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The Economics of Energy Storage in 14 Deregulated Power Markets

F. CRISTINA FIGUEIREDO,
PETER C. FLYNN, & EDGAR A. CABRAL

ABSTRACT

In a regulated market large scale storage of electrical energy, for example by pumped storage, time shifts the generation of power and has been used to defer generation investment. In a deregulated market power storage, when used for energy rather than as a source of spinning or standby reserve or frequency control, is a simple economic proposition: power is purchased during periods of low price and regenerated and resold during periods of high price. In this study historical diurnal price patterns in 14 deregulated markets are analyzed to give an initial prediction of the economic incentive for energy storage. We rank the 14 markets based on available revenue and potential return on investment; the incentive to store energy varies significantly between markets. The differences between markets arise because of different diurnal patterns of power price. Diurnal price patterns in turn reflect a complex set of factors in a market, including generation mix, market design and participant behaviours.

F. Cristina Figueiredo and Peter C. Flynn are with the Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, T6G 2G8 Canada.
Edgar A. Cabral is with the School of Business, University of Alberta, Edmonton, Alberta, T6G 2R6
Corresponding author is Peter Flynn: Tel. +1-780-492-6438; fax: +1-780-492-2200
E-mail address: peter.flynn@ualberta.ca (Peter Flynn)

INTRODUCTION

Any storage of electrical power requires an investment in capital and incurs the cost of inefficiency, i.e. the ratio of power recovered to power consumed. Pumped storage, in which water is pumped from lower to a higher water source and then later flowed from the higher source to the lower to produce electricity, is one means of time shifting, or storing, electrical power. It requires an investment in capital for reservoirs, penstocks, one or more pump/turbo-generators, and associated switching and transformer equipment to allow access to transmission. It consumes more power than it returns, due to inefficiencies in pumping and generation. Power purchase is the most significant operating cost, with maintenance and other operating costs being relatively minor.

Pumped storage has been applied in regulated power markets (see, for example, the first 4 references) to better utilize existing generation capacity and postpone more costly investment in generation; the justification is a reduction in the overall regulated price of power compared to the alternative of investment in new primary generation. In deregulated markets, the sale of electrical energy and/or ancillary services from pumped storage can be evaluated based on each individual project: given a forecast diurnal power and ancillary service price, does the revenue from the sale of power or services less the cost of purchased power cover the capital recovery and other operating costs?

In this study, we utilize historical power price data from 14 deregulated markets to assess the incentive to implement pumped storage for electrical energy; power price patterns in these markets have been analyzed by Li and Flynn [References 5-8]. Each market has a unique average diurnal power price profile that in turn leads to a unique price spread for pumped storage; each market will also have its own maximum profitable operating duration, i.e. the number of hours in which the revenue from the sale of power is higher than the purchase cost of power required to pump the water into the reservoir; this value is also dependent on the operating efficiency of pumped storage. We use the diurnal price pattern and efficiency of storage to assess the net income potential from energy sale from pumped storage for each market, and rank the markets in terms of the incentive to invest in pumped energy storage. We illustrate an optimal operating profile in detail based on historical price patterns for one of the markets. We then combine the net income potential with the capital and operating cost of pumped storage, and analyze the adequacy of return on investment for pumped storage by two different methods. First, we define a theoretical minimum level of investment in which all factors align to minimize net capital cost and calculate the expected maximum pre-tax return on investment for the 14 markets studied. Second, we determine the largest amount of investment per unit of power output that can be justified in each market to earn a pre-tax return on capital of 10%.

Deb [Reference 9] illustrated a bidding strategy for both energy and ancillary services sales in a day ahead market for which all prices are known. Lu et al. [Reference 10] developed an optimal strategy for pumped storage, including both the sale of electrical energy and ancillary services, for the New York ISO based on historical prices. We focus on the sale of electrical energy and do not include ancillary services in our comparison of the 14 deregulated markets because data on the price of ancillary services is not readily available, while price data for hourly or half hourly electrical energy is. In addition, the specific provisions for purchase of ancillary services vary widely between markets and are often different than those for the purchase of energy (for example, purchase of ancillary services on a day ahead basis in markets where energy is purchase on an hour ahead basis). We note, however, that any party implementing pumped storage would have the potential to increase their revenue in certain periods by selling ancillary services instead of energy.

1. POWER PRICE DATA

Table 1 summarizes the average of hourly or half hourly price data that were analyzed by Li and Flynn for 14 different markets (all cost figures in this study are expressed in 2004 US$). Table 2 shows the range of time over which the original power price data was averaged. Average prices in the local currency were converted to a single currency, US$, at the exchange rates as of October 7th, 2004 [Reference 11], shown in Table 3. Note that deregulated markets differ in the method by which the predominant power price is set; in some markets it is based on an hour or half hour ahead bid, while in others it is based on a binding day ahead bid, with a small hourly market for adjustments in day ahead bid volumes. Price data in this study is the predominant price, i.e. the price at which most of the power in the given market is sold. Data cleaning, dealing with missing or duplicate data points, was a minor issue, typically affecting less than 0.5% of data points and hence not a significant source of error [Reference 5]. Fig. 1 illustrates a sample average diurnal price pattern for weekdays and weekends in one market in this study. Weekday and weekend price patterns for all markets in this study can be found in Reference 5.

Diurnal price patterns in deregulated power markets are created by a number of factors, including the generation mix and the market design and operation. Generation mix, for example the blend of hydro, nuclear, coal and gas fired power, will lead to significant shifts in the marginal bid price of power as demand changes. Market design, e.g. binding day ahead vs. hour by hour bidding, influences volatility.

Table 1:
Average diurnal power price converted to a common currency (USD/MWh)

Hr	1-Canada: Alberta		2-USA: N. California		3-USA:PJM		4-USA: New England		5-Germany: Leipzig Exchange		6-Netherlands		7-Britain	
	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	wkend
0:00	51.80	52.79	57.22	48.24	18.00	16.87	30.12	30.40	11.50	9.87	30.18	26.61	28.15	25.70
0:30													25.19	22.72
1:00	43.77	48.45	51.00	49.69	15.73	15.98	28.20	26.14	10.17	9.55	26.54	26.19	24.86	22.72
1:30													25.17	26.92
2:00	41.19	44.95	46.75	45.20	14.86	14.81	26.66	24.35	8.97	8.28	24.18	23.93	28.06	29.73
2:30													28.71	30.69
3:00	39.62	42.79	43.65	41.98	16.96	13.68	24.80	24.12	8.33	7.56	24.48	23.01	26.95	27.82
3:30													27.85	27.57
4.00	38.79	41.89	43.92	40.85	13.63	12.93	24.99	24.73	8.07	7.17	23.27	22.38	27.51	26.41
4:30													25.56	23.61
5:00	38.71	40.61	45.81	40.77	14.13	13.07	27.24	27.60	8.37	6.97	23.35	22.18	24.33	21.83
5:30													22.89	21.10
6:00	42.63	40.30	53.08	41.69	16.56	13.75	31.10	33.22	9.39	6.81	24.13	21.77	21.31	21.10
6:30													21.14	20.21
7:00	54.44	42.00	56.06	39.60	24.64	14.01	34.52	41.06	11.87	6.42	27.19	21.69	23.28	21.04
7:30													28.61	21.47
8:00	78.05	48.22	61.43	42.45	29.21	14.94	36.99	45.97	16.24	7.42	53.75	25.62	36.83	22.14
8:30													41.28	23.26
9:00	93.02	57.44	63.73	47.99	26.48	20.45	39.89	46.27	18.58	9.38	67.17	28.07	46.01	24.82
9:30													48.72	27.15
10:00	98.85	65.10	67.84	52.28	28.76	23.39	41.58	47.66	19.61	11.21	72.47	31.37	49.92	30.32
10:30													53.36	34.23
11:00	110.04	72.69	71.33	55.49	33.59	24.55	42.65	49.65	21.34	12.95	92.54	34.67	51.61	36.96
11:30													48.54	38.42
12:00	114.37	74.67	73.90	48.55	35.91	23.96	44.25	59.12	26.98	14.66	107.56	36.84	51.54	38.08
12:30													55.12	38.96
13:00	115.97	76.78	76.08	58.47	36.65	23.23	43.05	75.00	21.12	12.98	75.97	33.62	58.18	39.67
13:30													55.63	37.89
14:00	114.15	75.72	79.47	58.90	43.11	22.85	41.22	74.96	19.89	11.23	85.74	31.48	45.04	34.49
14:30													42.22	29.63
15:00	119.47	71.83	81.31	58.55	43.66	22.33	40.60	72.18	17.87	10.03	72.21	29.87	42.03	26.58
15:30													41.65	24.84
16:00	119.03	72.21	81.53	58.38	43.28	22.18	40.63	67.60	16.49	9.61	62.00	28.87	39.29	23.38
16:30													38.59	22.78
17:00	130.76	81.76	82.28	61.66	43.13	25.81	43.19	50.10	17.23	9.93	53.61	29.19	45.22	23.93
17:30													56.36	28.83
18:00	151.28	95.51	81.95	72.76	45.33	29.71	46.08	56.17	20.41	11.78	74.66	41.58	64.35	35.95
18:30													53.00	39.03
19:00	119.59	88.41	79.71	71.70	36.90	28.40	44.79	55.90	20.22	12.71	56.94	45.71	53.25	40.19
19:30													52.15	40.31
20:00	107.43	77.22	76.82	70.59	33.03	26.03	42.62	48.43	17.21	12.54	42.30	41.21	51.03	39.85
20:30													46.95	37.09
21:00	110.58	74.39	75.16	71.06	34.98	27.95	40.43	43.33	15.02	11.62	39.72	34.90	43.76	35.13
21:30													43.05	34.44
22:00	106.43	80.41	65.64	57.54	30.01	24.99	35.00	36.99	13.34	11.31	35.53	31.05	44.45	34.13
22:30													43.19	34.39
23:00	78.52	65.62	61.46	56.00	22.03	19.86	31.62	31.98	12.92	11.93	34.30	31.56	37.29	31.94
23:30													32.86	29.65

Table 1 (cont'd):
Average diurnal power price converted to a common currency (USD/MWh)

Hr	8-Spain		9-Scandinavia		10-Australia South Australia		11-Australia New S Wales		12-Australia: Queensland		13-Australia Victoria		14-New Zealand: Benmore	
	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	Wkday	wkend
0:00	45.06	43.81	19.67	19.30	33.90	24.59	27.07	19.34	30.61	24.07	28.89	19.18	28.13	25.96
0:30					34.32	28.29	21.85	16.90	20.01	16.92	26.26	16.75	24.12	22.63
1:00	39.53	43.88	19.21	18.89	34.61	30.28	19.14	18.64	15.87	16.40	22.64	18.85	26.07	28.41
1:30					37.71	42.95	17.16	16.91	14.52	14.57	18.83	16.66	23.05	25.19
2:00	32.89	38.02	18.74	18.49	29.30	36.45	19.81	18.66	14.18	14.02	23.99	21.14	25.58	27.17
2:30					24.27	31.02	17.41	16.27	13.50	13.63	18.04	16.50	23.47	24.84
3:00	30.38	32.48	18.50	18.22	23.16	31.68	16.03	14.80	13.15	12.97	15.80	14.50	22.41	22.89
3:30					18.15	23.51	14.64	13.56	12.89	12.51	13.87	12.84	20.76	21.33
4:00	29.26	30.20	18.42	17.89	17.19	14.72	13.26	12.08	12.57	12.38	12.17	11.15	19.48	19.84
4:30					13.69	13.19	12.42	11.05	12.33	11.91	11.19	10.00	18.29	18.61
5:00	28.54	28.80	18.57	17.76	13.70	11.42	12.63	10.73	12.55	11.83	11.32	9.42	17.69	17.60
5:30					13.89	10.61	12.97	40.40	12.81	11.79	11.64	8.89	17.40	16.67
6:00	28.62	27.89	19.18	17.84	16.96	10.92	15.72	10.96	13.67	12.22	14.32	9.32	18.05	16.62
6:30					18.98	12.95	17.14	11.23	14.03	12.54	16.27	9.52	19.25	17.12
7:00	32.34	27.81	20.45	18.03	27.70	12.74	22.80	12.51	16.25	12.98	23.71	10.81	21.99	18.08
7:30					49.19	14.12	43.05	13.62	20.81	13.24	42.58	11.96	25.07	18.93
8:00	41.10	27.59	22.12	18.37	31.31	15.02	19.91	14.29	33.03	13.39	20.28	12.19	29.59	19.94
8:30					34.25	17.17	23.00	16.45	36.69	15.24	23.49	14.19	36.68	21.69
9:00	49.11	28.50	23.34	18.88	40.88	21.46	25.87	19.12	43.38	25.31	26.91	16.84	38.89	21.19
9:30					48.36	23.36	24.63	22.32	47.18	26.02	26.54	18.27	45.15	24.14
10:00	52.04	32.59	23.00	19.44	38.86	25.60	26.30	22.21	47.05	32.68	26.94	20.08	39.42	25.54
10:30					44.48	27.72	25.50	21.92	45.49	36.86	29.23	20.03	37.59	28.32
11:00	54.57	38.64	22.75	19.74	37.95	30.65	24.85	21.34	45.15	33.29	27.80	19.66	36.01	30.11
11:30					36.38	30.78	25.28	20.86	44.47	32.10	26.05	19.26	35.21	30.19
12:00	55.79	41.21	22.41	19.81	40.81	31.98	25.04	20.43	440.8	31.08	28.05	19.00	34.63	30.74
12:30					45.76	31.60	25.80	20.21	49.39	30.44	26.97	18.79	34.49	31.01
13:00	55.94	41.12	21.92	19.64	59.08	34.39	25.55	19.88	43.29	24.46	32.98	18.43	32.21	31.20
13:30					61.49	39.21	26.46	19.26	42.72	19.83	32.13	17.79	33.81	29.30
14:00	53.56	40.00	21.74	19.44	62.69	36.80	29.45	19.11	43.45	16.82	34.23	17.64	33.79	29.30
14:30					71.80	32.51	31.54	18.42	49.36	16.49	36.77	16.95	32.54	27.73
15:00	49.65	37.98	21.60	19.32	69.75	28.77	30.27	17.77	51.17	25.44	37.41	16.26	32.41	26.58
15:30					72.25	27.99	28.65	17.58	44.68	17.54	33.77	16.19	31.26	25.35
16:00	50.32	35.89	21.49	19.34	76.84	28.53	31.96	17.47	46.89	16.10	35.43	16.08	30.98	24.55
16:30					83.11	23.81	35.60	18.13	43.90	21.61	41.09	16.65	30.97	24.73
17:00	51.80	34.61	21.49	19.58	69.02	23.23	29.44	17.59	47.43	25.10	36.71	16.23	31.08	24.82
17:30					63.22	25.49	28.16	18.96	46.64	31.86	29.98	17.70	32.60	26.65
18:00	53.93	35.10	21.79	19.94	50.31	32.60	27.69	23.27	48.42	33.86	29.08	22.17	33.48	28.17
18:30					45.66	34.34	30.90	27.16	60.20	40.14	32.98	25.99	34.79	30.28
19:00	56.47	39.63	21.62	20.10	45.91	40.69	31.27	31.82	56.90	43.09	31.58	30.61	36.07	34.09
19:30					43.52	42.07	24.89	29.94	59.35	45.06	28.03	28.62	42.93	37.98
20:00	57.29	42.52	21.24	20.01	43.25	30.35	22.41	22.76	53.29	45.09	27.07	21.83	43.72	36.74
20:30					40.39	29.94	21.73	22.09	40.50	36.70	26.39	21.27	42.09	35.85
21:00	56.01	46.74	20.92	19.90	36.80	25.79	20.59	20.89	25.72	24.36	25.15	19.90	38.67	34.87
21:30					36.71	24.41	19.10	19.89	26.48	22.83	23.75	18.94	37.08	34.32
22:00	55.30	50.66	20.83	19.92	38.00	22.40	20.27	19.07	25.28	22.18	23.85	17.34	36.34	33.00
22:30					33.71	21.30	17.35	17.10	22.16	17.70	20.78	15.76	35.10	30.87
23:00	50.74	48.48	20.42	19.73	31.21	21.81	22.43	17.97	29.41	20.01	22.14	16.27	32.98	28.69
23:30					29.40	21.33	20.30	16.83	23.86	22.32	19.45	15.49	29.65	26.44

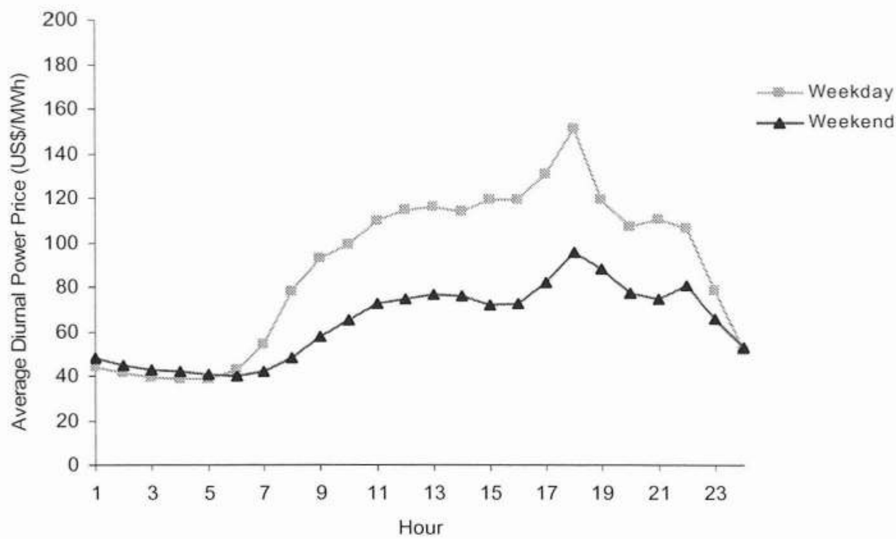
Table 2: Time span of power price data – Li & Flynn [Reference 5-6]

Market	Frequency	Duration	% of data cleaned
1. Canada: Alberta	Hourly	96/01/01 - 01/12/31	0.02
2. USA: North California	Hourly	98/04/01 – 01/01/31	0.80
3. USA: PJM	Hourly	97/04/01 – 01/12/31	0.73
4. USA: New England	Hourly	99/05/01 – 01/12/31	0.87
5. Germany: Leipzig Exchange	Hourly	00/06/16 – 01/12/31	1.07
6. Netherlands	Hourly	99/05/26 – 01/12/31	0.01
7. Britain	Half Hourly	96/01/01 – 97/12/31, 98/03/01 – 01/2/28	0.34
8.Spain	Hourly	98/01/01 – 01/12/31	0.08
9. Scandinavia	Hourly	92/05/04 – 01/12/31	0.03
10. Australia: South Australia	Half Hourly	98/12/13 – 01/12/31	0.01
11. Australia: New South Wales	Half Hourly	98/12/13 – 01/12/31	0.03
12. Australia: Queensland	Half Hourly	98/12/13 – 01/12/31	0.04
13. Australia: Victoria	Half Hourly	98/12/13 – 01/12/31	0.04
14. New Zealand: Benmore	Half Hourly	96/11/01 – 01/12/31	0.04

Table 3: Exchange rates at October 7th, 2004 [Reference 11]

Market	Currency	Exchange rate USD
1. Canada: Alberta	Canadian Dollar (CAD)	0.794
2. USA: North California	US Dollar (USD)	1.000
3. USA: PJM	US Dollar (USD)	1.000
4. USA: New England	US Dollar (USD)	1.000
5. Germany: Leipzig Exchange	German Mark (DEM)	0.628
6. Netherlands	Euro (EUR)	1.228
7. Britain	British Pound (GBP)	1.777
8.Spain	Euro (EUR)	1.228
9. Scandinavia	Norwegian Kroner (NOK)	0.149
10. Australia: South Australia	Australian Dollar (AUD)	0.724
11. Australia: New South Wales	Australian Dollar (AUD)	0.724
12. Australia: Queensland	Australian Dollar (AUD)	0.724
13. Australia: Victoria	Australian Dollar (AUD)	0.724
14. New Zealand: Benmore	New Zealand Dollar (NZD)	0.675

Figure 1: Average diurnal power price, US$/MWh, illustrated for Alberta



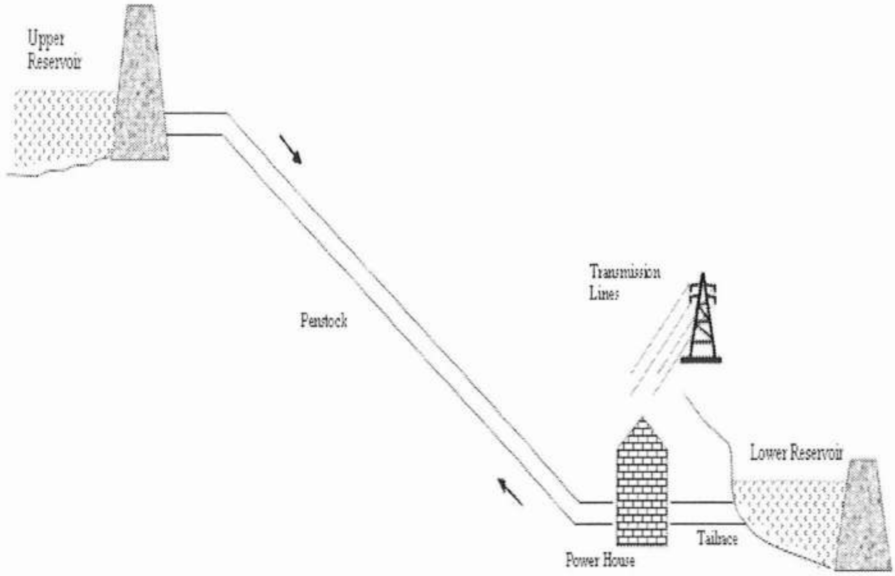
Finally, there is evidence that the exercise of market power is related to the effectiveness of market surveillance mechanisms in each market. All of these factors help to create a unique daily pattern of average power prices that is different for each deregulated power market.

The data set is dated, with no data points after 2001. However, it is the only cross market data set spanning a large number of deregulated power markets around the world, and hence it is useful for illustrating the wide range of diurnal price patterns and their impact on the economics of the storage of electrical energy. This study is illustrative of the feasibility of energy storage, but one requirement before any investment in storage would be a review of more recent price data in the proposed market.

2. SALE OF POWER FROM PUMPED STORAGE

Fig. 2 shows a conceptual layout of a pumped storage facility. When used for energy storage, the upper reservoir is typically filled on a daily basis, usually in the late evening and early morning during periods of low power demand and price, and drained during the day and early evening when demand and price are high. The majority of pumped storage utilizes a combined pump/turbo-generator, and efficiencies, measured as the power recovered per unit of power input, have ranged from 0.60 in plants built during the 1960's to around 0.80 in the most recent plants [Reference 12-13].

Figure 2: Typical layout of a pumped storage facility



The ratio from the electrical input when pumping to the electrical output when generating can range from 0.9 to 1.2. However the most common mode of operation of the pump/turbo-generator is at constant power or an input to output power ratio of 1 [Reference 14], and we assume this mode of operation in our study. As a consequence, pumping time exceeds generating time by $(\text{efficiency})^{-1}$.

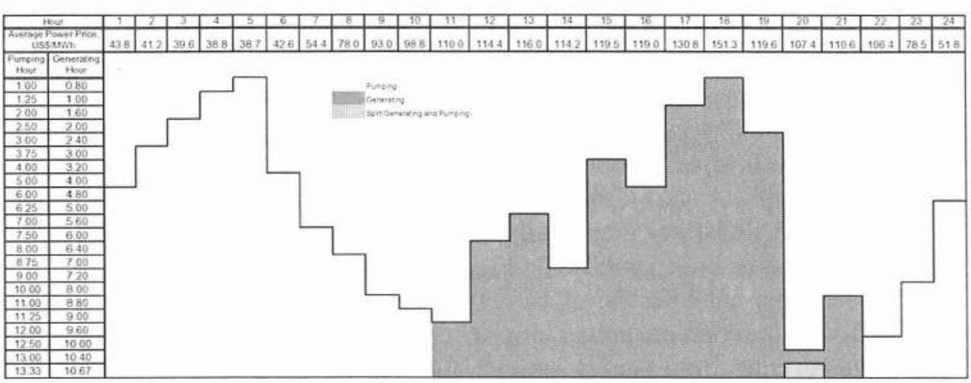
In a deregulated market, an operator does not know the system clearing price for future unbid time periods, and there is ample evidence of sudden changes in power price in markets where bids are gathered on an hour before basis. However, an initial assessment of the profitability of pumped storage of energy can be based on the long term average price behavior in a market. This is valid for a pumped storage investment whose capacity is small relative to the overall size of the power market. For very large or multiple pumped storage investments, the storage facility (or any other investment in new generation) will have an unknown impact on the diurnal price pattern. A prediction of the impact of incremental pumped storage on future diurnal patterns for 14 markets is beyond the scope of this study, and hence our analysis is based solely on historical price patterns; limitations of this approach are discussed below.

The operating strategy for pumped energy storage is to maximize the spread between the value of power sold and power purchased. Thus, at 80%

efficiency (used for the balance of this study) an operator would first identify the expected highest priced hour, and plan on purchasing power in the 1.25 hours with the lowest cost. The operator would proceed stepwise in this analysis until the cost of purchased power in 1.25 hours exceeded the cost of power sold in one hour, less the variable operating cost. Most direct operating costs associated with pumped storage, for example labor, are fixed rather than variable relative to power generation; even routine maintenance, for example, is typically scheduled on a fixed time interval rather than on operating hours. Hence, variable operating costs within the plant are very low. However, system operators can levy transmission access and dispatch charges that are purely variable, i.e. tied to the number of MWh of power put on the grid.

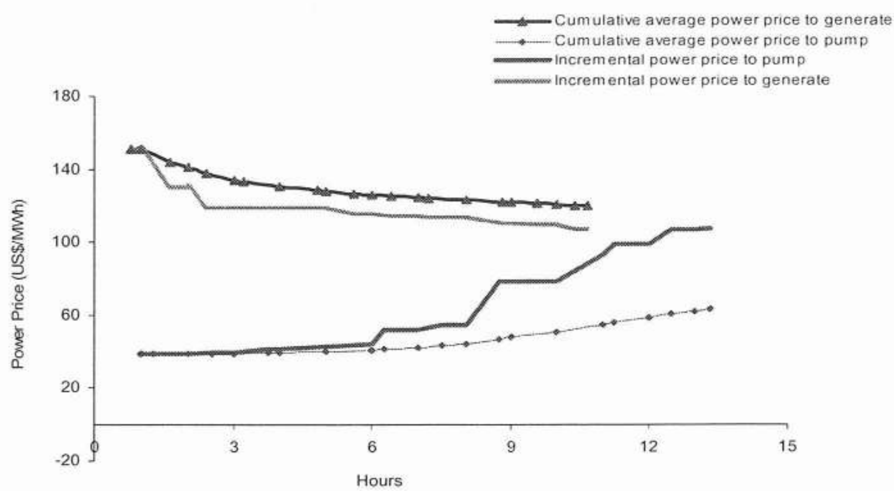
In this study we developed an operating plan for each market based on historical price patterns; Figure 3 illustrates such a plan for one market, Alberta, Canada. In the plan, hours of operation increase as one progresses down the table, and for each increment of time the available hour of highest priced power (generation) and 1.25 hours of lowest cost power (pumping) are determined. Clearly such a plan is specific to each market and to the assumed efficiency; it would have to be recalculated if the operating efficiency of the pumped storage were different than 0.8.

Figure 3: Operating plan illustrated for Alberta weekday operation with an efficiency of 80%.



From Figure 3 and the diurnal price pattern one can determine both the average and the incremental power sale and purchase price for each deregulated market. This is illustrated, again for the Province of Alberta, Canada, in Figure 4.

Figure 4: Incremental and cumulative average prices for generating from and pumping into a pumped storage facility, illustrated for Alberta weekday operation with an efficiency of 80%.



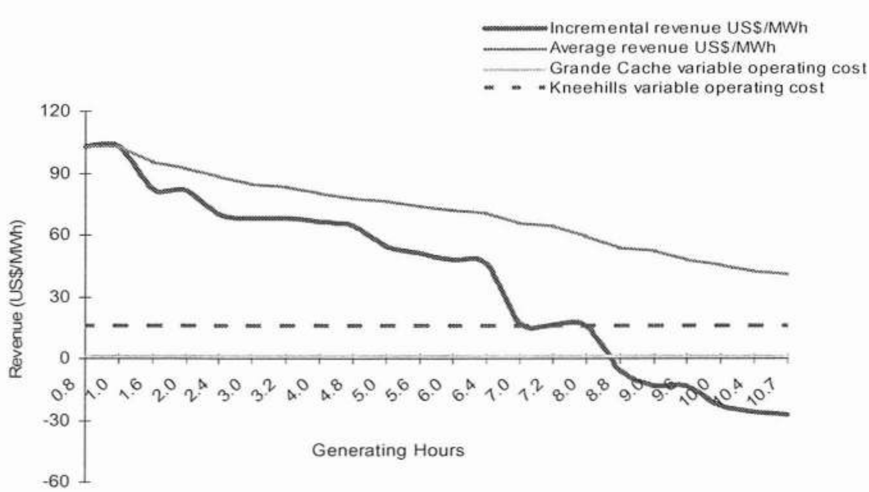
From Figure 4 and the operating plan in Figure 3 one can then calculate the expected incremental and average revenue per MWh of sold power from operating pumped storage for the sale of energy as a function of daily operating hours, by taking the difference in the value of power generated in an hour less the cost of power for the 1.25 hours that were required to fill the reservoir. Table 4 shows the details of the calculation for Alberta, Canada, and Figure 5 illustrates graphically the incremental and average revenue for Alberta, Canada; both Table 4 and Figure 5 are for weekday power prices. We conducted this analysis for all 14 deregulated markets in this study for both weekday and weekend power prices, and the profiles of incremental and average revenue from energy storage and sale for an efficiency of 80% for both weekday and weekend are shown in the Appendix. The profile identifies the maximum economic operating period for a pumped storage facility: when net revenue is negative, it does not make sense to continue operating pumped storage. The profiles are, in essence, a signature of energy storage economics that characterizes each market; they depend on both the diurnal power price pattern and the efficiency of the energy storage project.

Table 4: Revenue calculation by hr illustrated for Alberta weekday operation of pumped storage with an efficienty of 80%

Pmp hrs/ day	Gnrt hrs/ day	Oprt total hrs	Power price for pumping US$/MWh	Power price for generation US$/MWh	Incrmnt pumping power cst US$/ MW day	Incrmnt generating power revenue US$/ MW/day	Incrmnt net revenue US$/ MW// day	Cum net revenue US$/ MW/ day	Incrmnt revenue US$/ MWh	Avg. revenue US$/ MWh
1.00	0.80	1.80	38.71	151.28	38.71	121.03	82.31	82.31	102.89	102.89
1.25	1.00	2.25	38.79	151.28	9.70	30.26	20.56	102.87	102.80	102.87
2.00	1.60	3.60	38.79	130.76	29.09	78.46	49.37	152.24	82.28	95.15
2.50	2.00	4.50	39.63	130.76	19.82	52.30	32.49	184.72	81.22	92.36
3.00	2.40	5.40	39.63	11.959	19.82	47.84	28.02	212.71	70.05	88.64
3.75	3.00	6.75	41.19	119.59	30.90	71.75	40.86	253.60	68.10	84.53
4.00	3.20	7.20	41.19	119.47	10.30	23.89	13.60	267.20	67.98	83.50
5.00	4.00	9.00	42.63	119.47	42.63	95.58	582.95	320.15	66.19	80.04
6.00	4.80	10.80	43.77	119.03	43.77	95.23	51.46	371.60	64.32	77.42
6.25	5.00	11.25	51.80	119.03	12.95	23.81	10.86	382.46	54.28	76.49
7.00	5.60	12.60	51.80	115.97	38.85	69.58	30.73	413.19	51.22	7378
7.50	6.00	13.50	54.44	115.97	27.22	46.39	19.17	432.36	47.92	72.06
8.00	6.40	14.40	54.44	114.37	27.22	45.75	18.53	450.89	46.32	7.45
8.75	7.00	15.75	78.05	114.37	58.53	68.62	10.09	460.98	16.82	65.52
9.00	7.20	16.20	78.05	114.15	19.51	22.83	3.32	464.30	16.59	64.49
10.00	8.00	18.00	78.52	114.15	78.52	91.32	12.80	477.10	16.00	59.64
11.00	8.80	19.80	93.02	110.58	93.02	88.46	-4.55	472.55	-5.69	53.70
11.25	9.00	20.25	98.85	110.58	24.71	22.12	-2.60	469.95	-12.98	52.22
12.00	9.60	21.60	98.85	110.04	74.14	66.02	-8.11	461.84	-13.52	48.11
12.50	10.00	22.50	106.43	110.04	53.21	44.01	-9.20	452.64	-23.00	45.26
13.00	10.40	23.40	106.43	107.43	53.21	42.97	-10.24	442.40	-25.60	42.54
13.33	10.67	24.00	107.43	107.43	35.81	28.65	-7.16	435.23	-26.86	40.80

Figure 5 also illustrates the critical impact that variable operating costs, i.e. charges levied per unit of power sold, can exert on pumped storage. Examples include dispatch fees levied by a system operator and transmission access charges. We studied in detail two specific locations in Alberta: Kneehills, a medium head site using a natural prairie coulee as a reservoir by building an earthen dam, and Grande Cache, a high head mountainous site that would have the potential to use existing mining pits as reservoirs. From the perspective of the transmission system operator, one of these locations is far more favored than the other because it releases power into an area of net power consumption, and hence helps relieve transmission congestion. This is reflected in a different access charge between the two locations, and the impact, from Figure 5, is that operating hours would be lower for one location than the other: the transmission access charge is enough to remove any net revenue from operating past 7 hours in the case of Kneehills, while the Grand Cache location is forecast to make incremental net revenue by operating for an additional 1 hour per day. (This analysis presumes that at Grande Cache sufficient transmission capacity is available during the periods of power purchase, e.g. during the late evening and early morning hours.) Hence any prospective energy storage facility must assess location specific transmission charges in addition to expected power price patterns.

Figure 5: Pumped storage incremental and average revenue from energy sale illustrated for Alberta weekday operation with efficiency of 80%.

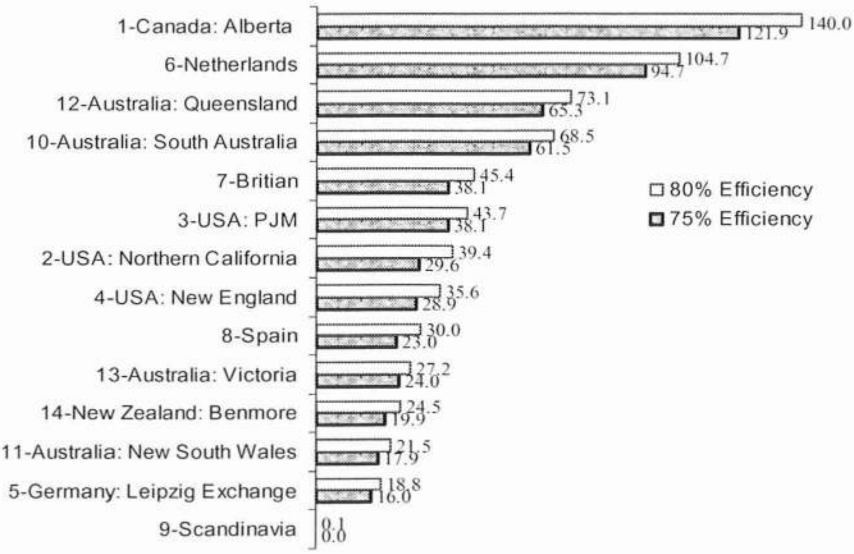


This data allowed us to finally calculate, for each of the markets, the aggregate income from operating pumped storage. We blend an average of five weekdays and two weekend days and rank the deregulated markets by daily revenue potential, as shown in Table 5. For each market we also calculated the annual average revenue that can be earned per MW of installed capacity from pumped storage, assuming an on line availability factor of 97%; results are shown in Figure 6 and illustrate the impact of 75% and 80% efficiency. It is clear that deregulated power markets show substantial differences in price patterns and that these in turn impact the economic benefit of energy storage. Alberta, Canada has the highest potential annual income from energy storage, in part due to its wide period of high power price, as shown in Figure 1. There is negligible revenue potential in Scandinavia because the price spread is so low that revenue from even the first hour of generation is near zero, while Alberta, the Netherlands and two markets in Australia show a significant revenue potential.

Table 5: Daily revenue from pumped energy storage in deregulated markets with an efficiency of 80%

Power markets ranked by annual revenue	Weekday cumulative net revenue (US$/MW/day)	Weekend cumulative net revenue (US$/MW/day)	Weighted Daily average (US$/MW/day)
1. Canada: Alberta	477	194	395
6-Netherlands	389	62	296
12-Australia: Queensland	234	138	207
10-Australia: South Australia	231	100	193
7-Briatin	153	67	128
3-USA:PJM	148	62	123
2-USA: North California	120	91	111
4-USA: New England	56	211	101
8-Spain	96	57	85
13-Australia:Victoria	90	45	77
14-New Zealand:Benmore	76	52	69
11-Australia: New South Wales	68	43	61
5-Germany:Leipzig Exchange	65	22	53
9-Scandinavia	0.30	0	0.21

Figure 6: Annual revenue (US$(000)/MW/Yr) from a pumped storage facility with 97% availability at 80% and 75% of efficiency.



3. INVESTMENT IN PUMPED STORAGE

The ultimate test for energy storage is whether there is adequate return on investment from the net revenue from purchase and resale of power. We analyze this for pumped storage by two different methods, both subject to the limitations noted above: income from sale of ancillary services, charges per MWh for dispatch and transmission access, and the impact of the investment in energy storage on future diurnal prices are not included in this study.

Our first approach is to define a theoretical minimum level of investment in pumped storage, i.e. a theoretical project in which all factors align to minimize net capital cost. This "best case" project would utilize existing bodies of water for the upper and lower reservoir, and an adjacent transmission line for access to the grid. Hence, the net investment in the project would be for the land and access, penstock, reversible pump/turbine and auxiliary machinery, power house, switchyard, investigation and engineering. For a high head pumped storage facility we estimate this investment to be US $275 per MW of capacity in a 550MW plant; Table 6 shows the breakdown of the estimated minimum cost plant. It is important to note that investment in pumped storage has an economy of scale, i.e. the capital cost is not directly proportional to the capacity [Reference 15]. Hence project size affects economics, and return on investment is specific to a project size. 550 MW was chosen in this study as a typical large project size, although we note that one recent project proceeded at 1 GW [Reference 16].

Table 6: Estimated capital cost for an idealized mimimum investment pumped storage case

High Head 5.50 MW	US$
Land and Access	2,777,778
Upper and Lower Reservoir	0
Penstocks	53,386,052
Powerhouse Structure	6,169,403
Power Plant Machiner	65,800,922
Interconnection & Transmission Line	0
Total 1 (Direct Costs)	128,134,154
Contingencies (10% Direct Costs)	12,813,415
Investigation and Engineering	6,272,289
Administration/Financinag	3,863,433
TOTAL	151,083,291
$KW	275

Figure 7: Pre-tax return on investment for an idealized minimum investment pumped storage case.

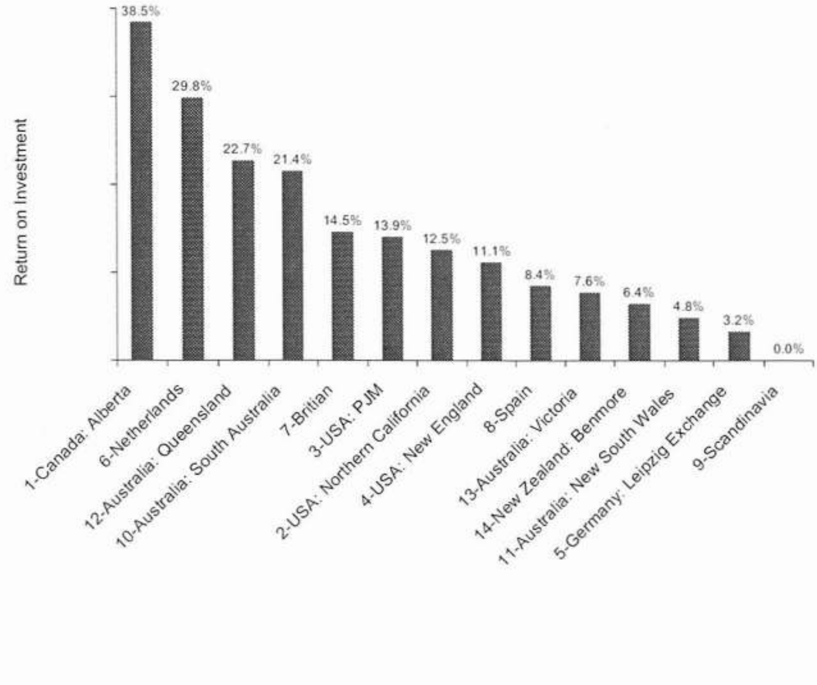


Figure 7 shows the expected return for the 14 markets in this study; the values can be thought of as the maximum possible pre-tax return on investment from pumped storage, since all real projects would have higher investment than the "best case" and thus a lower return. Hence, it is clear from Figure 7 that pumped storage can never pass a minimum test of adequate return, say 10% on capital deployed, in 6 of the 14 markets in this study. Note that projects smaller than 550 MW would have a lower return on investment than shown in Figure 7.

Our second approach is to determine the largest amount of investment per unit of power output that can be justified in each market to earn a pre-tax return on capital of 10%; Table 7 shows the values for each market in US dollars per KW. Alberta's historical diurnal price pattern would justify an investment of US $1,190 per KW, while New England, Spain, Australia Victoria, New Zealand Benmore, Australia New South Wales, Germany Leipzig Exchange and Scandinavia would not justify an investment in excess of US $300 per KW. It is again clear from Table 7 that no practical pumped storage scheme operated for the purpose of time shifting of energy will be justifiable in many deregulated power markets.

Table 7: Maximum investment to earn a return of 10% on capital, US$ per KW

Market	Allowable Investment
1-Canada:Alberta	1,190
6-Netherlands	858
12-Australia: Queensland	618
10-Australia: South Australia	579
7-Britain	382
3-USA:PJM	367
2-USA:North California	330
4-USA: New England	298
8-Spain	241
13-Australia:Victoria	226
14-New Zealand: Benmore	203
11-Australia: New Souoth Wales	177
5-Germany: Leipzig Exchange	154
9-Scandinavia	~0

DISCUSSION

Electricity has a time value in any deregulated market. In such markets, there is considerable volatility, and price patterns vary significantly from day to day [References 5- 8]. However, from the perspective of energy storage and resale on a diurnal cycle, the long term average price pattern in a deregulated market gives a good first prediction of the potential revenue from the storage and sale of energy.

In this work, we have used historical price patterns in deregulated markets to compare the potential for energy storage, using pumped storage as the model. All energy storage has both a capital cost and an energy inefficiency (power out vs. power in); the key question for a project developer is whether the expected net revenue from pumped storage justifies the capital investment.

The revenue from energy storage in a deregulated market is determined by the shape of the diurnal price pattern. Alberta, which has a long daily period of high power price and a long evening/morning period of low price, has the highest revenue potential for pumped storage identified in this study. An hour by hour analysis of pumped storage is required to fully assess an energy storage project. This study makes clear that in many markets, the diurnal pattern simply does not justify any practical energy storage application; the allowable investment, based on the revenue potential, is far below the cost of any real project. Deregulated power markets are not all alike.

We think of the process used in this study as a "first pass" screening, i.e. a method of first estimating the potential for energy storage in a given deregulated market. When an opportunity for energy storage is identified, several other factors need to be considered:

- Is the historical diurnal power price an accurate predictor of future price? Two elements must be considered in an analysis of the relationship between past and future prices: the likelihood of different price patterns, and the impact of the pumped storage itself on price patterns. Li and Flynn [Reference 7] did a time analysis of power price patterns and found that some markets have experienced a single period of high power prices. California and New Zealand are examples of this, with the California price excursions being related substantially to market bidding behaviors and the New Zealand price behaviors being related to an unusually severe period of drought. Neither of these circumstances is expected to reoccur in the next 20 years (bidding behaviors in US markets are under closer scrutiny and clearer rules, and the drought in New Zealand was severe enough to have a low frequency of expectation). On the other hand, there are legitimate concerns of major power price swings, i.e. "boom and bust" pricing, due to delays in investment in new generation capacity until prices are high coupled with a long construction period for major power plants; this concern has led, among other things, to a focus by some parties on separating energy and capacity auctions in deregulated power markets. As well, as noted above, simply building energy storage will have some impact on the price patterns in the market, particularly if the capacity of the storage is significant relative to the total market. In effect, energy storage "smoothes" the diurnal power price pattern, although the extent to which this is significant would depend on the amount of storage relative to the total size of the power market. Thus anyone screening investment in energy storage must give careful thought about what historical prices to consider and how representative these prices will be of future price patterns. As with all energy projects, the projection of future price is a major determinant of the viability of the project.

- What is the certainty of future revenue from energy storage? Many power markets have limited liquidity in the futures market, and forward buying and selling of power is normally by "on peak" and "off peak" blocks. The lack of liquidity means that an investor in energy storage will have limited opportunity to lock in future revenues, and instead will face the investment risk of possible future changes in diurnal price pattern.
- What is the impact of variable system charges on the net revenue? As this study shows for two examples in Alberta, Canada, system charges, in particular transmission access charges, can have a significant impact on the net revenue available from energy storage. Transmission related charges often are location specific, and this impact would have to be factored in to any analysis of investment in energy storage.
- Ancillary services can often be bid as an alternative to energy sales [References 9,10,13,14,17], and a pumped storage operator could make a day by day, and in some markets an hour by hour decision about whether to sell ancillary services or energy; such a decision would made based on maximizing expected revenue. The rules for bidding ancillary services are too complex, and the price data too difficult to source, to allow for the inclusion of an analysis of ancillary services in this study of 14 different deregulated power markets, but it would be a factor in analyzing any specific project.

CONCLUSIONS

Fourteen deregulated power markets were assessed for the potential for investment in energy storage, with pumped storage as the model investment. Net revenue from energy storage and resale depends on the energy efficiency of the project and the diurnal pattern of power price. There are significant differences in historical average price patterns between the 14 deregulated power markets. As a result, the potential for economic pumped storage varies widely. Alberta, the Netherlands, Australia Queensland and South Australia have some potential for adequate return on investment in pumped storage, but for the majority of markets in this study the diurnal price pattern does not justify the investment.

ACKNOWLEDGEMENTS

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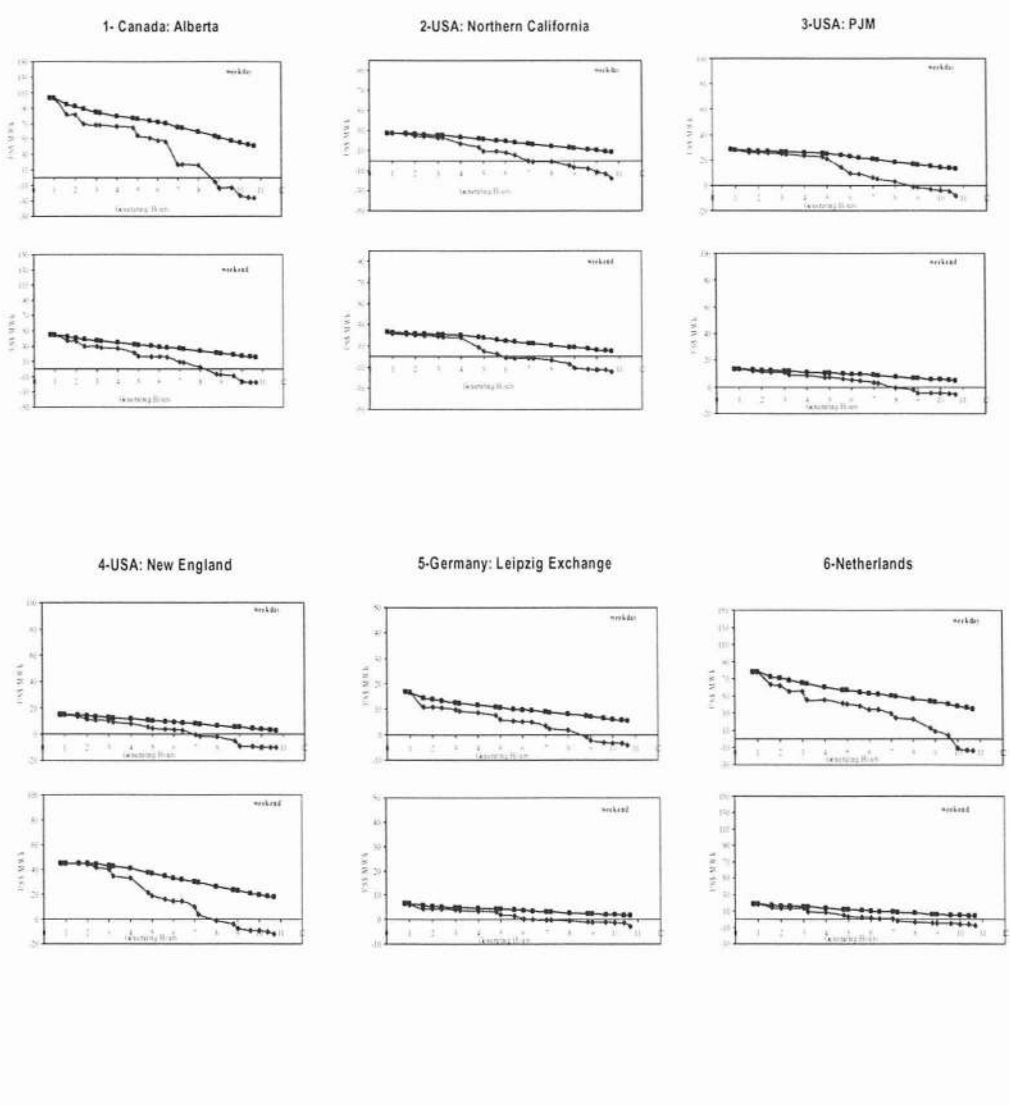
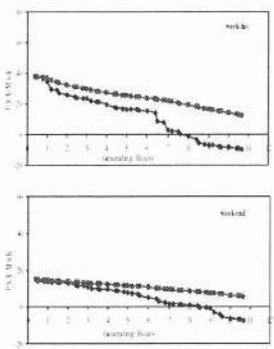
APPENDIX

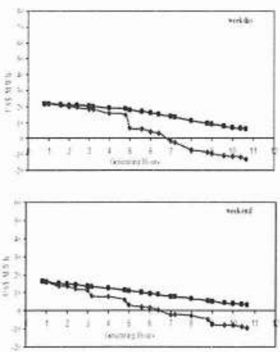
Figure A: Profile of Incremental and Average Revenue from Energy Storage and Sale Illustrated for 14 Deregulated Power Markets with an Efficiency of 80%



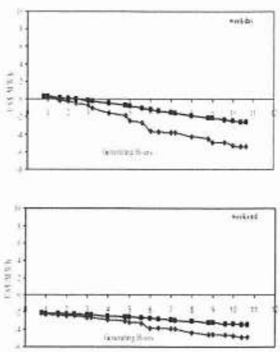
7-Britain



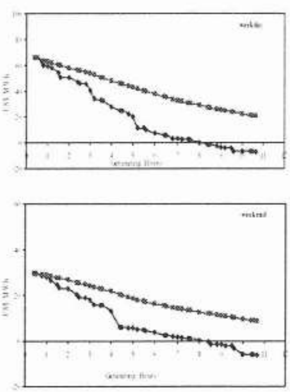
8-Spain



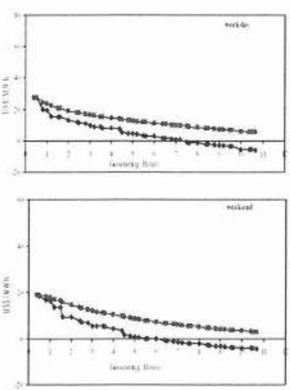
9-Scandinavia



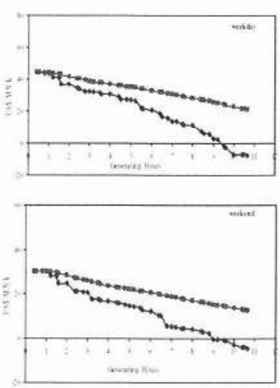
10-Australia: South Australia



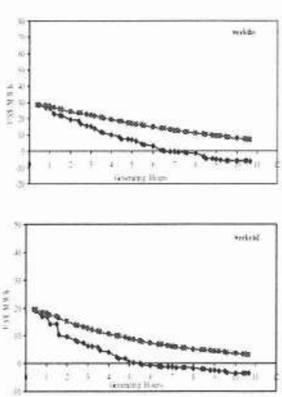
11-Australia: New South Wales



12-Australia: Queensland



13-Australia: Victoria



14-New Zeeland: Benmore