stevens, 2008). The maximization of this criterion function will be subject to the constraints represented by the private sector investment in R&D and commercialization, 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, which may emerge around the design and implementation of various 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. In the analysis reported in the article, we focus only on the probability distributions for future technology cost reductions.

Analysis

Elicitation Data

A crucial first step in executing a portfolio analysis of renewable energy is an estimation of probability distributions based on elicitation from experts in each field of technology. Expert elicitation has long been used to quantify uncertainty when historical data is unavailable by public, private, and academic research groups. Since the 1950s, this approach has been used to estimate uncertain probabilities in a variety of settings from the risks posed by long-term nuclear storage to the health impacts of sulfur air pollution (US Environmental Protection Agency [EPA], 2009).

The initial step in the expert elicitation process is to identify a population of renewable-energy experts working on technical/scientific breakthroughs for each technology, drawing from public, private, and academic research institutions. The experts were chosen based on citations, publications in academic journals, and participation in national laboratories or technology startups receiving venture capital funds.

A randomly selected sub-sample of the population of experts was interviewed with the objective of eliciting probability distributions of future costs under different funding scenarios (Table 5). After each interview, we fitted distributions to the responses, which were sent to the experts for feedback.

In Tables 6-9 we summarize the responses for the initial round of interviews in terms of the mean and standard deviation of the responses for the lower bound, median, and upper bound.

As expected, these preliminary results reveal a significant impact on cost reductions resulting from the hypothetical funding increase. An increase in funding is associated with a 16% decrease in the expected cost of batteries, a 13% decrease in the expected cost of fuel cells, a 10% decrease in the expected costs of solar cells, and a 10% decrease in the expected cost of biofuels. A funding increase also significantly decreases the expected variance of future cost reductions.

Though the current results indicate that the probability distribution of biofuels nearly stochastically dominates the other renewable energy technologies (with some overlap to be observed with solar photovoltaic [PV] technologies), we anticipate that further interviews will yield more concrete results and display an increase in the overlap between distributions, which will allow for rigorous portfolio analysis.

Table 7. Fuel cell data summary.

The cost ($/kW) of 80kW direct hydrogen PEM fuel cell stack for transportation applications						
Fuel cells	**Lower bound mean**	**Std dev.**	**Median mean**	**Std dev.**	**Upper bound mean**	**Std dev.**
2 yrs status quo	$42.00	4.47	$47.33	5.03	$51.60	4.77
5 yrs status quo	$37.40	4.34	$43.75	5.32	$49.00	7.42
10 yrs status quo	$33.60	3.13	$40.25	6.29	$46.00	9.62
2 yrs incr funding	$39.80	5.93	$44.20	5.81	$48.40	7.40
5 yrs incr funding	$34.00	6.28	$37.40	5.98	$44.00	10.22
10 yrs incr funding	$26.20	9.09	$30.60	9.84	$38.60	14.74

n=5

The current cost ($/kW) of a 80kW direct hydrogen PEMFC stack is estimated at $50/kW.

Table 8. Solar data summary.

The cost ($/kWh) of commercial-scale PV solar electricity generation						
Solar	**Lower bound mean**	**Std dev.**	**Median mean**	**Std dev.**	**Upper bound mean**	**Std dev.**
2 yrs status quo	$0.12	0.028	$0.16	0.021	$0.18	0.035
5 yrs status quo	$0.09	0.014	$0.12	0.004	$0.15	0
10 yrs status quo	$0.07	0.014	$0.10	0.028	$0.13	0.035
2 yrs incr funding	$0.11	0.035	$0.14	0.028	$0.17	0.028
5 yrs incr funding	$0.08	0.007	$0.11	0.004	$0.15	0.007
10 yrs incr funding	$0.06	0.007	$0.09	0.007	$0.11	0.014

n=2

The current cost of commercial-scale PV solar electricity generation is $0.18/kWh.

Table 9. Biofuel data summary.

The cost ($/kWh) of biofuels from the biochemical conversion of cellulosic biomass						
Biofuels	**Lower bound mean**	**Std dev.**	**Median mean**	**Std dev.**	**Upper bound mean**	**Std dev.**
2 yrs status quo	$0.10	0.014	$0.12	0.009	$0.18	0
5 yrs status quo	$0.07	0	$0.11	0.000	$0.14	0
10 yrs status quo	$0.05	0.007	$0.09	0.003	$0.11	0
2 yrs incr funding	$0.10	0.007	$0.11	0.009	$0.15	0.024
5 yrs incr funding	$0.06	0	$0.10	0.005	$0.12	0
10 yrs incr funding	$0.05	0.006	$0.08	0.008	$0.10	0.008

n=2

The current cost per gallon of biofuels from biological conversion of cellulosic biomass is estimated to be between $2.95 and $4. The energy content of biofuels is estimated as 75,700 btu per gallon.

The subsequent portfolio analysis is designed to allocate R&D investments across renewable energy technologies in a manner that minimizes the risk for a specified level of expected returns, taking into account both the expected reductions in cost and the variance of the expectations of cost reductions, thus providing an objective benchmark for efficient allocation of resources across renewable energy technologies.

Conclusion

Currently there is no clear ex-ante plan to guide upstream or downstream public support of renewable energy technologies. As a result, it will be difficult for the public sector to avoid the pull of special interests working to obtain insurance against the downside risks of clean energy investments made by private firms and to avoid the pitfalls of industrialization policies. It is with this motivation that we have outlined an analytical framework to determine the optimal combination of upstream R&D investments and downstream instruments. Our framework is based on the estimation of probability distributions for potential future cost reductions resulting from R&D investments from the public and private sectors.

Our early stage results reveal that a hypothetical increase in total R&D funding has a significant impact on cost reductions, as well as a decrease in the variance of the probability distributions. Though biofuels show the most promise among the initial probability distributions, we anticipate further interviews to reveal an increase in the overlap among the technology's future cost probability distributions. We anticipate that the portfolio analysis can guide the public sector as it invests amongst the numerous renewable energy technologies. Such an ex-ante guide is essential if the public sector is to achieve an efficient allocation of renewable energy public R&D investment in combination with downstream policy instruments across the emerging technologies. The challenge for governments is to exploit the complementarities between upstream R&D investments and downstream market and non-market incentives.

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