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Carbon footprint reductions via grid energy storage systems

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Abstract

This effort presents a framework for reducing carbon emissions through the use of large-scale grid-energy-storage (GES) systems. The specific questions under investigation herein are as follows: Is it economically sound to invest in a GES system and is the system at least carbon footprint neutral? This research will show the answer to both questions is in the affirmative. Scilicet, when utilized judiciously, grid energy storage systems can be both net present value positive as well as be total carbon footprint negative. The significant contribution herein is a necessary and sufficient condition for achieving carbon footprint reductions via grid energy storage systems.

Keywords: Energy demand and supply (JEL Code: Q41); Grid energy storage; Carbon footprint.

1. Introduction

The United States consumed 4,157 terawatt-hours of electric energy in 2007. The advent of time-of-use (TOU) kWh rates from the electric utility companies has incentivized both energy usage management techniques and the development of grid-energy-storage (GES) systems. This study investigates the latter from both net present value and carbon footprint points of view and proposes a framework for which to implement a grid energy storage system enabled energy arbitrage system.

The questions pertinent to the research herein are as follows: Are relatively small GES systems, with capacities on the order of 25 MWh, a sound financial investment and are they at least carbon footprint neutral? Our research catalogued herein suggests that the answers to both of these questions are yes. That is to say, when managed properly, GES systems can be both net present value positive as well as total carbon footprint negative. This research is organized as follows. The next section presents a terse literature review on economic arbitrage models in general and on literature that describes the various grid-energy-storage systems in use today. Following the literature review, the third section demarcates a framework for implementing GES enabled energy arbitrage system, an estimate of the payback period for a 10 MWh capacity GES system via a net present value analysis, and an analysis of the associated carbon footprint impacts of GES systems. This treatise concludes in section four with a brief summary.

2. Background

To wit, no prior research exists in the public domain on GES enabled energy arbitrage systems. Hence, this literature review describes the landscape of two closely related areas. First, we will present some of the relevant research on economic arbitrage in general and then, second, literature that describes grid-energy-storage systems currently in use today. Indeed, it was this void in the literature describing GES systems that spawned this research project in the first place.

2.1 Economic arbitrage

In frictional economies, the price functions are generally sub-linear and thus there will be incentives to innovate [1]. This is definitely the case in point regarding energy industry. As consumer prices continue to rise, people will look for alternatives methods to ease budgetary constraints. The economic aspects of energy arbitrage play a vital role in offering solutions to this quandary.

The best-known type of economic arbitrage is the exploitation of cheap labor [2]. Energy creation facilities are generally low labor intensive industries once they are established. This is particularly true of green energy collection methods such as solar and wind, which also help reduce carbon footprints.

Not all technology for energy arbitrage requires new, innovative technologies. Compressed air energy storage (CAES) is a technology that is almost 50 years old. The technology, which involves storing off-peak-generated energy in the potential form of compressed air, is being researched for its use as a load leveling management tool as well as its capability to function as a stand-alone intermediate generation source for capturing energy arbitrage, capacity payments, and ancillary services.

Unlike markets for storable commodities, electricity markets depend on the real-time balance of supply and demand [3]. Therefore, since demand fluctuations vary greatly due to seasonality this makes forecasting modeling essential. Also, supply can potentially be seasonal, since inclement weather may not yield sufficient levels of electricity to meet demand.

Walawalkar et al. [3] also determined that there is a strong economic case for installations in the New York City region for applications such as energy arbitrage. So, it is reasonable to assume an investment in such systems would be economically beneficial in other geographic regions.

A study done by Matteucci and Reverberi [4] confirmed a non-linear relationship between technology/market conditions and the first-mover's pricing strategy. So, newer technologies for energy arbitrage may prove to be less cost effective, until such time the technology is in less demand and costs have declined. Furthermore, the authors recommend that regulation provide manufacturers with adequate countervailing incentives to realize the long-term gains from such energy arbitrage systems.

2.2 Grid energy storage systems

Grid energy storage systems have recently been cited in the Wall Street Journal as one of the next great energy challenges. Despite this, and to wit, there are very few archival quality sources dealing with grid energy storage systems. Herein, we present the few manuscripts that were found in the open literature and try to describe the landscape for grid energy storage systems.

Grid-energy-storage systems come in an array of operating mechanisms. With the notable exception of flow battery, battery, and supercapacitor based systems (see, Gyuk, Kulkarni, Sayer, Boyes, Corey, and Peek [5] for a description of battery and supercapacitor systems in use today and see Divya and Østergaard [6] for a more technical analysis on battery based storage systems), that store energy in electrical form, per se, most GESs utilize some other potential energy as the energy storage medium.

The more notable GES systems in use today include pumped storage hydroelectric (PSHE), compressed air energy storage (CAES) [7], thermal systems in general, and battery based systems. PSHEs are the most common (approximately 30 in the United States) GESs and are mostly used by the utility companies. To operate effectively, PSHEs need two nearby lakes at different elevations in which water is moved between dependent on the energy demand profiles. Some PSHEs have two sets of pipes (also known as penstocks): one set for pumping water up to the higher lake and one set for flowing water down through the turbines. Some PSHEs have just one set of penstocks in which water flows, albeit with less efficiency, in both directions depending on need. An advantage for the former system is that the system can do both processes simultaneously. This is especially important if the PSHE derives some of the energy for the pumps from intermittent sources such as, say, wind and or solar. The downside is that these systems require more initial investment and more maintenance annually.

3. System models

The current energy delivery system delineated in Figure 1 below is antiquated. The model is a linear system of energy delivered from the power company to the grid and, in turn, distributed to the demand. Meters are uni-directional. Demand management is non-existent.

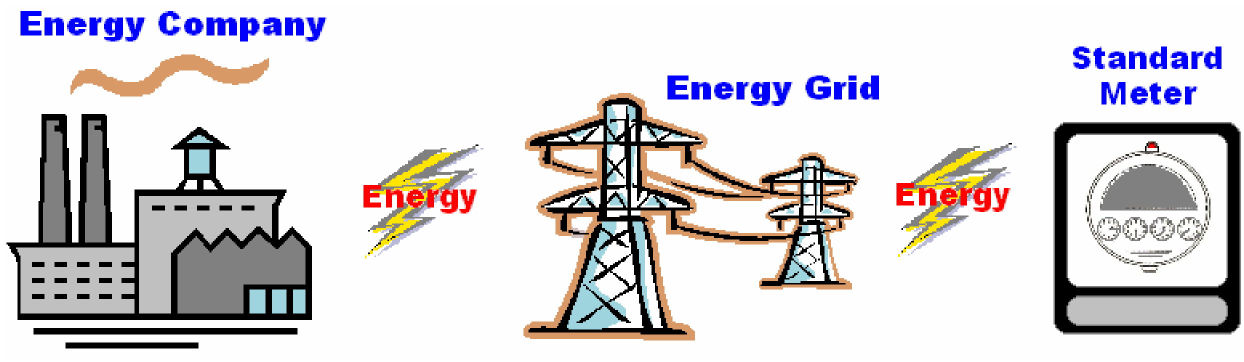

Figure 1. The current energy management system

3.1 Framework

A conceptual framework for the proposed system is depicted in Figure 2 below. Notice that in the proposed model, the "busiest" node (i.e., the node with the highest degree) in terms of both communication flows and energy flows is the advanced meter. This is the hub of the system. Energy and communications flow into and out of the meter in multiple directions. Energy flows in two directions (depicted with double lightning bolts in Figure 2 between the GES and the advanced meter, it flows in one direction (depicted with a single bolt in Figure 2) from the advanced meter to the energy sinks in the house/facility, and it flows in two directions between the GES and the smart energy grid.

The advanced meter is bi-directional, granular per circuit (energy flows are measured per circuit breaker switch) energy usage/delivery measurement system. Two way communications (depicted with two way arrows in Figure 2) are integrated between the GES and the electric company as well as in two directions between the GES and the end-user.

The end-user interfaces with an energy usage management system that includes a GES. The GES stores low-demand, low-cost energy from off-peak hours until the next afternoon when rates are higher. This is known in the business both as energy arbitrage and load leveling. It involves transforming electrical energy into potential energy in the middle of the night when demands are low, storing that as potential energy, and then transforming it back into electrical energy the next afternoon when rates and demands are high. However, energy is lost during the two energy conversion processes and, to a lesser degree, during storage. This loss is expressed as a ratio of energy delivered in the afternoon from the GES over energy used to provide the energy delivered and it is known as the system's efficiency.

Energy arbitrage (sometimes known as energy load leveling) is already done on a wide-scale basis by electric utility companies with massive grid-energy-systems capable of storing several gigawatt-hours of energy. For example, there are about 30 pump storage hydro electric (PSHE) facilities in the United States alone ranging from 0.031 to 2.71 gigawatt nameplate capacity. As outlined in section 2, PSHEs store energy in potential form by pumping water up an elevation in the middle of the night and then let this same water flow back down via gravity through large turbines.

The enormous start-up price tag of such GES systems as well as non-existent energy policies has always acted as a barrier to the market. Recent changes in laws (e.g., the Energy Policy Act of 2005 [8] in the United States) have lessened the policy barrier. However, the start-up cost barriers have remained. Indeed, electric utility companies have been officially recognized as natural monopolies for over a century [9]. New and emerging technologies such as flywheels that integrate high temperature, superconducting magnet systems into the hub chassis, high capacity lithium-ion batteries, and small scale, ultra high pressure compressed air systems would enable a GES system to function efficiently.

3.2 Net present value analysis

Coupling a 6 million dollar GES system with energy arbitrage via time-of-use (TOU) rates can provide positive net present values of the associated cash flows in approximately 14.23 years at a 3% discount rate and approximately 12.28 years employing a 6% discount rate. Table 1, below shows the average of 100 Monte Carlo simulations runs for discounted payback of various GES investment amounts from 1 million to 9 million dollars for a variety of discount rates. This provides some validation for the potential cost savings involved in such systems.

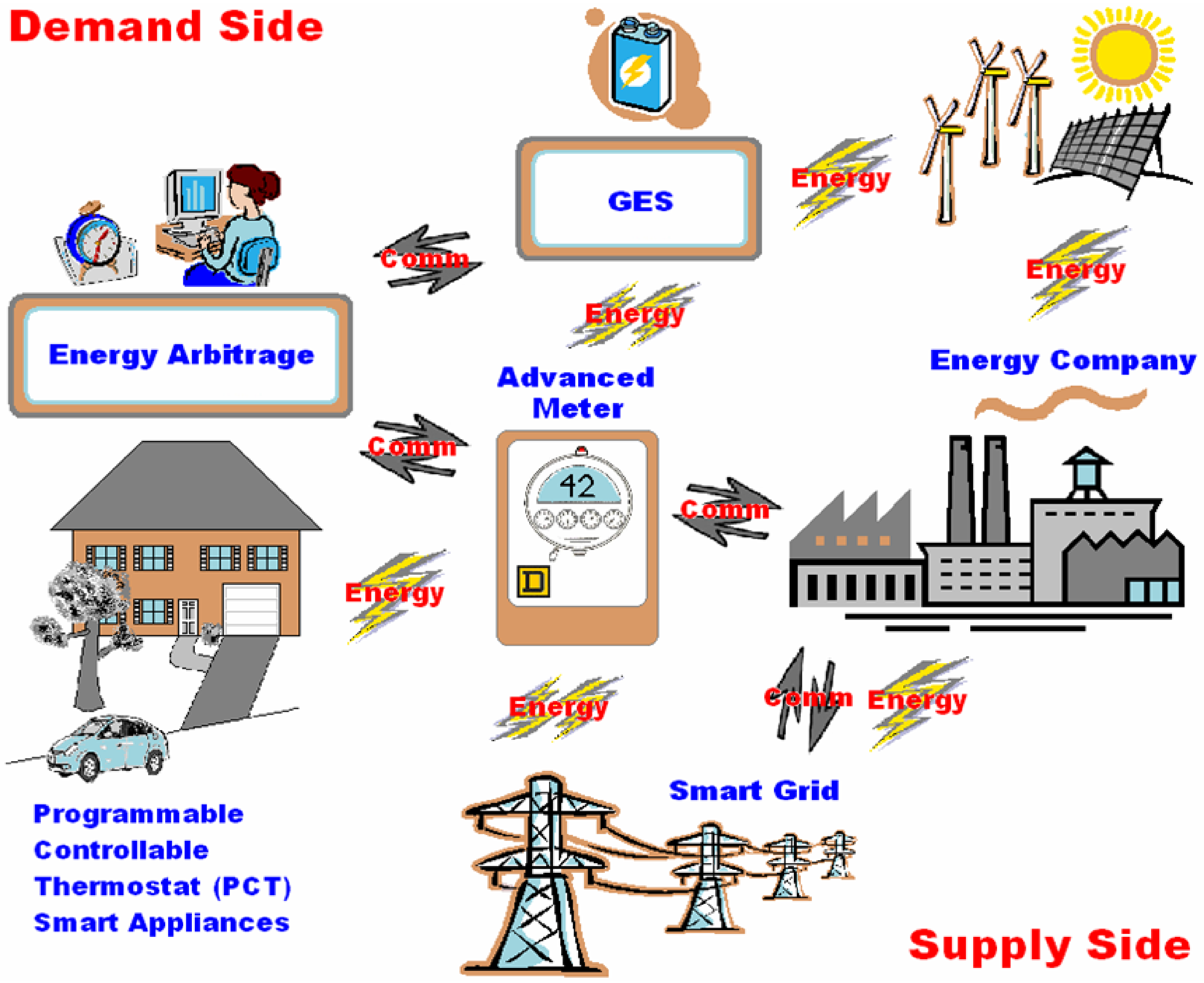

Figure 2. The proposed integrated GES enabled energy arbitrage conceptual framework

Table 1. Discounted Payback of GES System Investment in Years

	Discounted Payback in Years with an Annual Cost Savings of:							344,260
INV ||| RATE	1%	2%	3%	4%	5%	6%	7%	8%
-1,000,000	2.878	2.852	2.827	2.803	2.780	2.757	2.736	2.715
-2,000,000	5.675	5.551	5.435	5.328	5.227	5.132	5.043	4.960
-3,000,000	8.397	8.113	7.857	7.625	7.413	7.218	7.039	6.873
-4,000,000	11.047	10.552	10.117	9.732	9.388	9.078	8.797	8.540
-5,000,000	13.629	12.878	12.235	11.678	11.189	10.755	10.367	10.018
-6,000,000	16.146	15.101	14.229	13.486	12.845	12.284	11.787	11.345
-7,000,000	18.602	17.231	16.111	15.175	14.377	13.687	13.083	12.548
-8,000,000	20.999	19.275	17.895	16.758	15.802	14.984	14.273	13.650
-9,000,000	23.341	21.239	19.589	18.249	17.135	16.190	15.375	14.665

Indeed, from a financial standpoint the question of why one would invest in a grid energy storage system is better expressed in terms of why one wouldn't invest.

3.3 Carbon footprint analysis

At first blush, it would seem that due to their inherent energy loss, GES systems might actually emit more kilograms of carbon dioxide and carbon dioxide equivalents into the atmosphere than an energy system that simply met the demand at the time-of-use. This is a reasonable concern. That is to say, strictly in terms of percentages, a 1600 MWh demand placed on a grid-energy-storage arbitrage system with an efficiency of, say, 0.80 would actually need to expend enough fuel to provide for a 2000 MWh demand.

However, upon closer inspection, a properly designed and managed GES system uses energy from the middle of the night. As shown in Figure 3 below, the energy sources in the middle of the night are far less polluting than in the middle of the afternoon. Renewable sources, although currently provide just 7% of the total energy source make-up in the United States (conversely, Norway's hydroelectric generation meets 98.25% of Norway's total demand), because of the relatively constant production levels of renewable over the course of the day, they provide a larger percentage of the total sources in the middle of the night than they do in the middle of the day. Hence, buying electric energy at night, storing it, and then using it the next afternoon is ostensibly a smaller net carbon footprint process than buying electric energy in the afternoon and using it immediately.

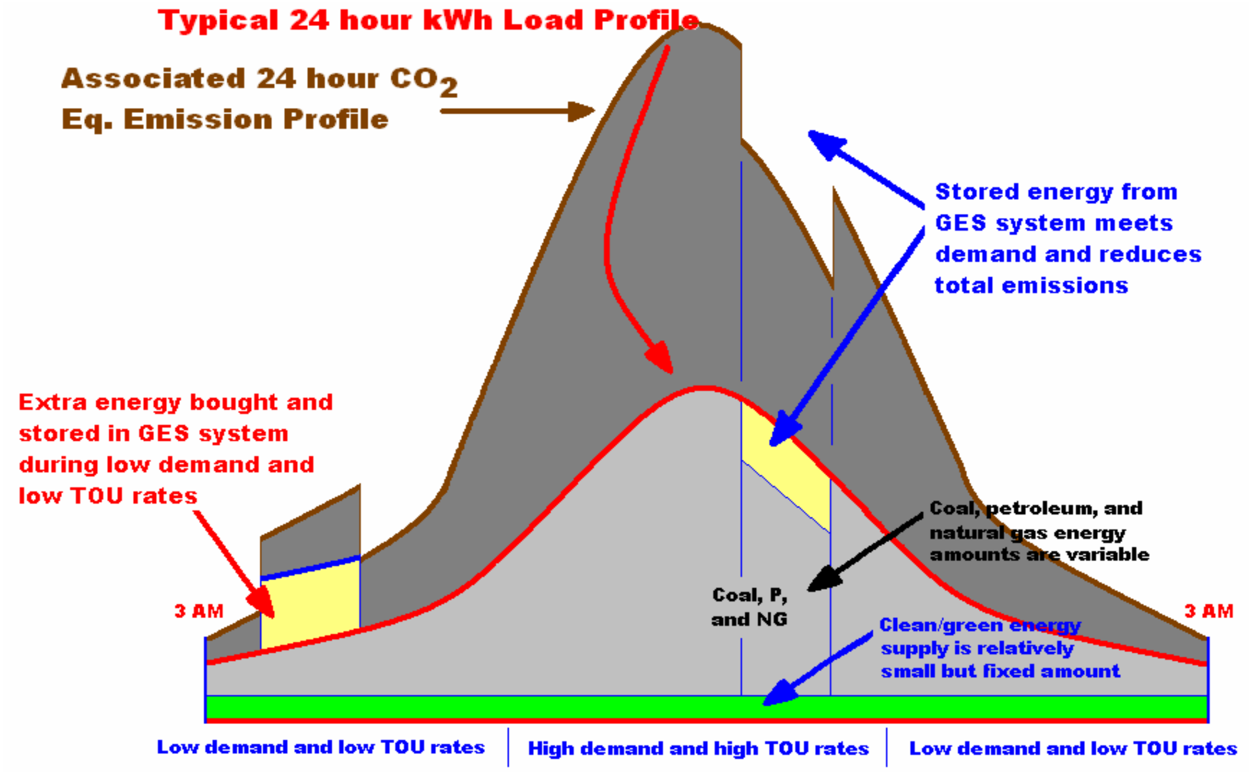

Figure 3. 24-hour CO2 equivalent emission profile versus 24-hour energy load profile

Additionally, fossil fuel burning electrical energy production systems known as "peakers" only operate in the middle of the afternoon to meet the high part (aka, the peaks) of the load profile. These systems produce more greenhouse gases per kWh than more stable, relatively constant load, twenty-four hour-a-day fossil fuel burning systems. To wit, reliable per hour-of-day energy source data isn't available publicly. However, some aggregate data sources (mostly from studies on the imminent infrastructure effects of plug-in hybrid electric vehicles) are available to support this argument.

3.4 Carbon footprint reduction

Combining the above theoretical analysis into a formula, we find carbon footprint neutrality of grid energy storage systems key on the efficiency, η, of the particular system as well as the ratio of fossil fuel content between the off-peak and on-peak loads. The inequality in formula 1 below shows when a particular grid energy storage system would actually reduce overall carbon footprint.

$$\eta_{\mathrm{GES}} \geq \left(\frac{\text{Fossil fuel energy source percentage at time of storage}}{\text{Fossil fuel energy source percentage at actual time of use}} \right) \tag{1}$$

The limiting factor here is, of course, if the energy bought and stored during off-peak hours completely eliminates the peaks and valleys of the load profile altogether. This scenario isn't expected to happen anytime soon.

4. Conclusion

A framework for implementing a GES system enabled energy arbitrage system was developed and shown. An associated NPV analysis found the payback period for such investments were sound and discounted paybacks can be measured in years, not decades. Moreover, it was shown that proper stewardship of grid energy storage systems can actually reduce net carbon footprint. The challenge set forth herein is then one of implementation of existing technologies to save money and reduce carbon footprints simultaneously.

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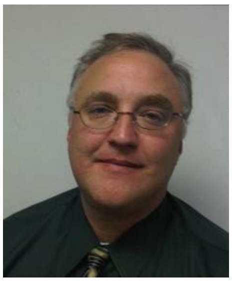

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