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An Estimate of the Cost of Electricity from Light Water Reactors and Fossil Plants with Carbon Capture and Sequestration

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Introduction

As envisioned in this report, LIFE technology lends itself to large, centralized, baseload (or "always on") electrical generation. Should LIFE plants be built, they will have to compete in the electricity market with other generation technologies. We consider the economics of technologies with similar operating characteristics: significant economies of scale, limited capacity for turndown, zero dependence on intermittent resources and ability to meet environmental constraints.
The five generation technologies examined here are:

- Light Water Reactors (LWR)
- Coal
- Coal with Carbon Capture and Sequestration (CCS)
- Natural Gas
- Natural Gas with Carbon Capture and Sequestration

We use MIT's cost estimation methodology [Du and Parsons, 2009]to determine the cost of electricity at which each of these technologies is viable.

Financial Model

In order to make a consistent comparison with LIFE economics, we assume that LIFE, LWR, and CCS technologies are perceived as having equal financial risk in the plant startup year of 2030. This assumption allows us to assign identical debt and equity fractions and discount rates and, resulting in identical weighted average costs of capital (WACC) across all technologies. Because WACC has a large impact on COE, and because WACC is extremely hard to predict under future scenarios, this assumption allows us to highlight the technical differences between generation technologies without introducing unwarranted assumptions about the notoriously unpredictable financial markets. The finance assumptions are listed in Table C1. The only difference between different generation technologies is the depreciation schedule that is used; we have adopted the current convention that gas and nuclear plants use a 15-year schedule while coal plants use a 20-year schedule [MIT 2003].

Table C1: Base Case Input Parameters Used in LIFE Cost Scaling Study

	Units	Nuclear	Coal	Coal with Capture	Gas	Gas with Capture
Inflation Rate	%	3.0%	3.0%	3.0%	3.0%	3.0%
O&M real escalation	%	1.0%	1.0%	1.0%	1.0%	1.0%
Fuel real escalation	%	0.5%	0.5%	0.5%	0.5%	0.5%
Tax Rate	%	37.0%	37.0%	37.0%	37.0%	37.0%
Debt Fraction	%	60.0%	60.0%	60.0%	60.0%	60.0%
Debt Rate	%	8.0%	8.0%	8.0%	8.0%	8.0%
Equity Rate	%	12.0%	12.0%	12.0%	12.0%	12.0%
WACC	%	7.8%	7.8%	7.8%	7.8%	7.8%
Depreciation Schedule	--	MACRS-15	MACRS-20	MACRS-20	MACRS-15	MACRS-15
Startup Year	yr	2013	2013	2013	2013	2013

Following the MIT methodology, the overnight capital cost, yearly operation and maintenance (O&M), annual additional capital and fuel and waste expenditures are calculated as a cash flow over the plant lifetime. Depreciation and taxes are taken into account. Annual expenses and revenue are adjusted for overall inflation as well as real escalation in the cost of fuel and O&M. The breakeven cost of electricity is calculated so that the net present value of revenue over the life of the plant is equal to the net present value of expenditures.

Environmental Considerations

In this analysis, we assume that emissions of carbon dioxide are likely to be regulated by the time LIFE is a viable technology. Whether there is a government-imposed carbon tax or a market-driven cap-and-trade system, there will be a break-even price point carbon emissions where fossil-fueled generators will choose to install capture equipment. Capturing and storing carbon dioxide imposes extra capital, operational and fuel charges on an electric generator. The exact magnitudes of these charges are still unknown, but they have been estimated in the literature. It is estimated that the application of CCS to a generator will decrease the generator's efficiency by 20% - 40% due to the parasitic load and pressure drop imposed by the capture equipment. This increases the fuel charge by a commensurate amount. In general, the capital cost of a fossil-fired plant can be expected to almost double: not only does the scrubber equipment have a large cost associated with its construction, but the entire plant must be made larger because of the efficiency penalty imposed by the scrubbing equipment. There are also additional O&M expenses with upkeep of the scrubbers, and there is an additional charge per ton of carbon dioxide associated with its permanent geologic disposal [Metz, 2005]. The costs and operational penalties for CCS were assembled from MIT's Future of Nuclear Power and corroborated elsewhere in the literature [Katzer and Herzog, 2008], [Burton et al., 2008]

Table C2 lists the cost multipliers for coal and gas plants used to estimate the cost of electricity for capture-equipped plants. When these factors are multiplied by the base-case (unsequestered) values, the resultant COE increases.

Table C2: Estimated costs of carbon management

	Units	Coal	Gas
Heat Rate Multiplier (efficiency)	--	1.31	1.17
Overnight Cost Multiplier	--	1.64	1.98
Incremental Capital Multiplier	--	1.64	1.98
Fixed O&M Multiplier	--	2.13	1.74
Variable O&M Multiplier	--	2.13	1.74
Carbon Disposal Cost	$/tonne-CO2	$8.00	$8.00

<u>Results</u>

Table C3 lists all of the input values and the resultant COE for the five generation technologies considered in this analysis.

Table C3: Nuclear, Coal and Gas Generation Plant Parameters

	Units	Nuclear	Coal	Coal with Capture	Gas	Gas with Capture
Capacity	MWe	1000	1000	1000	1000	1000
Capacity Factor	%	85%	85%	85%	85%	85%
Heat Rate	BTU/kWh	10400	8870	11620	6800	7956
Overnight Cost	$/kWe	$4,000	$2,300	$3,772	$850	$1,683
Incremental Capital Costs	$/kWe per yr	$40.00	$26.55	$43.54	$10.20	$20.20
Fixed O&M Costs	$/kWe per yr	$56.44	$24.30	$51.76	$12.65	$22.01
Variable O&M Costs	mills/kW-hr	0.421	3.57	7.6041	0.411	0.71514
Fuel Costs	$/MMBTU	$0.67	$2.60	$2.60	$7.00	$7.00
Waste Fee	$/kW-hr	$0.001	$0.00	$0.00	$0.00	$0.00
Decommissioning Cost	$/kW	$700.00	$0.00	$0.00	$0.00	$0.00
Carbon Intensity	kg-C/MMBTU	0	25.8	25.8	14.5	14.5
Carbon Disposal Cost	$/tonne-CO2	--	--	$8.00	--	$8.00
Nuclear Waste Fee	$/kWh	$0.001	--	--	--	--
Baseline COE	**cents/kW-hr**	**6.68**	**6.20**	**10.61**	**6.50**	**8.87**

Under the assumptions used here, it is clear that nuclear, unsequestered coal and unsequestered gas generation are reasonably competitive with one another. The addition of CCS technology significantly affects the cost of electricity for fossil fueled generation.

<u>Cost of Carbon</u>

In effect, the addition of capture technology imposes a “waste management” cost per kWh produced. While this cost directly impacts the competitiveness of fossil-fired generators, it is instructive to also look at the cost on a \$/ton-CO_2 basis, as that is likely to be the framework that is used to enforce environmental compliance. Furthermore, by applying a simple carbon-price to the unsequestered generators that results in an equivalent COE to the sequestered cases, we can quickly determine the breakeven cost of environmental compliance.

Tables C4 (A and B) show the impact of a carbon price on fossil generation. The highlighted rows show the breakeven point for CCS.

Tables C4 (A and B): Effects of a carbon price on the cost of electricity for coal and gas

Unsequestered Coal With Carbon Price	
Carbon Price	COE
\$/tonne-CO2	cents/kW-hr
\$0.00	6.58
\$25.00	8.68
\$50.00	10.77
\$52.61	**10.61**
\$100.00	14.97
\$150.00	19.16
\$200.00	23.36

Unsequestered Gas With Carbon Tax	
Carbon Price	COE
\$/tonne-CO2	cents/kW-hr
\$0.00	7.02
\$25.00	7.92
\$50.00	8.82
\$65.52	**8.87**
\$100.00	10.63
\$150.00	12.44
\$200.00	14.25

While the price of carbon emissions is neither stable nor effective in obtaining deep emissions reductions at the time this paper is being published, it is expected that a stable and effective price will be reached in the coming decades. It is expected that the price will be between \$20 and \$200 per metric ton of CO_2. A price less than \$20/ton would not encourage significant emissions reductions, and a price greater than \$200/ton would create unacceptable economic disruption. It is therefore seen as likely that carbon capture, which is expected to cost between \$50 and \$100/ton, will compete directly with other carbon-free baseload electricity sources.

Cost of Nuclear Waste

This analysis also examines the impact of an increase in the fee charged for the disposal of nuclear waste. In the United States, the fee is a statutory flat charge for each kWh of electricity produced from nuclear energy. In the absence of any evidence that this cost structure is likely to change, we have examined only one-time change to the fee, and we assume that the new fee is in effect for the entire life of the plant. It is interesting to note that because the plant is assumed to operate from 2013 to 2053, the net present value of the waste disposal charge is very small in present-dollar terms. In fact, an increase of the fee from 0.1 cents/kWh to 5 cents per kWh has an impact of less than 3 cents/kWh in present day dollars. Table C5 shows the impact of increasing the flat fee for nuclear waste disposal.

Tables 5: Effects of a increasing the nuclear waste fee on the cost of electricity from LWR

Nuclear Waste Fee Escalation	
Fee	COE
Cents/kWh	Cents/kWh
$0.000	6.63
$0.001	6.68
$0.002	6.74
$0.005	6.91
$0.010	7.19
$0.050	9.46

Clearly, if the nuclear waste fee were subject to general and real escalation, the impact of the fee would be greater.

Conclusion

It can be expected that if greenhouse gas emissions regulations reach the point where they encourage CCS from coal and gas plants, the cost of baseload electricity from fossil fired plants will rise to near 10 cents/kWh on a levelized, net present value basis. At that price, it appears that nuclear generation options including LWR and LIFE may be competitive if the financial community places equal risk premiums on nuclear and fossil technologies.

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