ETM

ENGINEERING & TECHNOLOGY MANAGEMENT

Title: Forecasting Energy Storage Technologies As applied to the North American Electrical Grid

Course Title: Technology Forecasting
Course Number: EMGT 532/632
Instructor: Dr. Daim
Term: Winter
Year: 2009

Author(s) : Georgina Harell, Aaron Tsai, and Lawrence Carter

Table of Contents

Abstract

In order to compliment the growing use of renewable energies in the United States, additional technologies must be employed on the bulk power system. This paper forecasts the most probable energy storage technologies. These include: compressed air energy storage, pumped hydro, flywheels, lead acid batteries, and advanced battery technologies. A SWOT analysis was performed on each of the storage types to identify potential benefits or disadvantages. This analysis provided a multi-perspective view of these energy storage approaches. Next Bibliometric and Patent searches were conducted for all of the key technology types. This data was then used to create growth curves applying the Gompertz and Pearl methods. An analysis of this research shows the how different rates of growth correspond to the maturity of the various storage types, and predicts when some of the newer technologies will overtake the mature technologies in this area.

Problem Statement

The US Department of Energy constructs energy forecasts annually [1]. In their February 2009 forecast, they estimate that our electricity demand will grow from 13,382 trillion Btu's in 2009 to a predicted 16,730 trillion Btu's in 2030. Similarly, the overall energy consumption of the United States is expected to top 120,000 trillion Btu's by 2020 as shown in Figure 1 [2]. With the increasing demand for energy in the United States along with rising concerns over natural resource depletion and environmental concerns stemming from traditional energy generation plants, there is a growing demand for affordable, commercially available, clean renewable energy sources.

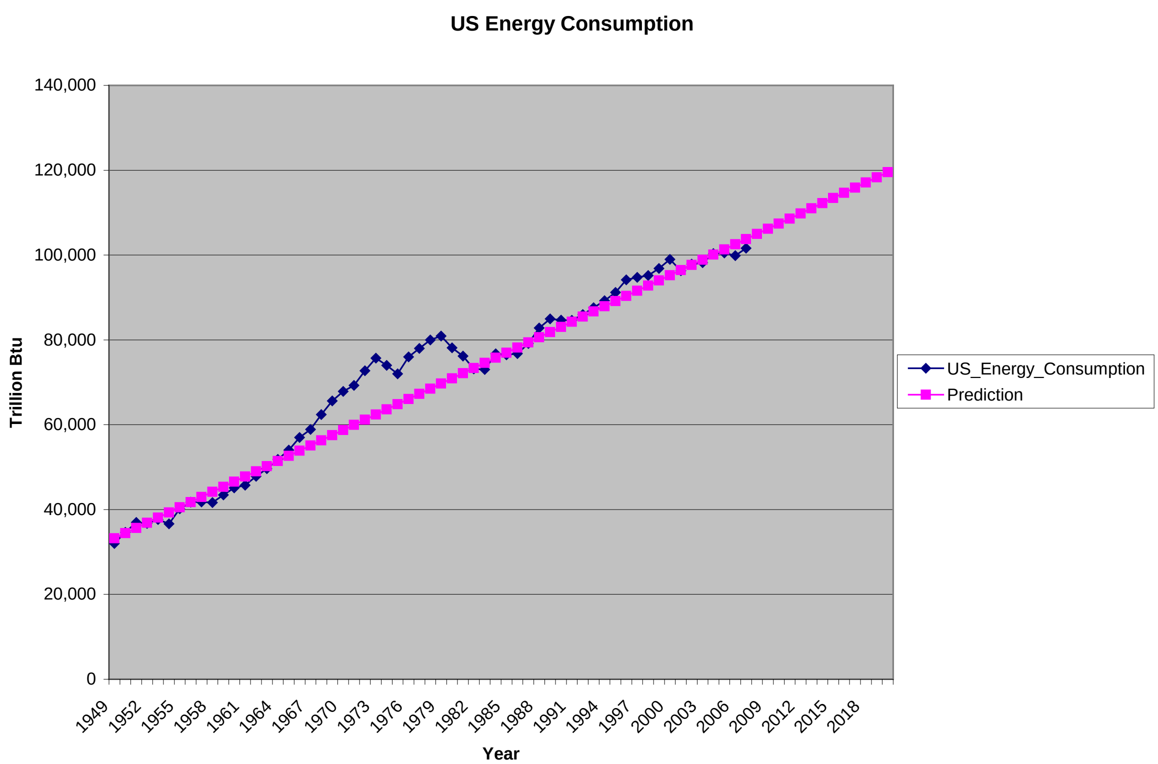

Figure 1: US energy consumption trend with linear prediction line [2]

While the need for renewable energy technologies is undeniable, as with most new technologies, the need for the complementary technologies to successfully implement the new technology is often lagging. In the case of renewable energy, many of the developing technologies are unpredictable or intermittent in their ability to produce energy and as such will require additional energy storage technologies to mitigate the erratic nature of the energy production. This energy storage dilemma is a key negative attribute of renewable energy that must be overcome to make it a viable alternative to traditional energy generation technologies. Ultimately if all the negative attributes of renewable energy are managed effectively, a unit of renewable energy will be interchangeable with the equivalent unit of base load energy. The purpose of this paper is to determine the potential energy storage technologies that could complement a wind turbine or photovoltaic system and forecast which of these complementary technologies is best poised to become a viable solution to the energy storage problem facing these renewable technologies.

Methodology

To properly predict the most likely energy storage technology to compliment a wind turbine or photovoltaic system in the near future, several steps were taken. First, a literature search of energy storage technologies was conducted in conjunction with wind and solar energy. From this search, the technologies were screened by the group members and paired down to the five most feasible technologies: pumped hydro energy storage, compressed air energy storage (CAES), flywheel energy storage, Sodium Sulfur (NaS) battery energy storage and Nickel Cadmium (NiCd) battery energy storage. Next, a SWOT analysis was done to qualitatively evaluate the five technology options. Then, a patent search and bibliometric search on specific key words is conducted and the resulting data is used to develop growth curves for the various technologies. The growth curves developed are done using the Gompertz and Pearl formulas to provide a comparison in the techniques. Finally the growth curves developed are forecasted and conclusions regarding the storage technologies are drawn.

Energy Technology Search

Within the realm of energy storage there are a plethora of technologies available, however, only a select few will be technically feasible as a complementary technology to renewable energy based on the amount and quality of energy that is storable along with other factors such as response time and duration of charge. To begin the discussion on energy storage technologies it’s valuable to examine the various classes of energy storage technologies.

According to Baker, [3] there are the following types of energy storage: electrochemical systems such as batteries and flow cells, kinetic energy storage such as flywheels, potential energy storage such as pumped hydro or compressed air systems and thermal energy storage such as phase change materials. Independently applied each of these energy storage techniques has positive and negative characteristics and as such, Baker further identifies the advantages of mixing storage technologies to address a variety of issues such as response time and duration of discharge. From the literature search it was determined that the five most likely technologies to complement a wind or solar power generation system are: pumped hydro energy storage, compressed air energy storage (CAES), flywheel energy storage, Sodium Sulfur (NaS) battery energy storage and Nickel Cadmium (NiCd) battery energy storage.

Pumped Hydro Energy Storage

Pumped hydro storage is a relatively simple concept that involved pumping water from a lower reservoir to an upper reservoir during off peak hours and then generating electricity during peak hours by flowing the water through turbines back down to the lower reservoir [4]. Figure 2 below depicts a pumped hydro storage plant. The concept of pumped hydro has been around since the late 1800s in Europe and is a fairly widespread technology today accounting for approximately 3% of the total global energy generation.

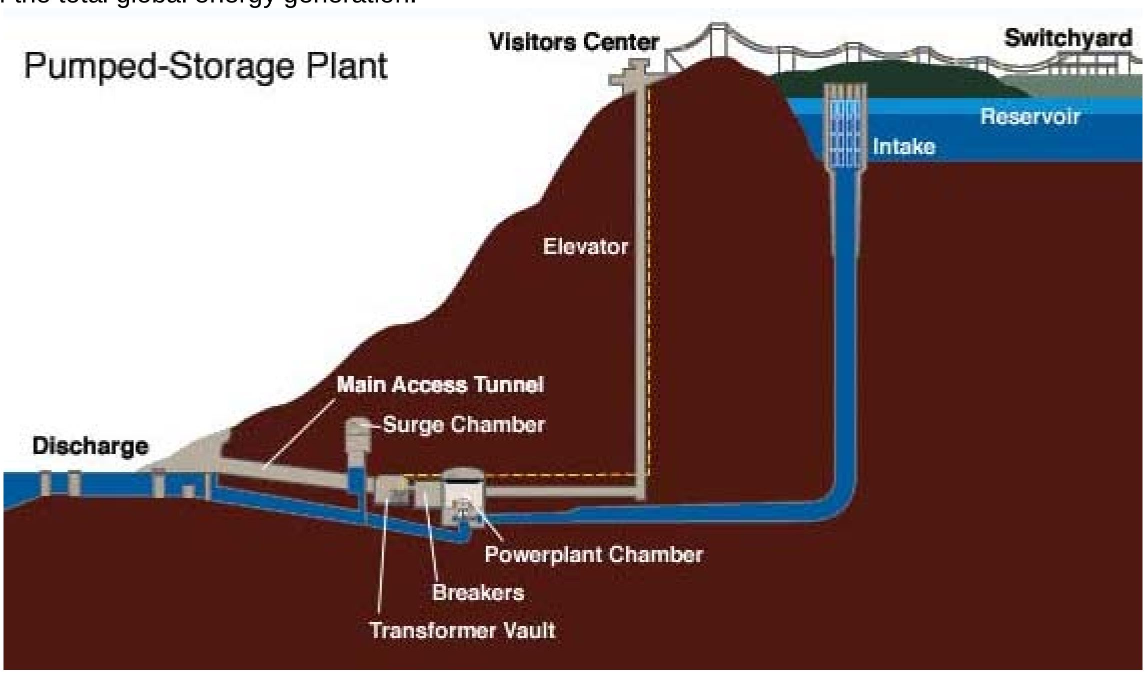

Figure 2: Pumped hydro storage plant depiction [5]

Compressed Air Energy Storage (CAES)

Similar to pumped hydro storage, compressed air storage uses electricity during off peak electricity to compress air a storage reservoir (typically underground) and then during peak times the compressed air is heated and run through a series of expanders to power a generator that produces electricity [6]. The concept of compressed air energy storage has been around for roughly 30 years and there are currently two sites operating, one in Alabama and one in Germany, a depiction of such a plant can be seen in Figure 3.

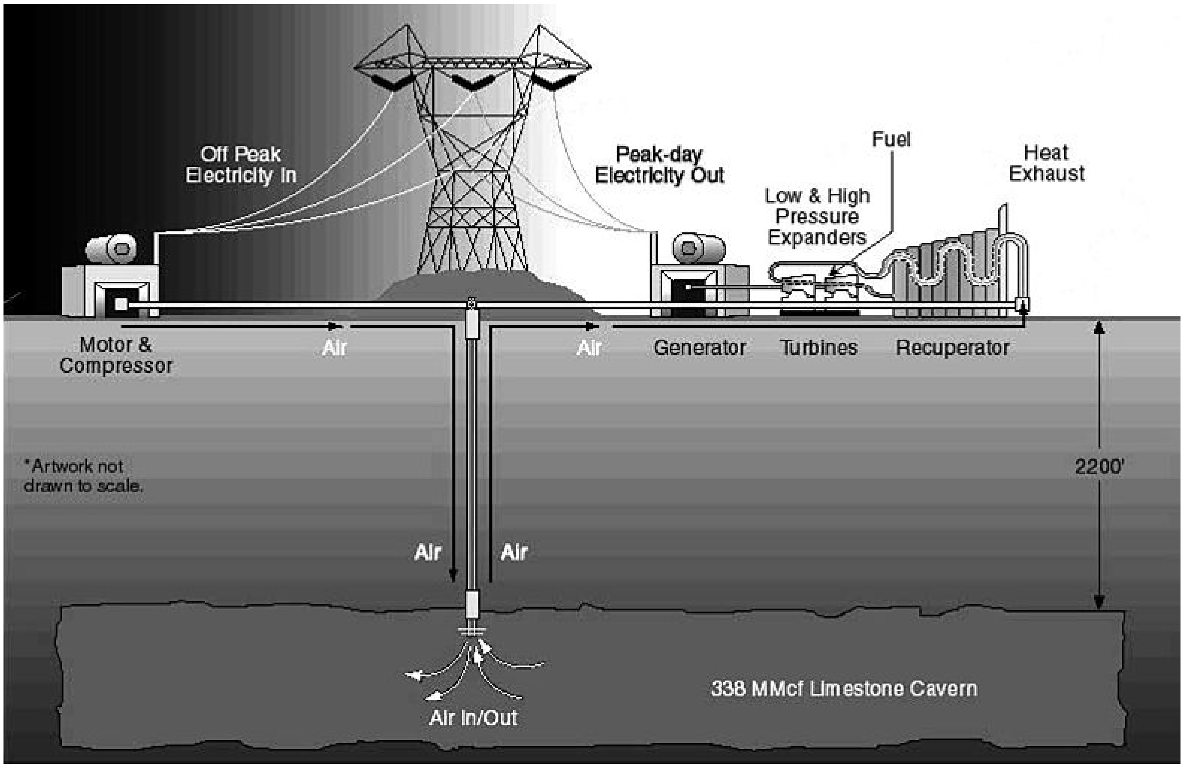

Figure 3: Compressed air energy storage plant depiction [7]

Flywheel Energy Storage

While pumped hydro and CAES are potential energy storage technologies, flywheel energy storage is a kinetic energy storage technology. The concept of flywheel energy storage is simple, a heavy mass is rotated to a high speed and then the torque generated by slowing down the mass is used to create electricity [8]. Flywheels typically come in two categories, low speed (up to 6000 rpm's) and high speed (up to 50,000 rpm's). The low speed versions are commercially available, lower power, less efficient and are typically constructed of conventional materials. On the other hand, high speed flywheels are still in development, higher power, more efficient and use advanced composite materials.

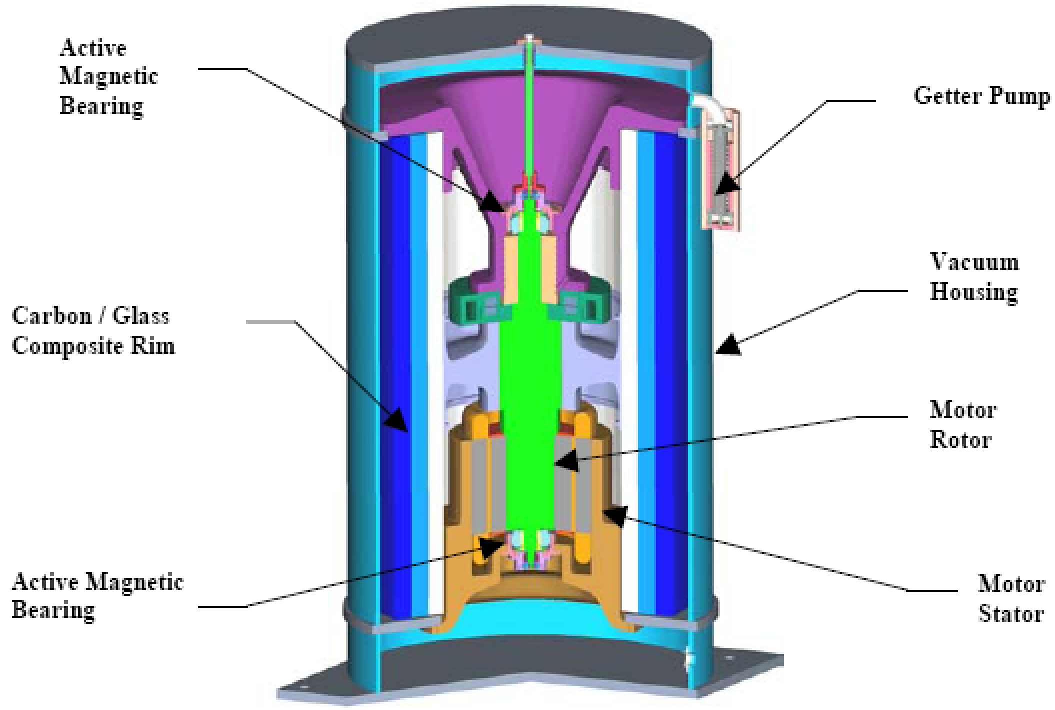

Figure 4: Flywheel energy storage system [9]

Battery Energy Storage

Battery energy storage systems are electrochemical systems that convert chemical energy into electrical energy through the use of batteries [10]. The necessary power requirements of the system are achieved by stacking the batteries in series and parallel configurations. There are numerous battery technologies available however for use in a wind or solar energy system Nas and NiCd batteries are amongst the most promising.

NaS Battery Energy Storage

A sodium sulfer battery consists of molten sulfer at the cathode and molten sodium at the anode separated by a solid beta alumina ceramic electrolyte [10]. The ceramic electrolyte only allows the sodium ions to pass through which then combine with the sulfur to form sodium polysulfides. The battery operates around 300 C and generates roughly 2V, Figure 5 depicts the system. Sodium sulfur battery technology has been around for about 30 years and became commercially available in 2002 [3].

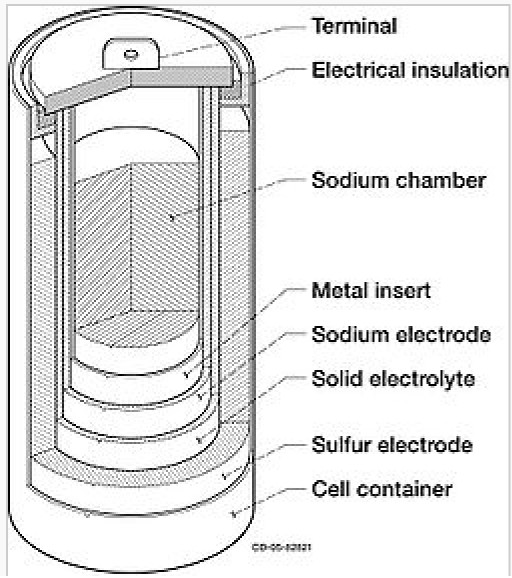

Figure 5: NaS Battery [11]

NiCd Battery Energy Storage

Compared to NaS batteries, NiCd batteries are a rather mature technology having first been created in 1899 [12]. In a NiCd battery the anode is Cadmium, the cathode is NiO_2 and the electrolyte is a basic solution [13]. The NiCd battery reaction generates roughly 1.2 volts which is significantly less than the NaS system [14].

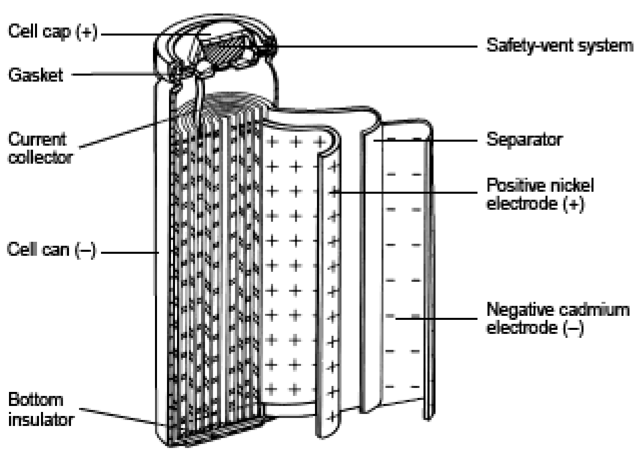

Figure 6: NiCd Battery [14]

SWOT Analysis

From the literature it was determined that five energy storage technologies are likely to compliment a wind or solar energy generation system: pumped hydro energy storage, CAES, flywheel energy storage, NaS battery energy storage and NiCd battery energy storage. In order to help capture the less tangible aspects of each system a SWOT analysis is performed on each technology to help understand their strengths and weaknesses. Eppler et all describes the need for using processes that can take advantage of qualitative input and transform this into a visual analysis [15]. This provides an opportunity to conduct analysis and develop strategies when little or no quantitative data exists.

Pumped Hydro Energy Storage

The SWOT analysis for pumped hydro energy storage is shown below in Table 1. From the analysis we see that a key strength of the pumped hydro system is it's the most cost effective means of storing large amounts of energy. On the downside the pumped hydro system requires a large upfront capital expenditure and can only be feasibly created in certain geographic locations.

Strength	Weakness	Opportunities	Threats
most cost-effective means of storing large amounts of electrical energy	Capital costs [16]	Balance out renewable energy sources [16]	Batteries are cheaper and can be set up anywhere [16]
Plant size 300Mw to 1800Mw [16]	Geographical locations [16]		
	Environmental damage		

Table 1: Pumped hydro energy storage SWOT analysis

CAES

The SWOT analysis for a CAES system can be seen in Table 2. On the positive side the CAES system has a longer lifespan than a typical battery system and in general employs less hazardous materials compared to batteries. In terms of weaknesses, the CAES system poses a considerable safety risk if an above ground pressure vessel is used to store the air and suitable underground storage is difficult to find and not opportunely located.

Strengths	Weaknesses	Opportunities	Threats
Longer life time of pressure vessel compare with batteries and Lower toxictiy of materials used [16]	Safety concerns[16]	Balance out renewable energy sources [16]	Safety concerns [16]
Lower cost [16]	Pressure vessel expensive to develop and safety test [16]		Can be replace by massive produce batteries [16]
Plant size: 270MW to 2700MW [17]	Suitable underground reservoirs not plentiful		

Table 2: CAES SWOT analysis

Flywheels

The Flywheel SWOT analysis can be seen in Table 3. From the analysis on flywheels, the key strengths that stand out are a long life span, high energy density and efficiency. On the other hand, flywheels require considerable maintenance and have a high cost compared to batteries. Flywheels also pose an increasing safety concern with size of unit.

Strengths	Weaknesses	Opportunities	Threats
Long life, high energy density and very efficient [17]	Required high maintenance [17]	New production with new composite material reduce the cost [17]	Safety concerns: explostion hazard so hard to use in large scale [17]
	High cost compare with batteries [17]		

Table 3: Flywheel energy storage SWOT analysis

Battery Energy Storage (BES)

As previously discussed, within the BES technologies NaS and NiCd batteries where determined to be the most likely battery technologies to complement a renewable energy system.

NaS Battery Energy Storage

The SWOT analysis for NaS battery energy storage can be seen in Table 4. From the table it is clear that for an NaS battery a key strength is the high energy density. However, NaS batteries have considerable concerns regarding safety as Sodium is highly reactive with water. NaS technology also faces the threat of being replaced by other battery technologies and concerns over used system disposal.

Strengths	Weaknesses	Opportunities	Threats
High energy density [18]	Safety concerns: Pure Na reacts violently with water. In modern NaS cells, seal techniques make fires unlikely [18]	Work with wind and solar plant [18]	Replacement by other technology
Can be operated in space [18]			Environmental concerns - special care for disposal [18]
Plant size 270MW (Japan) [18]			

Table 4: NaS Energy Storage SWOT analysis

NiCd Battery Energy Storage

Table 5 shows the SWOT analysis for NiCD battery energy storage. The NiCd battery has several strengths including a robust recharge cycle, durability and higher energy density than some competing battery technologies. On the down side, the heavy metals used in construction pose an environmental concern at end of life and there is always the threat of competing battery technologies.

Strengths	Weaknesses	Opportunities	Threats
Portable: niche market, telephone and emergency lighting [18]	Higher cost: extra labor to manufacture (compare with Lead acid) [18]	Portable device	Environmental concerns - special care for disposal [18]
Compared to other batteries, hard to damage & tolerates deep discharge [18]	Memory and lazy battery effects [18]		
Higher energy density (compare with Lead Acid) [18]	Over charge can damage the battery [18]		

Table 5: NiCd battery energy storage SWOT Analysis

The SWOT analysis provided a comparison of the less tangible aspects of the energy storage technologies being considered to supplement a renewable energy system. The next section of this paper will examine the energy storage technologies in a more quantifiable approach by constructing qrowth curves from patent and bibliometric data searches.

Growth Curves

There are numerous techniques available for technology forecasting, the selection of specific forecasting methods used within this paper was driven by the availability of data that could be used to predict the subset of energy storage technologies [19]. Willis suggested that forecasts should be developed as a baseline to study the behaviors of the specific trend being studied. Daim et all writes that direct measurement of a given technology may not be possible, and that a combination of tools could be necessary to properly forecast adoption rates [20]. This is beneficial in situations where there is little or no directly measurable data available. Rueda et all suggests that bibliometrics can be used to identify the technical panel group for a given topic [21]. Growth curves were chosen as a convenient method to forecast which technologies are developing more rapidly using the available patent and bibliometric data available. Growth curve formulas are also quite numerous, Phillips felt that the knees and tipping points of the growth curves are determined by the number of parameters in the growth curve and the fundamental model [22]. As such, it was desired to compare a couple different growth curve formulas to determine if the results changed dramatically; therefore, our team chose the Gompertz and Pearl formulas for our growth curves.

The Gompertz formula can be seen below in equation 1. Franses describes the Gompertz curve as a better tool for forecasting markets with short introduction periods and a decreasing growth rate in the maturity stage [22].

$$y = a * e^{(b*e^{(c*t)})}$$ Eq. 1 [23]

Where:
y is the data to be predicted
a is the upper asymptote on the dataset
b and c are growth rate parameters and are negative numbers
e is Eulers Number (2.71828…)
t is the time period

The Pearl formula can be seen below in equation 2. Willis indicates that the growth curve originally suggested by Pearl and Reed may introduce problems with “statistical evaluation of model fit and in estimating the precision of forecasts”, developed with this method [19]. Willis further explains how using a curve fitting approach (suggested by Yule) a more precise method is obtained.

$$y = \frac{L}{1+10^{(A-B*t)}}$$ Eq. 2 [24]

Where:
y is the data to be predicted
L is the upper asymptote on the dataset
A and *B* are growth rate parameters
t is the time period

A convenient transformation of the Pearl equation, seen in Equation 3, can be derived to make approximation of the *A* and *B* coefficients simpler. Equation 3 shows by plotting the logarithm of the data to be predicted a linear function is obtained where the intercept of the line is –*A* and the slope is *B*.

$$Y = \log\left[\frac{y}{L-y}\right] = -A + B*t$$ Eq. 3

Data Collection and Analysis

To develop the growth curves two datasets were developed, one for publications and one for patents. From the SWOT analysis and literature search the following key words were chosen as the best complimentary technologies for wind energy and were chosen to use in the database search to give us our data set:

- Flywheel energy storage
- Compressed air energy storage
- Sodium sulfur battery

- Nickel cadmium battery
- Pumped Hydro

The first dataset was gathered by doing a bibliometric search using Science Direct to search published journals. The key words were searched for in the abstract, title and keywords [25]. The data was then separated into publications per year. The publication data gathered can be seen below in Table 6.

Year	Pumped Hydro	CAES	Flywheel	NaS Battery	NiCd Battery
1993	329	241	33	66	68
1994	324	197	38	63	97
1995	355	250	17	72	116
1996	311	244	26	90	83
1997	295	231	38	83	76
1998	136	216	26	64	99
1999	125	268	23	90	133
2000	134	307	65	110	152
2001	135	377	61	114	153
2002	144	397	45	129	167
2003	174	489	86	146	172
2004	192	544	65	151	172
2005	209	645	74	182	224
2006	218	591	100	146	234
2007	250	801	102	204	277
2008	293	865	117	237	350

Table 6: Energy storage technology publications per year [25]

The second dataset was gathered using the World Intellectual Property Organization (WIPO) database, Patent Scope, which gives a list of international patent applications that have the key word on the front page [26]. The data was then separated into patent applications per year. Table 7 below shows the international patent application data be energy storage technology.

Year	Pumped Hydro	CAES	Flywheel	NaS Battery	NiCd Battery
1986	1	0	0	2	2
1987	0	0	0	0	0
1988	0	0	0	1	0
1989	0	0	0	0	0
1990	0	0	0	0	0
1991	1	0	0	0	0
1992	0	0	0	0	0
1993	0	1	2	0	4
1994	0	0	1	0	0
1995	0	0	4	0	0
1996	1	1	0	0	1
1997	1	2	0	0	0
1998	1	0	2	1	1
1999	2	1	0	1	0
2000	1	2	1	1	1
2001	2	1	1	0	0
2002	0	1	2	0	0
2003	0	4	6	0	0
2004	0	2	1	0	0
2005	1	3	1	1	0
2006	0	0	1	0	1
2007	2	6	0	0	0
2008	2	7	0	0	0

Table 7: Energy storage technology internation patent applications by year [26]

Growth Curve Development

As previously stated, the Gompertz and Pearl formulas are used to develop the growth curves for the publication and patent application data. To make the analysis clearer it is convenient to make the upper asymptotes of the formulas *a* and *L* equal to 100%. To do this the data for each year must be a cumulative value of all the previous years and then divided by a determined max cumulative value. The determine max cumulative value was determine by doing a similar search on Science Direct and WIPO databases for a mature energy technology, nuclear power. From the database searches on nuclear power an upper cumulative value for publications was determined to be 13500 and the cumulative total for patent applications was determined to be 500. Using these values tables 6 and 7 were converted into percentages of cumulative maxes. It is important to note that for the Gompertz formula, the coefficients of *b* and *c* are easier to solve for in excel if the time period t is valued from 1 to *x* rather than the actual years, so for example in the publications data 1993 would be 1 and 1994 would be 2 and so on for the calculations. Also, the Pearl formula's logarithmic function does not handle 0 and so for the case of CAES and Flywheel patent applications in year 1 which were 0, a value of 0.1 was used in the calculations.

For the purpose of this paper, the growth curve development for pumped hydro publications will be explained in detail for both the Gompertz and Pearl methods, for the remaining technologies and patent data only the final curves will be shown. The publication data for pumpeed hydro along with the cumulative publications and percent of max publications, recall the max publications was chosen at 13500, is shown in Table 8.

Year #	Year	Pumped Hydro Publications	Cumulative Publications	Percent
1	1993	329	329	2.4
2	1994	324	653	4.8
3	1995	355	1008	7.5
4	1996	311	1319	9.8
5	1997	295	1614	12.0
6	1998	136	1750	13.0
7	1999	125	1875	13.9
8	2000	134	2009	14.9
9	2001	135	2144	15.9
10	2002	144	2288	16.9
11	2003	174	2462	18.2
12	2004	192	2654	19.7
13	2005	209	2863	21.2
14	2006	218	3081	22.8
15	2007	250	3331	24.7
16	2008	293	3624	26.8

Table 8 Pumped hydro energy storage publications and overall percentages

Gompertz Growth Curve

Taking the Year # and Percent columns from Table 8 and applying the Gompertz formula (Eq. 1), a prediction and error can be generated for the data, shown below in Table 9. Recall that *a* is assigned a value of 100 since the publication data has been converted into a percentage value. For the initial prediction guess values for *b* and *c*, recalling that they are negative numbers. The error column can be done in many ways for the sake of this paper the y(Error) is defined as the square of the difference between *y* actual (Percent column) and *y* prediction (y(Gompertz) column). Finally, at the bottom of the error column the sum of the error is tallied. Now in order to optimize the prediction, Excel's solve function can be used to minimize the summed error by changing the guessed values of *b* and *c*.

Year #	Year	Percent	y(Gompertz)	y(Error)
1	1993	2.4	3.78	1.81
2	1994	4.8	6.85	4.04
3	1995	7.5	11.13	13.44
4	1996	9.8	16.57	46.29
5	1997	12.0	22.96	121.05
6	1998	13.0	29.98	289.44
7	1999	13.9	37.29	547.71
8	2000	14.9	44.59	882.79
9	2001	15.9	51.62	1277.48
10	2002	16.9	58.20	1701.44
11	2003	18.2	64.20	2112.32
12	2004	19.7	69.57	2490.84
13	2005	21.2	74.30	2818.55
14	2006	22.8	78.41	3089.81
15	2007	24.7	81.94	3279.71
16	2008	26.8	84.95	3376.83
			Summed Error	**22053.57489**

Gompertz	
y = a*exp(b*exp(c*t))	
a	100
b	-4
c	-0.2

Table 9: Initial prediction of hydro publications using Gompertz formula

The solve function can be found under the drop down menus of Excel under Tools → Solver. If solver is not present, it may need to be installed and can be done so by going to the Tools drop down menu and selecting Add-Ins, which will bring up the window shown in Figure 7 showing the solver Add-in.

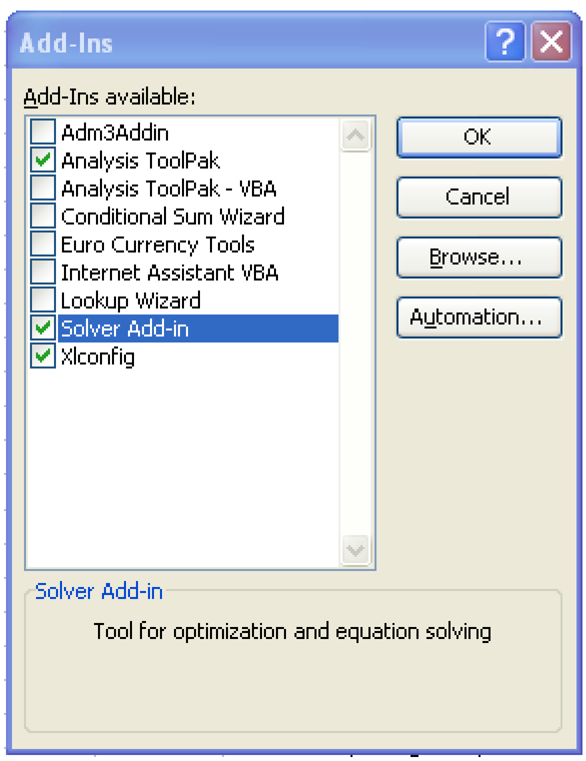

Figure 7: Excel Add-in window showing Solver Add-in feature

After solver has been installed, simply highlight the summed error cell and run solver to get the window shown in Figure 8 to appear. Make sure that the cell containing the summed error is the Target Cell, in this case $J$18 and that the Min radial button is highlighted as we are going to minimize the error function. Next, specify the cells containing the values for b and c are in the By Changing Cells box, in this case $Q$4:$Q$5. Additional constraints can be added such as specifying the *b* and *c* must be negative, however, in this case it is not necessary so to optimize the data Solve is simply checked.

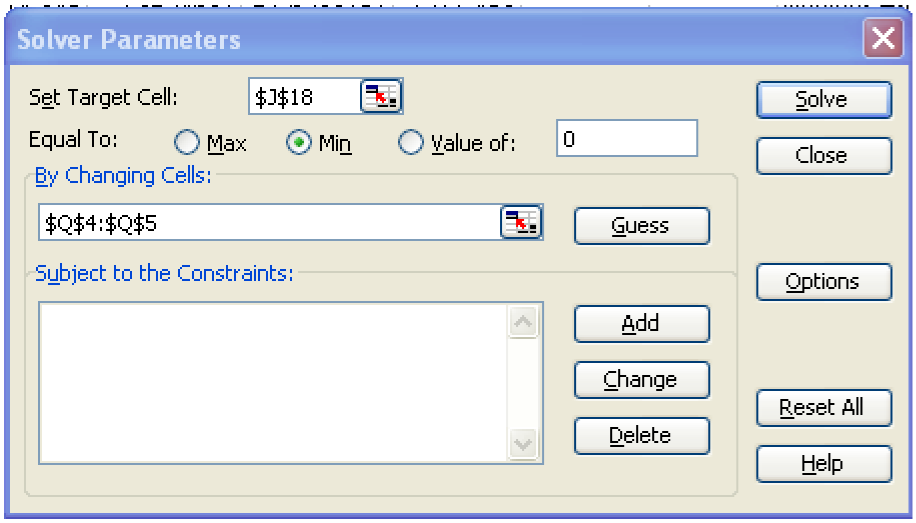

Figure 8: Solver window in Excel

Another window will appear asking if the solver solution should be kept and after clicking OK the optimized parameters, predictions and error can be seen in Table 10.

Year #	Year	Percent	y(Gompertz)	y(Error)
1	1993	2.4	6.01	12.78
2	1994	4.8	6.91	4.30
3	1995	7.5	7.89	0.18
4	1996	9.8	8.95	0.68
5	1997	12.0	10.08	3.51
6	1998	13.0	11.29	2.78
7	1999	13.9	12.58	1.71
8	2000	14.9	13.94	0.88
9	2001	15.9	15.37	0.26
10	2002	16.9	16.87	0.01
11	2003	18.2	18.42	0.03
12	2004	19.7	20.03	0.14
13	2005	21.2	21.69	0.23
14	2006	22.8	23.40	0.33
15	2007	24.7	25.14	0.22
16	2008	26.8	26.92	0.01
			Summed Error	**28.04**

Gompertz	
y = a*exp(b*exp(c*t)	
a	100
b	-2.9579
c	-0.0508

Table 10: Optimized Gompertz parameters and prediction for pumped hydro publications

From Table 10 the optimized values of *b* and *c* are shown to be -2.9579 and -0.0508 and the new summed error has reduced from many thousands down to 28. The prediction can then be extended forward in time and plotted vs the actual data to visually see how well the prediction models the known data and what it shows in the future. Figure 9 shows the Gompertz prediction of the hydro publication data forecasted out twenty years.

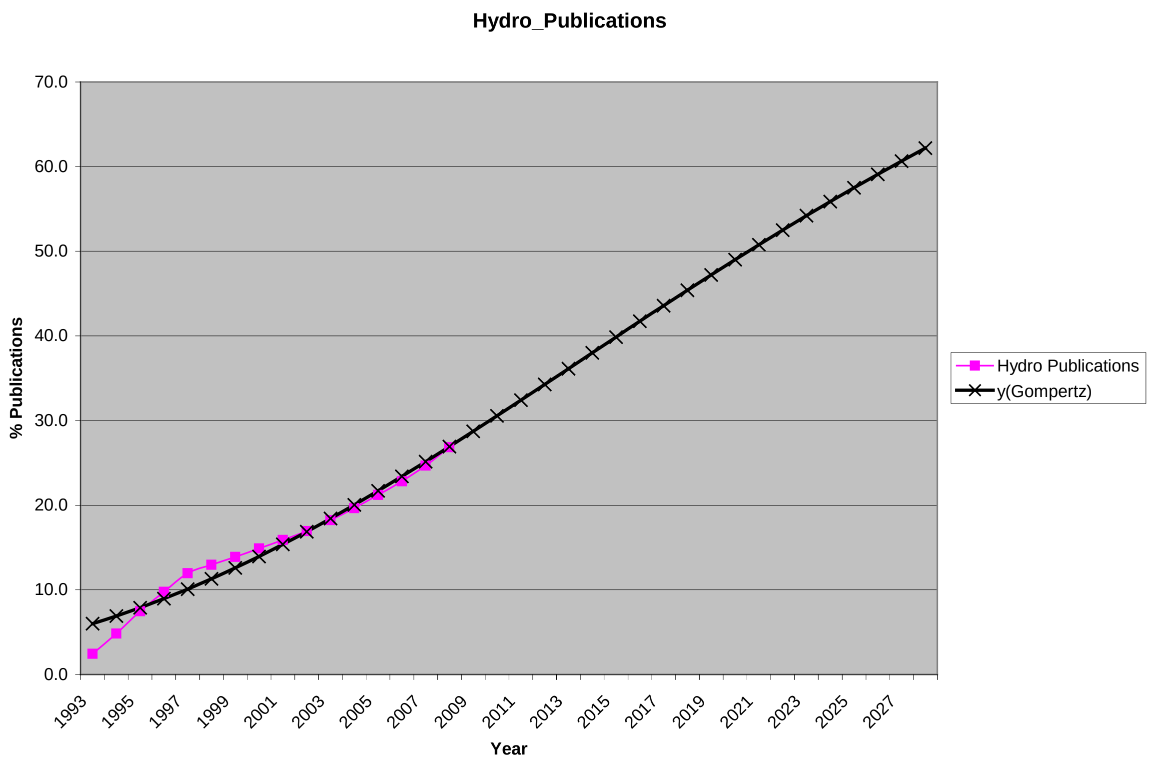

Figure 9: Gompertz growth curve for pumped hydro publication data

Pearl Growth Curve

To generate the Pearl growth curve the data from Table 8 is again going to be used, but first the percent publications data is going to be transformed using Equation 3 to generate the values of *Y* shown in Table 11. With the linearized values of *y* in Table 11 the coefficients of *A* and *B* are easily determined using the slope and intercept functions in excel. In the cells that should contain the values of the coefficients *A* and *B* the functions shown in Figure 10 are applied where F2:F17 refers to the cells containing the values of *Y* and B2:B17 refers to the cells containing the years for the publications.

Year #	Year	Percent	Y
1	1993	2.4	-1.60
2	1994	4.8	-1.29
3	1995	7.5	-1.09
4	1996	9.8	-0.97
5	1997	12.0	-0.87
6	1998	13.0	-0.83
7	1999	13.9	-0.79
8	2000	14.9	-0.76
9	2001	15.9	-0.72
10	2002	16.9	-0.69
11	2003	18.2	-0.65
12	2004	19.7	-0.61
13	2005	21.2	-0.57
14	2006	22.8	-0.53
15	2007	24.7	-0.48
16	2008	26.8	-0.44

Pearl	
L	100
A	
B	

Table 11: Pearl linearization data for pumped hydro publication data

Pearl	
L	100
A	-120.8225
B	0.0600

=INTERCEPT(F2:F17,B2:B17)

=SLOPE(F2:F17,B2:B17)

Figure 10: functions for determining coefficients *A* and *B* in the Pearl formula

The resulting values for *A* and *B* are then applied to the Pearl equation (Eq. 2) and a predicted value of *y* is calculated for the publication data along with an error term similar to that used in the Gompertz growth curve.

Year	Percent	Y	y(Pearl)	y(Pearl)Error
1993	2.4	-1.60	5.3	7.95
1994	4.8	-1.29	6.0	1.32
1995	7.5	-1.09	6.8	0.43
1996	9.8	-0.97	7.7	4.10
1997	12.0	-0.87	8.8	10.01
1998	13.0	-0.83	10.0	8.99
1999	13.9	-0.79	11.3	6.83
2000	14.9	-0.76	12.7	4.62
2001	15.9	-0.72	14.3	2.35
2002	16.9	-0.69	16.1	0.67
2003	18.2	-0.65	18.1	0.02
2004	19.7	-0.61	20.2	0.32
2005	21.2	-0.57	22.5	1.79
2006	22.8	-0.53	25.0	4.96
2007	24.7	-0.48	27.7	9.34
2008	26.8	-0.44	30.6	13.97
			Summed Error	**77.67**

Pearl	
L	100
A	-120.8225
B	0.0600

Gompertz

Table 12: Optimized Pearl parameters and prediction for pumped hydro publications

From Table 12 the optimized values of *A* and *B* are shown to be -120.8 and 0.06 and the summed error is approximately 78. The prediction can then be extended forward in time and plotted vs the actual data similarly to what was done with the Gompertz prediction. Figure 11 shows the Pearl prediction appended to the graph shown in Figure 9.

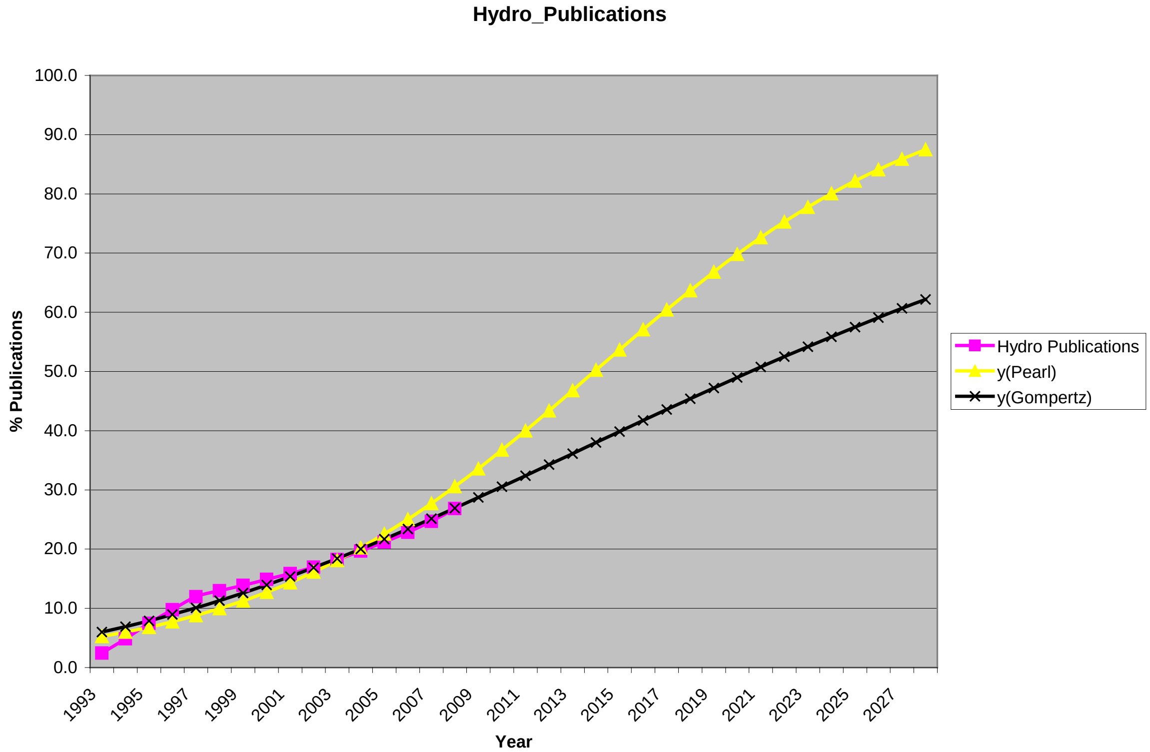

Figure 11: Gompertz and Pearl growth curves for pumped hydro publication data

Comparing the two growth curves shows that the Gompertz curve fits the publication data better for the more recent data and tends to be a less optimistic foercast. Meanwhile, the Pearl equation tends the fit the earlier publication data better and then begins to over predict the later data and becomes quite optimistic in the forecast.

Growth Curve Results

The methodology outlined in the previous section was applied to the publication and patent application data for all technologies and the results are presented in the following section.

Publication Growth Curves

The growth curves for the publication data can be seen in Figures 12 and 13. Figure 12 shows the Gompertz growth curves and clearly shows CAES publications outpacing the other technologies and pumped hydro is the second fastest technology until the mid 2020's when NiCd technology catches up. Meanwhile, NaS and flywheel technologies both lag behind in terms of publication growth.

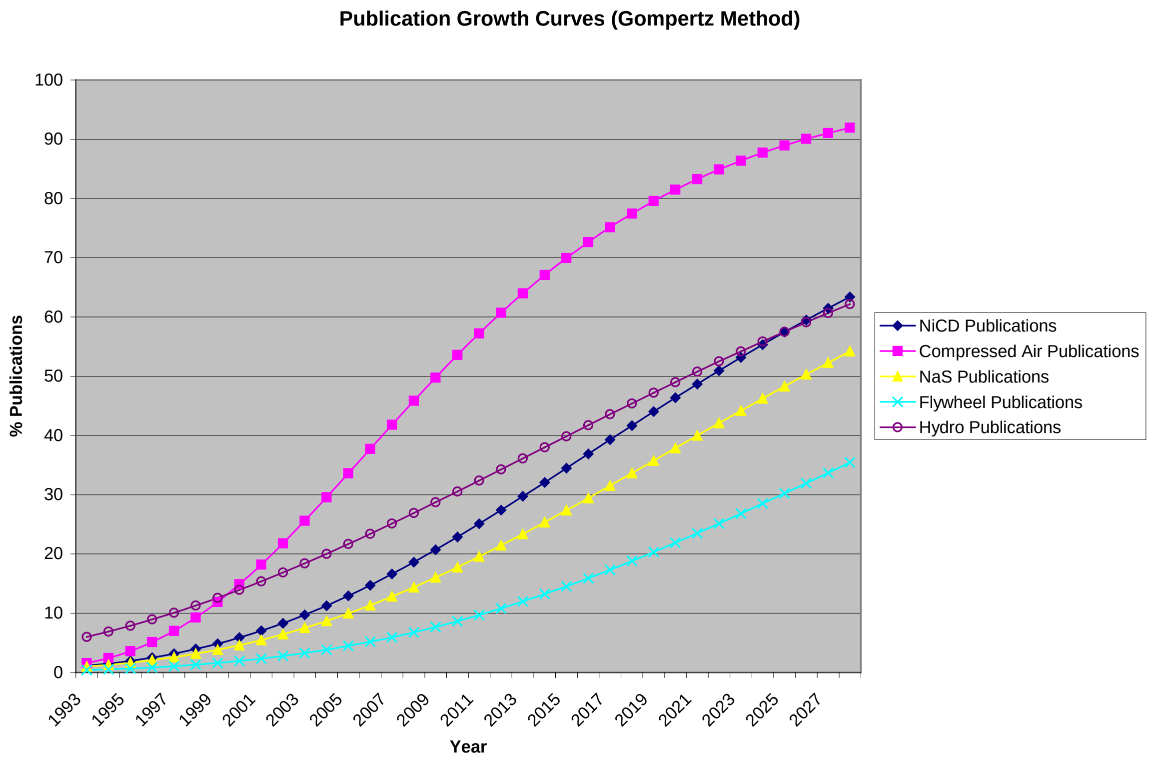

Figure 12: Gompertz growth curves for energy storage technologies publication data

Figure 13 shows the Pearl growth curves and similarly to the Gompertz method CAES far outpaces the other technologies in terms of publication growth. The Pearl curves also show pumped hydro as the current second fasting growing technology, however unlike the Gompertz pumped hydro is quickly overtaken by NiCd technology around 2013. The Peal curves also shows NaS and Flywheels as lagging behind similar to the Gompertz curves; however, in the Pearl forecast NaS technology has some potential to catch up in terms of publication growth around 2020 and pass pumped hydro.

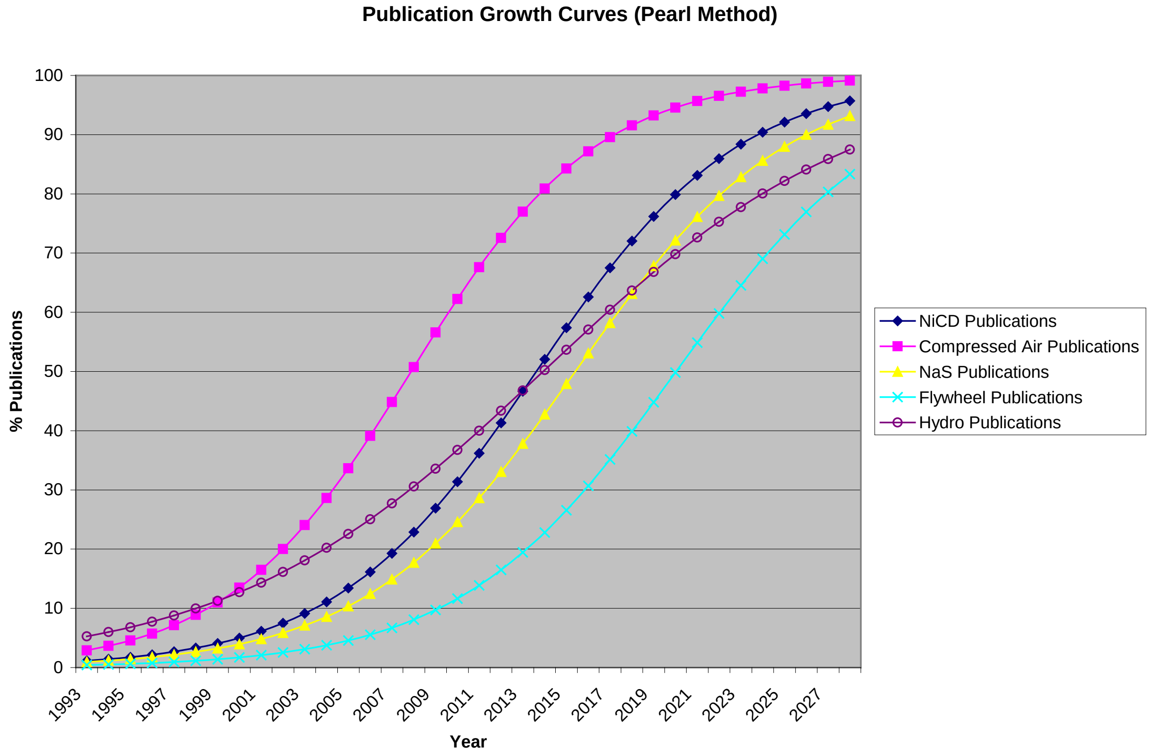

Figure 13: Pearl growth curves for energy storage technologies publication data

Patent Application Growth Curves

The growth curves for the patent application data can be seen in Figures 14 and 15. Figure 14 shows the Gompertz growth curves for the patent application data. Similar to the publication data CAES is the fastest growing technology. One major difference in the patent data shows the flywheel technology as the second fastest growing technology compared to being the slowest in terms of publications.

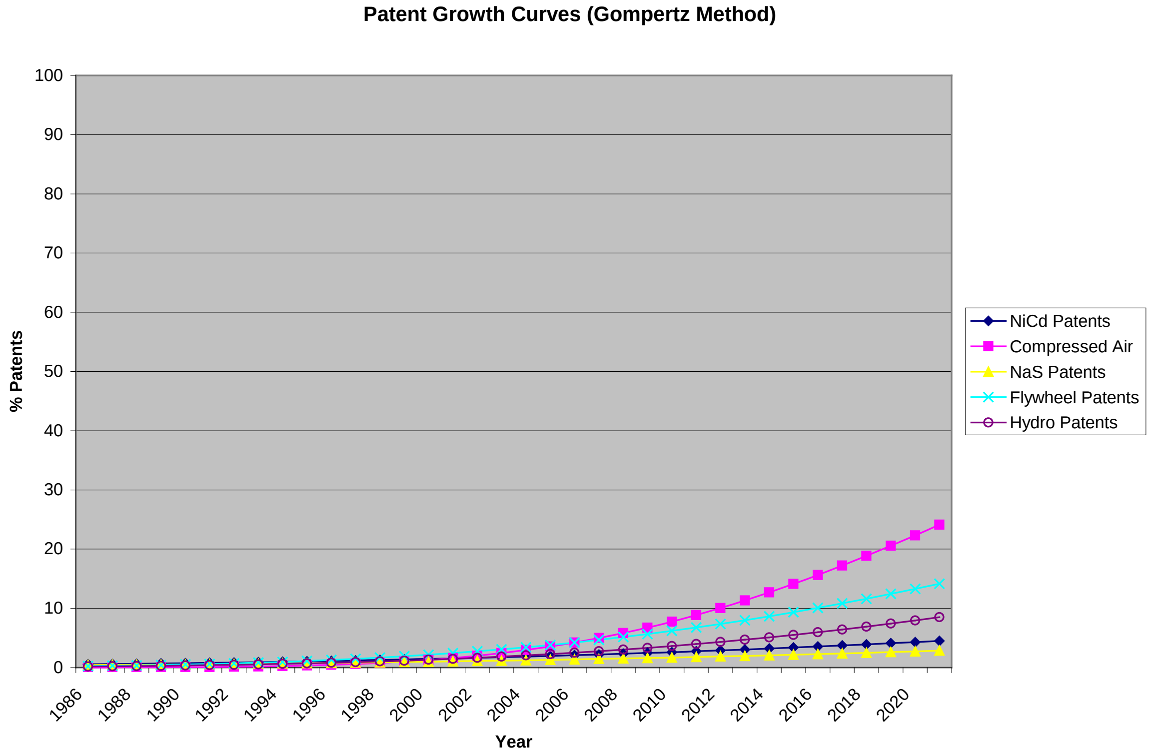

Figure 14: Gompertz growth curves for energy storage technologies patent application data

Figure 15 shows the Pearl growth curves for the patent application data. Similar to the Gompertz curves the fastest growing technology is CAES followed by flywheels. The major difference between the Gompertz and Pearl curves is the Pearl curves are forecasting that the CAES and flywheel technologies in the Pearl curves are approaching the upper asymptote whereas the Gompertz curves show the technologies not even reaching 30% of the maximum by the mid 2020s.

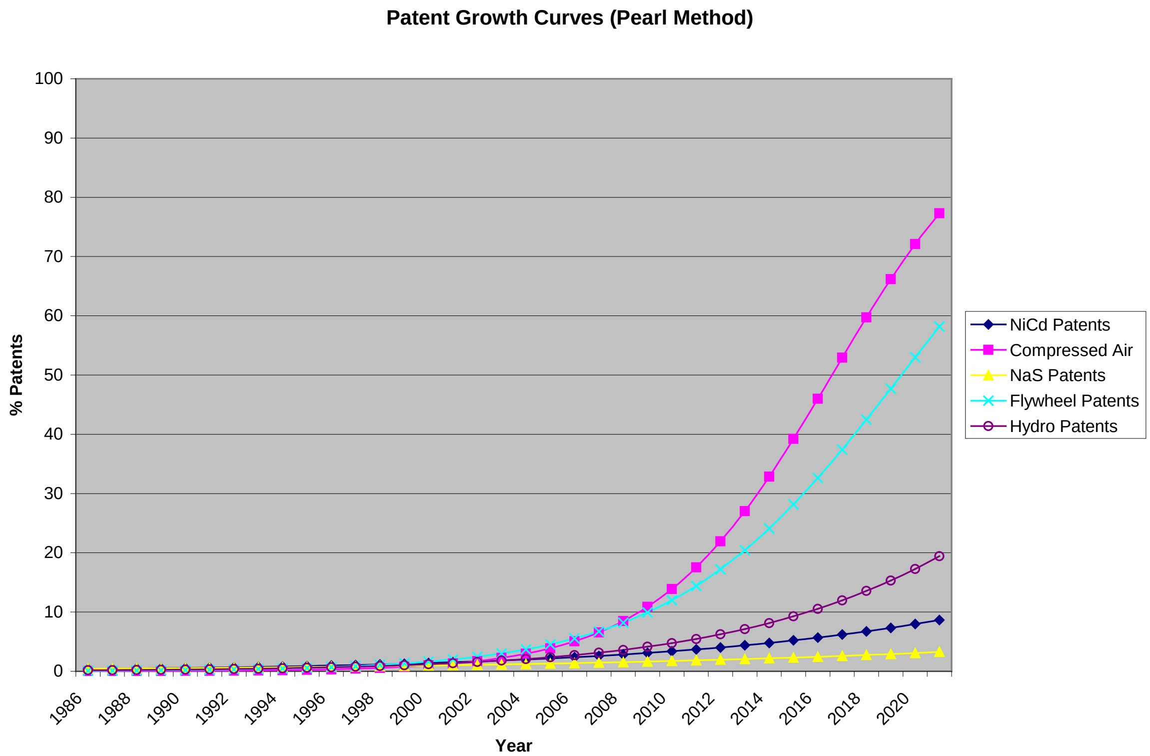

Figure 15: Pearl growth curves for energy storage technologies patent application data

Conclusions

Based on the publication and patent data Compressed Air Energy is set to be the fastest growing complimentary technology to wind energy. Two of these types of plants are currently in existence today as mentioned previously indicating the technology is commercially available. This technology has great potential however implementing this technology involves finding or creating underground airtight caverns in usable locations.

Of the remaining complimentary technologies pumped hydro seems to be the next fastest growing technology for the short term in terms of publications; however, NiCd battery technology is poised to overtake it within as few as 5 years according to the Pearl forecast. According to the patent search the second fasted growing complimentary technology is flywheel which is a relatively young technology so the patent growth is higher than some of the more established technologies. According to Dennis Phillips an expert from the Bonneville Power Administration's office of innovation technology, the growth rates for the various technologies made sense in relation to there various developmental phases, CAES and flywheel technology are emerging technologies showing strong growth whereas, pumped hydro is a more mature technology that is leveling off in terms of growth [27].

Despite the growth in publications and patents of Compressed Air, Flywheel and Pumped Hydro energy storage the technologies are still expensive and not readily available. Therefore, if the energy storage requirements can be met by Nickel Cadmium and Sodium Sulfur batteries then they are still the most logical choice. In comparing the growth curve techniques it appears that the Gompertz formula is a much more pessimistic forecast; however when modeling the data it consistently provided a lower sum squared error than the Pearl forecast. On the other hand, the Pearl formula provided a more optimistic growth curve for a technology, but it was also probably more realistic for a technology that is truly being adopted as a new standard.

The push for renewable energy needs to take into account the complimentary technologies needed to successfully implement a renewable energy resource and advance them into a larger portion of the overall energy production in the United States. The way renewable energies are currently being marketed they are an incomplete technology since they are not truly interchangeable (apple to apple) with other energy production processes (base loads do not compare).

Future Work

The authors of the paper plan to expand the research by delving into the energy storage capacities of the complimentary technologies and cost of each option, both from an environmental and monetary perspective.

References

[1] Energy Information Association, "Annual Energy Outlook 2009". January 2009 <http://www.eia.doe.gov/oiaf/aeo/pdf/overview.pdf>.

[2] Energy Information Association, "Annual Energy Review". June 2008 <http://www.eia.doe.gov/emeu/aer/txt/stb0101.xls>

[3] Baker, J. "New technology and possible advances in energy storage". Energy Policy December 2008: 4368-4373.

[4] "Tchnologies| Pumped Hydro Storage". Electricity Storage Association. March, 2008 <http://www.electricitystorage.org/tech/technologies_technologies_pumpedhydro.htm>.

[5] "Pumpstor racoon mtn.jpg". Wikipedia. March, 2008 <http://en.wikipedia.org/wiki/File:Pumpstor_racoon_mtn.jpg>.

[6] "Compressed Air Energy Storage". US Dept. of Energy. March, 2008 <http://www.eere.energy.gov/de/compressed_air.html>.

[7] "Minebw-large.jpg". Wikipedia. March, 2008 <http://en.wikipedia.org/wiki/File:Minebwlarge.jpg>.

[8] Ruddell, Alan. "Investigation on Storage Technologies for Intermittent Renewable Energies: Evaluation and recommended R&D strategy". Investire-Network. March, 2008 <http://www.itpower.co.uk/investire/pdfs/flywheelrep.pdf>.

[9] Rojas, Alex. "Flywheel Energy Matrix Systems – Today's Technology, Tomorrow's Energy Storage Solution". Beacon Power Corp.. March 2008 <http://www.beaconpower.com/products/EnergyStorageSystems/docs/Flywheel%20Energy%20Matrix%20Systems%20-%20white%20paper.pdf>.

[10] Battery energy storage technology for power systems—An overview K.C. Divya∗,1, Jacob Østergaard1 *Technical University of Denmark, Kgs. Lyngby 2800, Denmark*

[11] "Sodium-sulfur battery". Wikipedia. March 2008 <http://en.wikipedia.org/wiki/Sodium-sulfur_battery>.

[12] "Nickel-cadmium battery". Wikipedia. March 2008 <http://en.wikipedia.org/wiki/Nickel-cadmium_battery >.

[13] "NICKEL-CADMIUM CELL (NICAD BATTERY)". Chemistry-Dictionary.com. March 2008 <http://www.chemistry-dictionary.com/definition/nickel-cadmium+cell+(nicad+battery).html>.

[14] "Nickel Cadmium Technical Handbook". GP Batteries. March 2008 <http://www.gpbatteries.com/html/pdf/NiCd.pdf>.

[15] Eppler, M.J. & Platts, K.W. 2009, "Visual Strategizing: The Systematic Use of Visualization in the Strategic-Planning Process", *Long Range Planning,* vol. 42, no. 1, pp. 42-74.

[16] Schoenung, Susan M., and Clayton Burns. "Utility Energy Storage Applications Studies." IEEE Transactions on Energy Conversion 11 (1996): 659-60. IEEE Xplore.

[17] Lead Acid Batteries. 17 May 2006. Department of Energy - Distributed Energy Program. 10 Feb. 2009 <http://www.eere.energy.gov/de/batteries_leadacid.html>.

[18] Advanced Batteries. 17 May 2006. Department of Energy - Distributed Energy Program. 10 Feb. 2009 <http://www.eere.energy.gov/de/batteries_advanced.html>.

[19] WILLIS, R. E. "Statistical Consideration in the Fitting of Growth Curves." Technological Forecasting and Social Change, Oct. 1979.

[20] Daim, T. U., Guillermo, R., Et. Al.. "Forecasting emerging technologies: Use of bibliometrics and patent analysis". Technological Forecasting and Social Change April 2006: 981-1012.

[21] Rueda, G, Kocaoglu, D. G.. "Diffusion of emerging technologies: An innovative mixing approach". PICMET 2008: Portland International Conference.

[22] Franses, Philip Hans. "Gompertz Curves with Seasonality". Technological Forecasting and Social Change 1994: 287-297.

[23] "Gompertz Function". Wikipedia. March 2008 <http://en.wikipedia.org/wiki/Gompertz_Curve>.

[24] Co, Henry. "Pearl Curve on Excel." February 2009. California Polytechnic and State University.

[25] Elsevier B.V., "ScienceDirect Search". ScienceDirect. February 2009 <http://www.sciencedirect.com/>.

[26] Headquarters of WIPO, "PatentScope". World Intellectual Property Organization. January 2009 <http://www.wipo.int/pctdb/en/>.

[27] Phillips, Dennis. Office of Innovation Technology, Bonneville Power Administration, March 2009