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THE ECONOMICS OF SUSTAINABLE GEOTHERMAL DEVELOPMENT

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ABSTRACT

In planning the development of a geothermal field, there is a trade-off between plant capacity and the cost of make-up drilling. A larger plant benefits from economies of scale in the construction and operation of surface facilities. On the other hand, a larger plant also places a greater load on the geothermal reservoir, which causes higher rates of decline in well productivity. Greater decline rates for existing wells require a larger number of make-up wells. Because the cost of make-up wells occurs later in the project life, this cost has relatively less impact on project economics than the up-front cost of plant construction. Similarly, the loss of revenue from a decline in output late in a project's life is much less significant than revenue foregone at the start of a project due to limited plant capacity.

By way of illustration, this paper compares conservative and aggressive development scenarios for a hypothetical geothermal field. In the conservative scenario, the developer installs plant capacity that is assumed to represent a modest load on the reservoir (30 MW). Declines in well productivity are less than 2% per year, plant output is sustained at full capacity throughout the project life, and make-up drilling increases the number of production wells by about 40%. In the aggressive scenario, the developer installs three times the amount of plant capacity (90 MW), which is assumed to be at or near the maximum sustainable capacity of the reservoir. Declines in well productivity start at 20% per year and taper gradually to 3% per year. Plant output is sustained at full capacity only through year 20 of a 30-year project life, declining gradually thereafter to about 70% of full capacity. Make-up drilling increases the number of production wells by more than 2½ times.

An economic analysis based on these assumptions shows that the aggressive scenario has a better discounted return on investment (DROI) and a present worth (PW) almost three times as large as the conservative scenario, despite the large amount of make-up drilling and the late-term declines in output.

1. INTRODUCTION

As electricity markets move toward a greater degree of consumer choice in the selection of energy sources, sustainability is one of the main selling points of geothermal energy. An earlier paper (Lovekin, 1998) has described a conceptual model of the life cycle of a geothermal field (Figure 1). Under the hypothetical condition of unlimited demand for electricity at a profitable price, this model says that a geothermal developer will install plant capacity that can be sustained for a number of years by make-up drilling (the sustaining period), followed by a period of declining output as make-up drilling becomes less profitable (the declining period), followed in turn (if economic conditions remain favorable) by a period of negligible declines, in which mass withdrawals from the reservoir are balanced by natural recharge and injection (the renewable period). But if the public perception of sustainability is important, why would the developer not limit plant capacity from the start to a level at which declines are negligible and constant output can be sustained indefinitely?

The answer is that installing the higher level of plant capacity and mitigating declines with make-up drilling is generally more economical and thus contitutes a better use of society's limited resources for energy development. Larger geothermal plants benefit from economies of scale in the use of capital and labor. For example, construction of a plant site and a transmission line incurs certain up-front costs that can be borne more easily if spread over a larger plant capacity. Similarly, staff requirements are not proportional to the size of the plant; a larger plant can run effectively with fewer operators per megawatt (MW). In addition, larger plants are generally more efficient thermodynamically. On the other hand, a larger plant puts a greater load on the geothermal reservoir. This is typically reflected in higher rates of decline in the capacity of individual production wells. Thus, in choosing the optimal size for a geothermal plant, there is a trade-off between getting maximum advantage from economies of scale and keeping make-up drilling costs to manageable levels.

To illustrate this trade-off, this paper compares the economics of two alternatve development scenarios (one conservative, the other aggressive) for a hypothetical geothermal field. Table 1 summarizes the assumptions for the two scenarios. The scenarios differ in plant capacity (30 MW vs 90 MW), productivity decline rates (2% harmonic vs 20% harmonic), and savings from economies of scale (10% reduction for the aggressive case in costs per kilowatt [kW] for initial capital and for ongoing operations and maintenance [O&M]). The initial capacity per well (5 MW) and the drilling cost per well ($2,000,000) are assumed to be the same for both scenarios. The initial capital costs ($74 million for the conservative scenario and $204 million for the aggressive scenario) are functions of each scenario's respective cost per kW installed. In real life, decline rates, well capacities, and capital and O&M costs for plant facilities and individual wells can vary widely, but the values used here are well within the typical range.

The developer in both scenarios is assumed to receive a constant energy price of 6.5¢ per kilowatt-hour (kWh), with no payment for plant capacity. The economic calculations are simplified by assuming that the development is financed with 100% equity (no debt), by estimating zero inflation, and by neglecting taxes. These simplifications do not distort the underlying economics, but allow the impact of discounting calculations on the revenue stream and on make-up well drilling costs to be highlighted. The analysis assumes an annual discount rate of 10%; the relative attractiveness of the two scenarios is not affected by varying this discount rate over a reasonable range.

2. CONSERVATIVE SCENARIO

Figure 2 illustrates the projected field performance for a 30-year project life under the conservative scenario. At start-up there are seven production wells, yielding a capacity of 35 MW at the wellhead, 17% above the plant capacity of 30 MW. (MW values expressed in this paper are considered to be net megawatts available for sale.) Because the load on the reservoir is modest, the decline in well productivity starts at the relatively low rate of 2% per year. The decline is assumed to be harmonic (that is, the decline rate itself declines with time, as has been observed, for example, at the Geysers [Sanyal *et al*, 1992]). When the MW capacity at the wellhead approaches the minimum required to maintain plant output at full power, a make-up well is drilled (once every eight or nine years in this scenario). At the end of the project life, the number of production wells has risen to ten (an increase of 43%), and plant output remains at full power.

Table 2 summarizes the economic results of the conservative scenario. The constant plant output of 30 MW generates annual energy sales of 262,800 megawatt-hours (MWh) and annual revenue of over $17 million. The O&M cost of $200 per kW installed yields an annual O&M cost of $6 million. This results in a net cash flow of about $11 million per year, except for years in which the drilling of a make-up well reduces net cash flow by $2 million. After applying the 10% discount factor, the cumulative cost of the three make-up wells is shown to be just $1.665 million, and the cumulative net cash flow totals about $113 million. When the initial investment of $74 million is subtracted, the project is seen to have a present worth (PW) of about $39 million. Dividing this amount by the initial investment yields a discounted return on investment (DROI) of 53.0%.

3. AGGRESSIVE SCENARIO

Figure 3 shows a contrasting picture of performance of the same field under the aggressive scenario. Initially, 21 production wells provide a wellhead capacity of 105 MW, 17% above the plant capacity of 90 MW. Because this plant capacity is hypothezised to be at or near the maximum sustainable capacity of the field, the decline in well productivity is assumed to start at the relatively high value of 20% per year. The decline is harmonic, as before; this results in annual declines tapering to approximately 3% by the end of the 30-year project life. The high initial decline rates in well productivity require an active program of make-up drilling: four wells are drilled during the first year , tapering to one well per year by year 13. In this example, make-up drilling is assumed to stop in year 20, after the number of production wells has risen to 55 (2½ times the initial number of production wells). As a result, plant output begins to decline at the same rate as the decline in well productivity, reaching a level of 64 MW (71% of full power) by the end of the project life.

Table 3 shows the economic results of this scenario. The plant output of 90 MW yields annual electricity sales of 788,400 MWh and annual revenues of $51 million through year 19, declining threreafter to electricity sales of 552,706 MWh and revenues of $36 million in year 30. The O&M cost of $180 per kW installed (10% less than the conservative scenario) yields an annual O&M cost of $16.2 million. This is assumed to stay constant even after the actual electrical output starts to decline, because the plant and its associated infrastructure remain the same. Make-up well costs start at $8 million per year, taper to $2 million per year in year 13, and cease altogether in year 20. The annual net cash flow during the first 20 years is in the range of $27 million to $35 million (depending on the amount of make-up drilling each year), and it declines over the next ten years to about $20 million as plant output drops off. After discounting, the cost of drilling 34 make-up wells is shown to be about $40 million, and the cumulative discounted net cash flow is about $315 million. After subtracting the initial investment of $204 million, the PW of the project under the aggressive scenario is about $111 million, with a DROI of 54.3%.

4. DISCUSSION

A comparison of these two scenarios shows that, for a reasonable set of assumptions about resource performance and development costs, the aggressive scenario has a higher DROI and a PW almost three times greater, despite the steep initial declines in well productivity, the large number of make-up wells, and the drop in electrical output in the last 10 years. This is simply a consequence of the time value of money, working in two ways: the strong impact of three times the annual revenue in early years, even after subtracting the cost of make-up wells; and the minimal impact on PW of revenue losses late in the project life.

The more favorable DROI for the aggressive scenario in the current example is a direct result of the assumed economies of scale. If capital and O&M costs were linear functions of plant capacity (that is, if there were no cost reduction per kW for a larger plant size), then any reduction in output would necessarily decrease the DROI. For the example presented here, if the factor for economies of scale were reduced from 10% to zero, the DROI of the agressive scenario would be reduced to 33.4%. However, even without economies of scale, the PW of the aggressive scenario would still be about $74 million, almost twice as large as for the conservative case.

So which approach to geothermal development is preferable? The scenarios described above suggest that an aggressive approach is better: the developer gets a better return on investment, and society gets a greater amount of environmentally beneficial power at a lower cost per kW. Admittedly, this hypothetical example is somewhat artificial, because of the underlying assumption of an unlimited market. In practice, the size of plant facilities is more often dictated by market constraints than by the physical limit of what the geothermal reservoir can produce. Another caveat is that the relationship between the load on the reservoir and the steepness of productivity declines is imperfectly known at the start of a project. This relationship can be estimated by numerical simulation, but such estimates are not well constrained until the field has some operating history. Still, the example described here is useful in illustrating that there can be real economic and social advantages in developing geothermal resources to their full potential, rather than insisting that constant electrical output throughout the project life must be assured.

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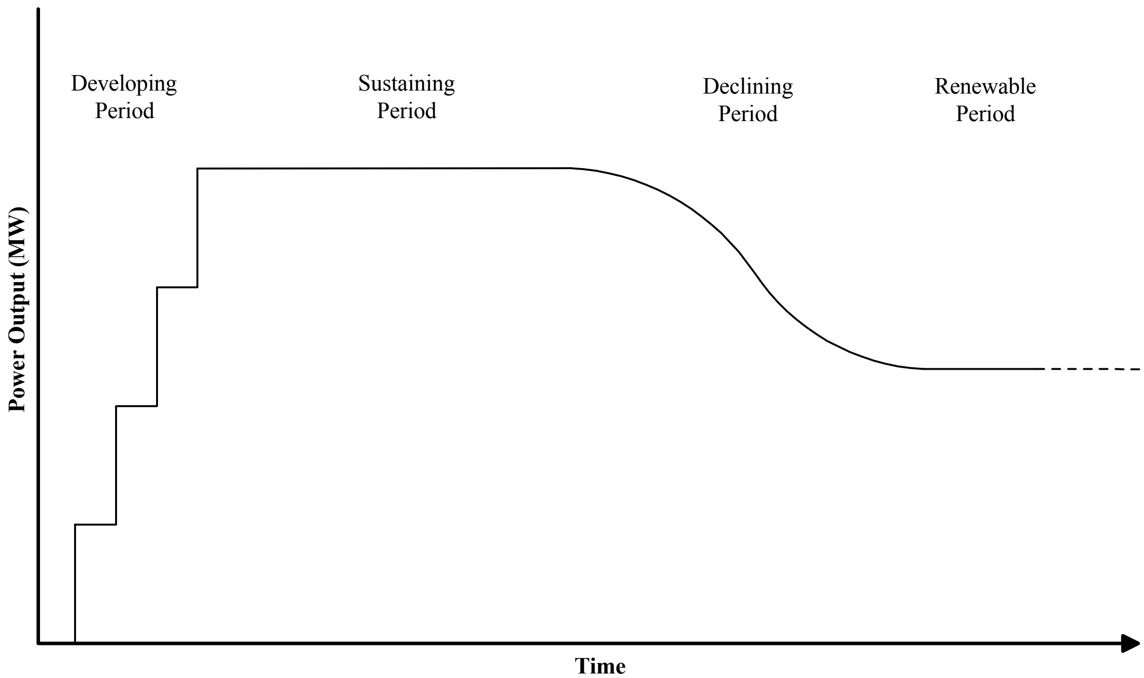

Figure 1. Life Cycle of a Geothermal Field (Lovekin, 1998)

Table 1. Assumptions for Conservative and Aggressive Development Scenarios of a Hypothetical Geothermal Field

	Conservative Scenario	Aggressive Scenario
Installed plant capacity	30 megawatts	90 megawatts
Number of production wells at start	7	21
Annual decline in productivity of existing wells	2% harmonic	20% harmonic
Number of make-up production wells over 30-year project life	3	34
Initial capacity per well	5 megawatts	5 megawatts
Average well cost	$2,000,000	$2,000,000
Initial capital cost per kilowatt installed	$2,000	$1,800 (10% reduction)
Total Initial Capital Cost	$74,000,000	$204,000,000
Operations and maintenance (O&M) costs per kilowatt installed	$200	$180 (10% reduction)
Energy price received per kilowatt-hour	6.5 cents	6.5 cents
Capacity price received	none	none
Annual discount rate	10.0%	10.0%
Annual inflation rate	0.0%	0.0%
Financing	100% equity	100% equity
Taxes	not considered	not considered

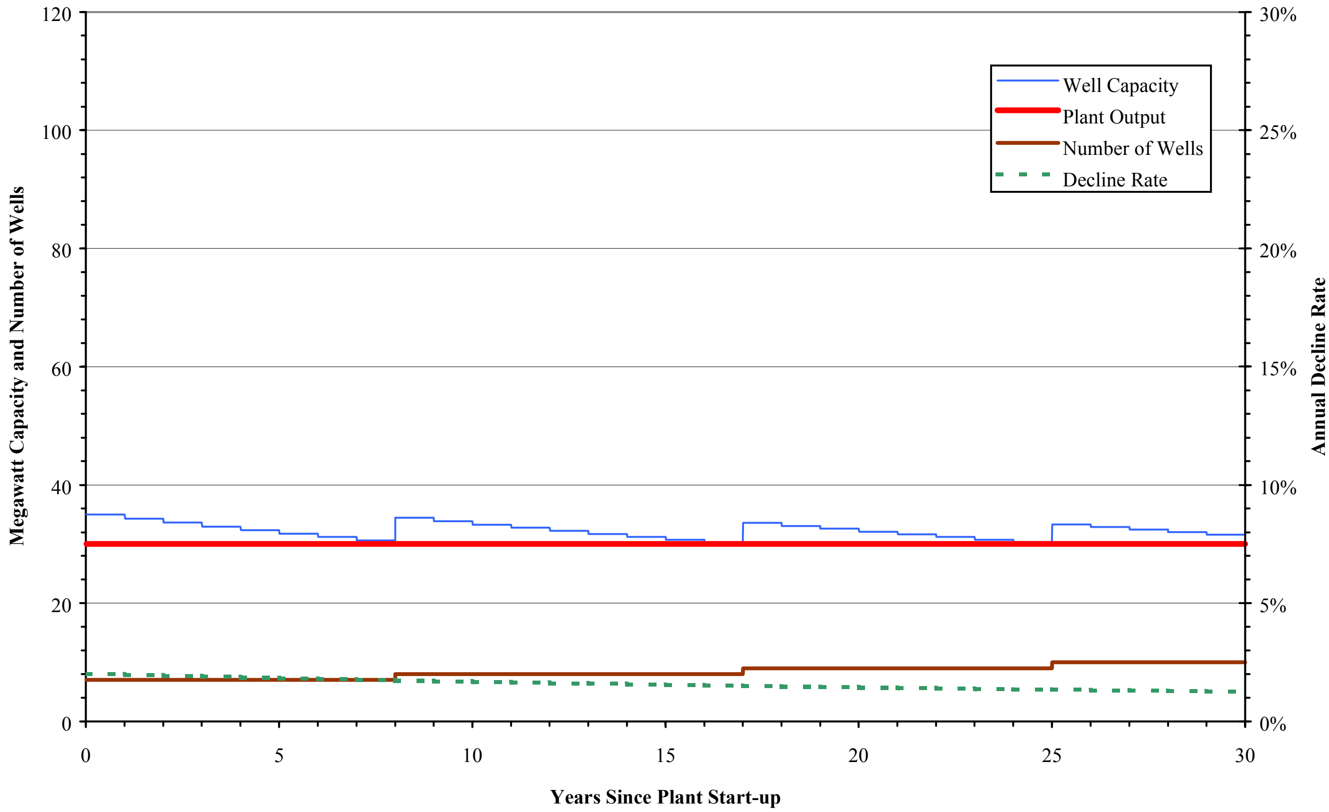

Figure 2. Conservative Scenario (Plant Capacity = 30 MW): Projected Field Performance

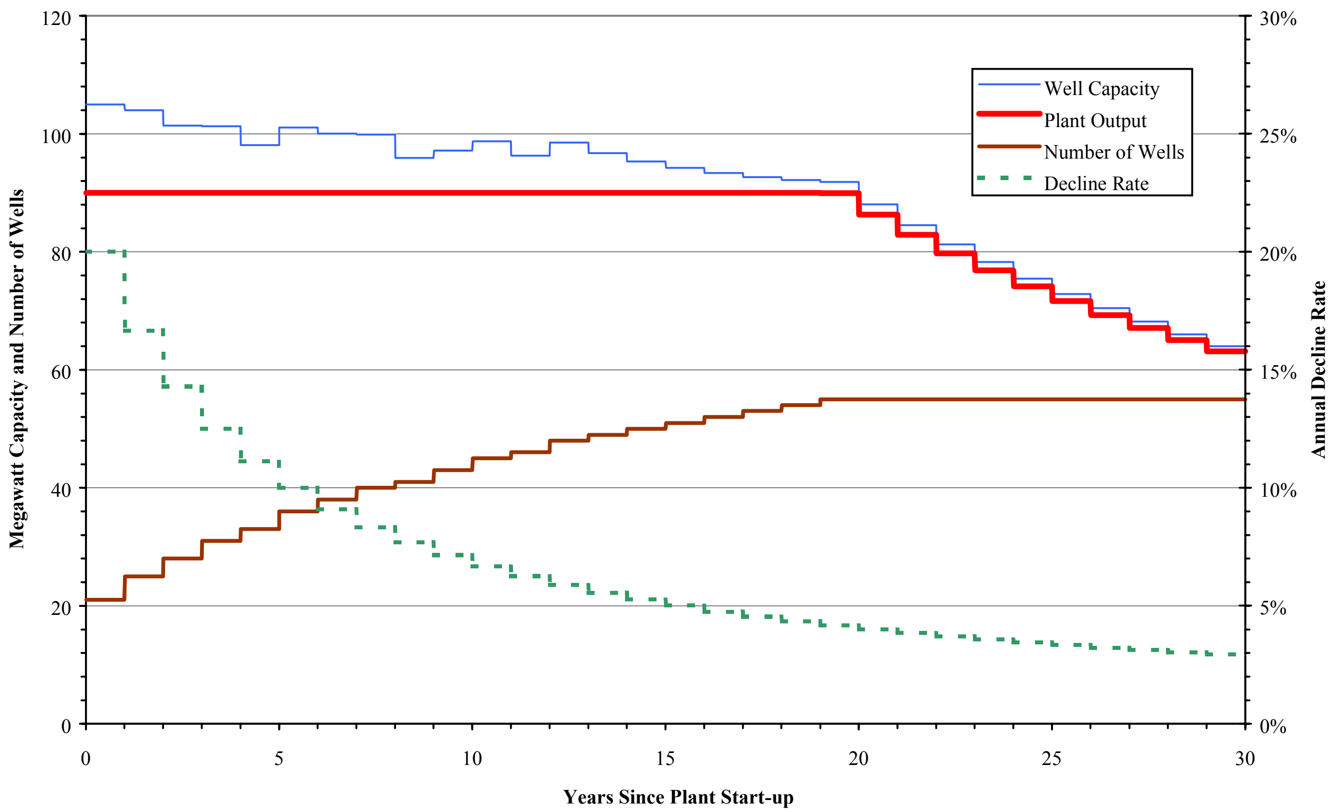

Figure 3. Aggressive Scenario (Plant Capacity = 90 MW): Projected Field Perfomance

Table 2. Conservative Scenario: Economic Results

Year	Elec-tricity Sales (MWh)	Reve-nue ($000)	Annual O&M Cost ($000)	Make-up Well Cost ($000)	Net Cash Flow ($000)	Dis-count Fac-tor	Discounted Make-up Well Cost ($000)	Cumulative Discounted Make-up Well Cost ($000)	Discounted Net Cash Flow ($000)	Cumulative Discounted Net Cash Flow ($000)	Cumulative Discounted Net Cash Flow Minus Initial Investment ($000)
1	262,800	17,082	6,000	0	11,082	1.000	0	0	11,082	11,082	-62,918
2	262,800	17,082	6,000	0	11,082	1.100	0	0	10,075	21,157	-52,843
3	262,800	17,082	6,000	0	11,082	1.210	0	0	9,159	30,315	-43,685
4	262,800	17,082	6,000	0	11,082	1.331	0	0	8,326	38,641	-35,359
5	262,800	17,082	6,000	0	11,082	1.464	0	0	7,569	46,210	-27,790
6	262,800	17,082	6,000	0	11,082	1.611	0	0	6,881	53,091	-20,909
7	262,800	17,082	6,000	0	11,082	1.772	0	0	6,256	59,347	-14,653
8	262,800	17,082	6,000	2,000	9,082	1.949	1,026	1,026	4,661	64,008	-9,992
9	262,800	17,082	6,000	0	11,082	2.144	0	1,026	5,170	69,177	-4,823
10	262,800	17,082	6,000	0	11,082	2.358	0	1,026	4,700	73,877	-123
11	262,800	17,082	6,000	0	11,082	2.594	0	1,026	4,273	78,150	4,150
12	262,800	17,082	6,000	0	11,082	2.853	0	1,026	3,884	82,034	8,034
13	262,800	17,082	6,000	0	11,082	3.138	0	1,026	3,531	85,565	11,565
14	262,800	17,082	6,000	0	11,082	3.452	0	1,026	3,210	88,775	14,775
15	262,800	17,082	6,000	0	11,082	3.797	0	1,026	2,918	91,693	17,693
16	262,800	17,082	6,000	0	11,082	4.177	0	1,026	2,653	94,346	20,346
17	262,800	17,082	6,000	2,000	9,082	4.595	435	1,462	1,977	96,323	22,323
18	262,800	17,082	6,000	0	11,082	5.054	0	1,462	2,193	98,515	24,515
19	262,800	17,082	6,000	0	11,082	5.560	0	1,462	1,993	100,508	26,508
20	262,800	17,082	6,000	0	11,082	6.116	0	1,462	1,812	102,320	28,320
21	262,800	17,082	6,000	0	11,082	6.727	0	1,462	1,647	103,968	29,968
22	262,800	17,082	6,000	0	11,082	7.400	0	1,462	1,498	105,465	31,465
23	262,800	17,082	6,000	0	11,082	8.140	0	1,462	1,361	106,827	32,827
24	262,800	17,082	6,000	0	11,082	8.954	0	1,462	1,238	108,064	34,064
25	262,800	17,082	6,000	2,000	9,082	9.850	203	1,665	922	108,986	34,986
26	262,800	17,082	6,000	0	11,082	10.835	0	1,665	1,023	110,009	36,009
27	262,800	17,082	6,000	0	11,082	11.918	0	1,665	930	110,939	36,939
28	262,800	17,082	6,000	0	11,082	13.110	0	1,665	845	111,784	37,784
29	262,800	17,082	6,000	0	11,082	14.421	0	1,665	768	112,553	38,553
30	262,800	17,082	6,000	0	11,082	15.863	0	1,665	699	113,251	39,251

Discounted Return on Investment (DROI) = 39,251 / 74,000 = 53.0%

Table 3. Aggressive Scenario: Economic Results

Year	Elec-tricity Sales (MWh)	Reve-nue ($000)	Annual O&M Cost ($000)	Make-up Well Cost ($000)	Net Cash Flow ($000)	Dis-count Fac-tor	Discounted Make-up Well Cost ($000)	Cumulative Discounted Make-up Well Cost ($000)	Discounted Net Cash Flow ($000)	Cumulative Discounted Net Cash Flow ($000)	Cumulative Discounted Net Cash Flow Minus Initial Investment ($000)
1	788,400	51,246	16,200	8,000	27,046	1.000	8,000	8,000	27,046	27,046	-176,954
2	788,400	51,246	16,200	6,000	29,046	1.100	5,455	13,455	26,405	53,451	-150,549
3	788,400	51,246	16,200	6,000	29,046	1.210	4,959	18,413	24,005	77,456	-126,544
4	788,400	51,246	16,200	4,000	31,046	1.331	3,005	21,418	23,325	100,782	-103,218
5	788,400	51,246	16,200	6,000	29,046	1.464	4,098	25,517	19,839	120,621	-83,379
6	788,400	51,246	16,200	4,000	31,046	1.611	2,484	28,000	19,277	139,898	-64,102
7	788,400	51,246	16,200	4,000	31,046	1.772	2,258	30,258	17,525	157,422	-46,578
8	788,400	51,246	16,200	2,000	33,046	1.949	1,026	31,284	16,958	174,380	-29,620
9	788,400	51,246	16,200	4,000	31,046	2.144	1,866	33,150	14,483	188,863	-15,137
10	788,400	51,246	16,200	4,000	31,046	2.358	1,696	34,847	13,167	202,030	-1,970
11	788,400	51,246	16,200	2,000	33,046	2.594	771	35,618	12,741	214,771	10,771
12	788,400	51,246	16,200	4,000	31,046	2.853	1,402	37,020	10,881	225,652	21,652
13	788,400	51,246	16,200	2,000	33,046	3.138	637	37,657	10,529	236,181	32,181
14	788,400	51,246	16,200	2,000	33,046	3.452	579	38,237	9,572	245,754	41,754
15	788,400	51,246	16,200	2,000	33,046	3.797	527	38,763	8,702	254,456	50,456
16	788,400	51,246	16,200	2,000	33,046	4.177	479	39,242	7,911	262,367	58,367
17	788,400	51,246	16,200	2,000	33,046	4.595	435	39,677	7,192	269,558	65,558
18	788,400	51,246	16,200	2,000	33,046	5.054	396	40,073	6,538	276,096	72,096
19	788,400	51,246	16,200	2,000	33,046	5.560	360	40,433	5,944	282,040	78,040
20	788,082	51,225	16,200	0	35,025	6.116	0	40,433	5,727	287,767	83,767
21	755,888	49,133	16,200	0	32,933	6.727	0	40,433	4,895	292,662	88,662
22	726,222	47,204	16,200	0	31,004	7.400	0	40,433	4,190	296,852	92,852
23	698,797	45,422	16,200	0	29,222	8.140	0	40,433	3,590	300,442	96,442
24	673,369	43,769	16,200	0	27,569	8.954	0	40,433	3,079	303,520	99,520
25	649,728	42,232	16,200	0	26,032	9.850	0	40,433	2,643	306,163	102,163
26	627,690	40,800	16,200	0	24,600	10.835	0	40,433	2,270	308,434	104,434
27	607,099	39,461	16,200	0	23,261	11.918	0	40,433	1,952	310,386	106,386
28	587,816	38,208	16,200	0	22,008	13.110	0	40,433	1,679	312,064	108,064
29	569,721	37,032	16,200	0	20,832	14.421	0	40,433	1,445	313,509	109,509
30	552,706	35,926	16,200	0	19,726	15.863	0	40,433	1,244	314,752	110,752

Discounted Return on Investment (DROI) = 110,752 / 204,000 = 54.3%