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Grid Energy Storage in Shallow Geothermal Boreholes as a Higher-Performing and Lower-Cost Solution to Grid and Building Decarbonization

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Keywords

Borehole, Battery, Storage, Thermal Energy Storage, GABESS, BTES, GHP, GSHP, BESS, Geothermal Heat Pump, Ground Source Heat Pump, ASHP, Air Source Heat Pump, utility, grid, incentive, CO_2 , efficiency, electrification, decarbonization, jobs, investment, green energy.

ABSTRACT

A particular type of Geothermal Heat Pumps or Ground Source Heat pump (GHP or GSHP) technology incorporating Borehole Thermal Energy Storage (BTES) using Air Source Heat Pumps (ASHP) to charge the BTES can be deployed as a better alternative to electrochemical batteries for grid energy storage to provide building heating/cooling energy. Both diurnal and seasonal (multi-month) storage are demonstrated. This combination of BTES, GHP, and ASHP is called Grid Amplified Building Energy Seasonal Storage (GABESS) in this paper. GABESS slashes the total energy required from the grid for building heating and cooling, especially at peak hours, and flattens the electric grid load in most climates. The BTES provides longer and greater energy storage than any battery technology with an ultimate point of use of building heating/cooling. GABESS provides a round-trip efficiency at the point of use of greater than 200%, compared to 90% or less for electrochemical batteries. For these reasons, the largest value-driver for this technology is electric utility grid CO_2, load, and cost management. A large building energy efficiency gain is also achieved, but the energy cost reduction from efficiency for the building owner is of secondary value compared to the grid benefits.

GABESS uses vapor compression refrigeration systems (ASHPs), operating either as heat pumps or chillers to store “cool” or “warm” in the BTES when advantageous to do so from a grid perspective, e.g., spring (seasonal storage), or for off-peak diurnal storage in winter or summer. The use of radiators and solar thermal as additional energy storage mechanisms is also discussed.

The distinctions between a BTES array of geothermal boreholes and a conventional GHP borehole array are explained. Innovative BTES array designs and hybrid technologies to

maximize the value of the GABESS system overall and to reduce BTES energy losses are provided.

Technology improvements over existing BTES installations, utility valuation methodologies, and hypothetical case studies are provided. Attractive ROIs can be achieved on multi-billion-dollar investment potential over the next 10 years.

1. Introduction

This paper presents a concept for a particular type of Geothermal Heat Pump (GHP) system which makes use of the ability of the ground to store large amount of externally injected low-temperature heating and cooling energy, primarily be electric-driven Air Source Heat Pumps (ASHPs). The concept is built on lessons and observations from two similar systems built and operated in North America for which there are published papers, but that operate with different energy storage sources. This paper is neither a report on an existing system, nor the detailed analysis of a particular proposed system. Instead, it is intended to introduce an approach, explain the reasoning of why this would be a valuable system and technology for grid and building heating/cooling decarbonization, and provide an initial evaluation methodology upon which electric utility operators can build to evaluate the beneficial effects on the cost of service. Utility grid financial benefits then allow monetary incentives to encourage system construction by developers and facility owners. Building energy cost savings are a secondary financial benefit and are not adequate to justify investment. Every attempt is made in this paper to make the technology public domain, or "open access", without proprietary intellectual property, and so help effect more rapid decarbonization of the grid and building heating and cooling.

This concept accomplishes building energy efficiency and decarbonization. However, the greatest value and real intent of the approach is to provide a grid management technology which reduces both the all-in cost of the grid (capex, opex, and transmission) and its CO_2 emissions. Unlike other renewable energy technologies, the deeper the deployment of GABESS, the larger the reduction in the cost of grid-supplied energy to all users. In so doing, it intrinsically provides and advances social and environmental justice.

2. Technology Overview

Grid-Amplified Building Energy Seasonal Storage (GABESS, pronounced "gabes") is a combination of three proven and existing technologies in a new arrangement that delivers large grid value. The three technologies are a Borehole Thermal Energy Storage (BTES) array of geothermal boreholes, a Water Source Heat Pump (WSHP) to provide building heating/cooling thermal energy, and an Air Source Heat Pump (ASHP) to store building heating and/or cooling energy[1, 2] GABESS provides multiple and large grid benefits which justify utility investment to

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[1] As used in this paper, an Air Source Heat Pump (ASHP) is a general shorthand term which means a refrigerant-based vapor compression device that either extracts heat from the air or rejects heat to the air (i.e., a chiller) by blowing air over the heat exchange coil. Throughout this paper, ASHP should also be understood to include any of a wide variety of water-cooled refrigerant vapor compression devices which use water to remove heat, including cooling towers, evaporative condensers, once-through exchangers using wastewater, irrigation water, or surface water sources, etc., all of which improve the efficiency of heat transfer. The use of radiators with fans in conjunction with ASHP is also possible, for example in climates that have a high grid cooling load and cold winters.

lower grid operation cost and accelerate grid and building decarbonization, along with many other benefits.

The principles of operation of the GABESS are simple. The ASHP creates warm or cold water during both daily and seasonal electric grid off-peak hours. The water from the ASHP is circulated through the BTES and so heats or cools the ground between the boreholes that comprise the BTES. The energy storage is in the ground itself, not in the fluids in the borehole plastic pipes. When the building needs to be heated or cooled, water is circulated through the BTES and the WSHP extracts or rejects heat into the water to provide building space conditioning via any conventional building HVAC technology. The water then circulates back to the BTES to be heated or cooled by thermal exchange with the ground via the BTES boreholes.

The meaning of the term "GABESS" is as follows. The ASHP delivers a greater quantity of cold or heat energy to the BTES than the electric power used by the machine. Therefore, the stored energy in the BTES has been *Grid Amplified* through the operation of the ASHP. Hours, days, or months later the heat or cold stored in the BTES will be recovered for *Building Energy* heating or cooling. Process cooling (e.g., data centers) or heating (greenhouses) is also possible. Since the BTES can store hot or cold for months at a time, it provides *Seasonal Storage*.

A more detailed description of the three major components of the GABESS as follows:

1) A BTES is an array of boreholes in which each borehole is typically about 100 to 500 feet deep. Each conventional geo-exchange borehole is a drilled hole, with a loop(s) of plastic pipe installed, and the hole filled with conductive grout. Water is circulated through the plastic pipe to conductively exchange energy between the water and the ground formation beyond the borehole. There are large and significant differences between a BTES array and a conventional Geothermal Heat Pump (GHP) borehole array. They include that the boreholes can be drilled with greater density (closer together) and they are connected so that flow is in radial pattern from either inside to outside (charging), or outside to inside (discharging). The BTES is designed to be able to store up to several months of all or a portion of the building(s) needed thermal energy requirements for heating or cooling. Since it can store the grid-amplified energy for months at a time, a BTES is a thermal energy storage "battery". It is also designed to avoid heat transfer with the undisturbed earth beyond the BTES, whereas a conventional GHP array is designed to maximize that heat transfer. Unlike a GHP array, the larger the BTES array gets, the more efficient it becomes because the surface area to volume ratio decreases. In a BTES, the center wells of the array increase in effectiveness due to lower losses, while in a typical GHP borehole array useful heat transfer decreases or stops.
2) An ASHP(s) operates to add either heat or cold (remove heat) to the BTES. The ASHP amplifies the grid power it consumes into hot or cold thermal energy to "charge" the BTES whenever it is advantageous to do so, under a variety of criteria. For example, if there is excess low-carbon power on the grid, the ASHP can amplify that excess power as cold or hot to the BTES. Two examples are that a BTES in California could store cold using surplus solar power to then reduce power demand in summer, while a BTES in Ireland could use excess wind power in the fall to charge a BTES to provide winter heating. The ASHP may

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[2] As used in this paper, the BTES will be described as able to "store cold" as a shorthand notation for the process of removing heat from the BTES. Cold is technically a lack of heat, not a separate physical property.

also be used diurnally to time-shift energy consumption so that the ASHP operates when it is more efficient (i.e., during winter afternoons for heating, and at night for cooling). In the charging mode, water is pumped from the outside boreholes of the BTES to the ASHP and returns to the center of the BTES where it flows radially through the BTES back to the outermost boreholes. The radial flow pattern creates a thermal gradient (either hot or cold) where the hottest or coldest temperature is in the center and the temperature cools or warms respectively toward the outside. Figure 1 conceptually illustrates a hot and cold BTES. The ASHP accomplishes a time-shifting of electric power use, and in so doing it also decreases the annual total energy and annual CO_2 emission for both the building and the grid as a whole. When the ASHP operates is critical to the value it creates. In the ideal system, the electric utility determines when to operate the ASHP to charge the BTES, just as they do with an electrochemical battery. This gives the utility the flexibility to use the ASHP in multiple ways. It can be used when the air temperature is most advantageous (a cool summer night or a warm winter afternoon). It can be used when there is excess electric energy available even if the ASHP efficiency is not as great because of air temperature (e.g., cold nights during a springtime hydro and wind surge or Sunday afternoons in summer when solar output and air temperatures are both high, but commercial A/C power demand is low.)

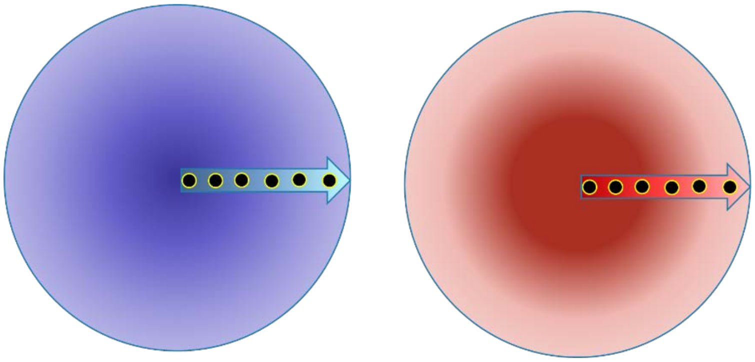

Figure 1: Conceptual illustration of a cold and hot BTES showing one line of boreholes for radial flow being used to charge the BTES with colder or warmer water, respectively. Any number and arrangement of boreholes is possible. Details of two arrangements are available in the papers by Hammock (2017) about a cool BTES at a Marine Corps Base in Albany, Georgia and by Mesquita (2017) about a hot BTES at the Drake Landing housing development near Calgary, Alberta.

3) A WSHP delivers heating or cooling to the building by extracting or rejecting heat to the water circulating through the BTES. The WSHP is the key to the energy efficiency and peak load reduction of the building heating and cooling system. In summer, the WSHP provides efficient building with cool water from the BTES instead of hot air in a conventional air-conditioning system (air cooled A/C or chiller). The combination of water as a heat transfer fluid instead of air, and the difference in temperature, can slash the peak hour cooling demand by 50% or greater. In winter, the WSHP extracts heat from the water circulating through the BTES instead of using natural gas (providing decarbonization of the building) or trying to extract building heat from the air when the demand for heat is highest and the air temperature is lowest (a major problem when ASHPs are used for on-demand heating). In winter, the combination of warm water versus cold air can result in peak electrical demand for the WSHP being only 25% of that required for the ASHP. There are multiple building

heating and cooling system designs that use different types of WSHPs, or that use the WSHP in different way, but all deliver the same basic benefit.

Figure 2 illustrates the overall concept of GABESS used for a cooling-dominant application.

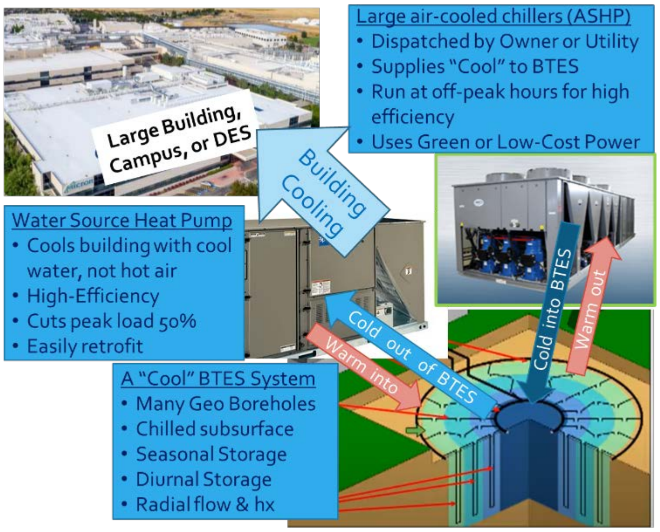

Figure 2: A conceptual GABESS system using, from upper right moving clockwise, an air-cooled chiller (ASHP) to charge the BTES using chilled water. A BTES array, with the boreholes arranged radially (image from Hammond, 2017). A WSHP which could be a one or multiple small unit(s) feeding single buildings or building zones in a District Energy System (DES), a large unit creating a chilled water loop, or other variations.

3. The Big Picture

GABESS is a mechanism which simultaneously:

- Reduces the number, and hence the total installed cost, of GHP borehole arrays.
    - Active ASHP replenishes the thermal energy available in the array to the WSHP and produces a greater annual dT from start to end of the heating/cooling season.
- Effectively and efficiently decarbonizing winter building heating.
    - GHP systems use less energy and have lower peak demand than ASHPs when ASHPs are used as the primary on-demand heating source.
- Provide the most energy efficient building heating and cooling possible.
    - Both annually and at peak hours, especially, GHP system are superior to ASHPs.
- Enables faster and greater use of low-carbon power generation via thermal storage
    - Excess variable (wind and solar) and 24/7 baseload (geothermal, nuclear, etc.) generation can be continuously stored as thermal energy for many days straight.
- Provides the lowest possible cost of a low-carbon grid.
    - The need and cost for electrochemical batteries and gas peaking units is slashed. Seasonal storage ability reduces shoulder-season clean power curtailments (costs).
- Serves as dispatchable load for the utility and provides grid ancillary services

  - The ASHP mostly separates “charging” from air temperature, so a utility can optimize the amount and duration of power used by the ASHP. The utility can provide ancillary services by when and how heavily the ASHP is loaded.
- Achieves >200% round trip electric energy storage efficiency (See Section 7).
  - Compared to batteries at 90% round trip efficiency.
- Increases grid resiliency and building climate resiliency.
  - Less power is needed for building heating/cooling, even with rising temperatures. Larger BTES can store more seasonal energy for longer.
- Eliminates the clean energy cost burden on low-income communities and countries.
  - It reduces energy costs for all users. The high density of many low-income communities improves the cost-effectiveness of District Energy Systems (DES) using GABESS.
- Provides an investment pathway for all utility types, including natural gas.
  - Delivering building energy using water in underground conduits is similar to what all regulated and municipal gas, water, and electric utilities already do. Thermal batteries, like electrochemical batteries, can be valid utility investments.
- Is a mechanism for high economic activity in every country.
  - No geothermal boreholes are imported. They are all made in country by skilled craft workers. Building heating and cooling systems are replaced and upgraded with craft labor, and most replacement systems will be manufactured in-country, creating additional jobs.
- Green energy investment and green energy jobs
  - It is easy to calculate the investment potential at billions of dollars a year. As a hypothetical example, 100,000 buildings per year at $10,000 per retrofit occurring in 50 states is $50 Billion dollars per year and could occur over several decades.
- Is efficient and applicable in every climate zone, whether heating or cooling dominant.

Traditionally, GHPs systems are viewed primarily as building efficiency devices which have a grid benefit which has seldom, if ever, been fully defined. However, GHPs when deployed at large scale, especially when coupled with BTES, are a grid energy and CO_2 management tool which lower the overall cost of electricity through building heating and cooling efficiency. Their value to the grid can and should be defined using conventional electric utility load planning tools. One example of grid cost reduction is that GHPs provide large reductions in peak demand at both the coldest and hottest hours of the day compared to ASHPs. Reducing peak demand reduces the need for very expensive Battery Energy Storage Systems (BESS) and/or gas peaking plants. Approaching all types of GHP system (including GABESS) as being primarily a utility asset is a critically needed change in both approach and perspective because the grid financial benefits are much greater than the building energy cost savings.

4. Review of Existing BTES Systems in North America and Comparison to GABESS

Two systems have been installed in the North America and have papers published about them. Other BTES systems have been installed in Europe, including some that use GHPs. (Kallesøe, 2019)

The Drake Landing BTES is located near Calgary, Alberta in Canada where the mid-winter average air temperature is about 20°F (-7°C) and the low is below -10°F (-23°C). It is a remarkable project because the 52 home DES collects solar thermal energy (heat not power) from rooftop flat-plate solar thermal collectors and delivers it to the BTES. Solar thermal energy is collected throughout the year, and whatever is not used for space heating (water heating is a separate system) is stored in the BTES. The system has been able to achieve the supply of up to 92% - 100% of the required annual space heating from stored and daily solar thermal collection. In the early part of winter, most of the building heating energy is delivered from the BTES and in the second half of winter, the majority of energy is delivered from daily solar thermal collection.

The Drake Landing project has been in operation since 2007, but no other project similar to it has ever been built. There are likely multiple reasons for the lack of replication, but some of the issues include the low cost of natural gas and the high cost of solar thermal collectors. Another important factor is that the BTES operates at high temperatures of up to 80 ℃ (180 °F), the losses to the cold ground are considerable. Most of the reported value of 55% energy loss from the solar thermal collection and storage system would be avoided by GABESS because the storage temperature is lower, and heat loss is proportional to the difference in temperature. Lastly, the Drake Landing BTES provides a huge decarbonization benefit, but it does not provide a grid benefit, and so there is no justification for utility financial support to enable widespread adoption. It should be noted that retrofit of such a system to existing building stock would be challenging if not impossible, while GABESS is highly applicable to retrofit using low-temperature heat pump DES.

A BTES array began operation in 2015 at a Marine Corps Base in Albany, Georgia in the United States to provide building cooling and heating as a retrofit to a large older building in an environment in which the average mid-summer temperature is about 83°F (28℃) and the peak summer temperature is above 95°F (35℃). This system uses a bank of fans pulling air through a large radiator to cool the water circulating through the BTES to charge the BTES with “cool”. Although the winter is not particularly cold, the radiators provided both seasonal storage and allowed the BTES array to be smaller by providing a way to remove heat from the array of boreholes. The BTES resulted in a >30% reduction in the number of boreholes required compared to a conventional GHP system. The designer of the Albany BTES system told the author that two other BTES arrays were installed at the same military base, but he has installed no others, nor was aware of any other system other than Drake Landing. (Hammock, 2020)

These two technically successful systems both face some economic viability challenges as a result of the source energy system that are employed to charge the BTES. The next two sections of the paper describe the benefits that would result from a GABESS using ASHPs to charge the BTES at the same two locations.

5. Example GABESS in Calgary, Alberta in Canada.

A GABESS to fill the same function as the solar thermal BTES at Drake Landing would operate at a lower temperature and would circulate water to the homes at lower temperature. Each home would have a WSHP which would extract heat (or cooling) from the water pipes. The water pipes themselves would be less expensive because of a) a cheaper plastic (HDPE) b) less insulation, and c) the potential to use a 1-pipe delivery system instead of the 2-pipe system.

From 2015 to 2017, the Drake Landing BTES operated with a maximum storage temperature of about 160°F (70℃) at the center in summer falling to about 105°F (40℃) in winter for a dT of about 55°F (30℃) through the year. At the outer boreholes, the temperature starts out at about 131°F (55℃) in summer, falling to about 90°F (32℃) in winter with a similar, with a 41°F (23℃) dT over the year. The overall dT of the borehole system from summer max to winter min is about 70 °F (47 ℃).

A WSHP operating across a wide variety of water temperatures can average about 25% of the heat from the electricity and the other 75% from the water, or a Coefficient of Performance (COP) of 4. Thus, the BTES must only supply 75% of the heat. Therefore, the 41°F dT for the outer borehole would only need to be about 30°F with GABESS, and assuming a desired end temperature above freezing of 40°F, means that the outer wellbore would only need to be at 71°F (27℃) in summer. The losses out the sides of the BTES are proportional to the dT to the undisturbed ground beyond the BTES. The annual average side loss dT would drop in the summer from over 90°F in summer to about 30 °F, effectively cutting losses by 66%. This would further lower the maximum required outside temperature that would have to be achieved at the end of summer. Using a similar approach, the center borehole temperature would only need to get to 70 °F + 30 °F = 100 °F (38 ℃). The losses out the top and bottom are more complicated to calculate but would be greatly reduced by the lower dT to the shallow ground affected by winter air temperature and undisturbed earth below the BTES.

Figure 3 graphs the annual average ambient drybulb temperatures in Calgary.

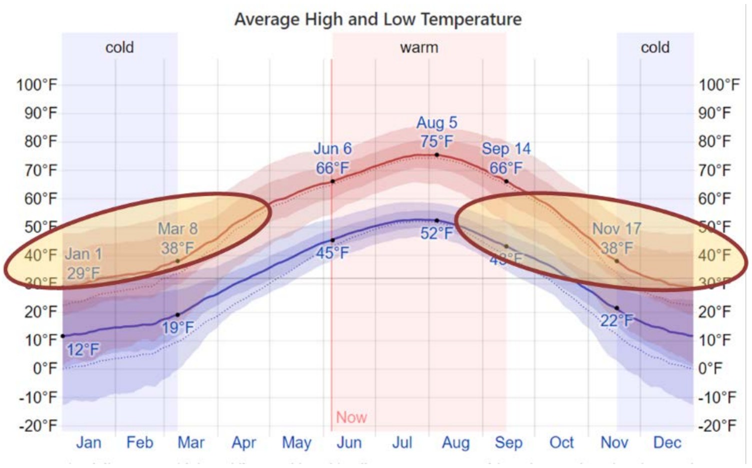

Figure 3: Calgary average high and low temperatures with shading for 25th/75th and 10th/90th percentile bands. The circles demonstrate that there are many hours available to charge the BTES using ASHP even in the winter, as well as through the entire fall period.

As the graph shows, from early May to early October, air temperatures are nearly continuously above 40°F (4℃), a temperature at which heat pumps work very effectively and daytime highs are generally above 50°F (10℃). Even in December and January, maximum air temperatures are commonly at temperatures that can allow high-performance cold weather ASHPs to extract heat with a high COP, and that heat would, by definition, be obtained when the electric load on the grid is at a winter minimum (i.e., warm daytime hours), thus flattening the electric load, which is a utility cost advantage that can be monetized via incentives or utility investment.

Another advantage of a GABESS system over the high temperature system at Drake Landing is that the same water pipes to each home can also be used to provide space cooling via the same building WSHP. It is reported that many homes have retrofitted air-conditions, so this would address that consumer need at much lower installed cost, and much lower summer peak electric demand.

Several hybrid GABESS systems would also be possible to integrate some of the goals of the Drake Landing original development. These include:

- Using a small number of solar thermal collectors to add heat to the BTES. Solar thermal collectors have greater capacity (collect more heat) the lower the temperature of the water that they are heating, so between the lower temperature and the reduced thermal losses, fewer collectors would be needed. They could also be used in conjunction with an ASHPs to reduce the cost of both pieces of equipment and be able to capitalize on a greater range of heat storage opportunities. A dedicated WSHP+collector is also viable.
- Solar electric panels (PV) could be used to operate the ASHPs and water pumps during daytime hours.
- Water source heat pumps could be used to provide domestic water heating from the same water pipe that connects all the buildings. Integrated units that provide space heating, space cooling, and water heating are commercially available. This would also save cost compared to the installed system at Drake Landing which is a stand-alone solar domestic water heater on each home.

6. Example GABESS in Albany, Georgia in the U.S.

A GABESS system could fill the same function as the fan-cooled BTES in Albany Georgia by replacing or supplementing the dry-cooler with an ASHP. The ASHP could deliver colder water to the BTES for more hours of the day during the summer, and the WSHP that serves the building would operate with a lower water temperature and a higher COP.

The exact operating points of the install dry-cooled BTES system are not detailed in the report, but a fan-cooled radiator (dry cooler) will have a return water temperature to the BTES higher than the dry-bulb temperature. Therefore, if the dry cooler runs in the summer, the temperature to the BTES can generally not be lower than about 80°F, based on June to August low temperatures and a 10°F approach. By contrast, an ASHP (chiller) could deliver water to the BTES at below 60°F at any hour of the day, lowering the overall temperature of the BTES and allowing colder water to be supplied to the WSHP(s) that are cooling the building. Detailed calculation on whether the overall electric consumption would be reduced have not been done, but the reduction in peak hour demand would be substantial. For example, a WSHP operating with an inlet water temperature of 60°F may only require half the power needed for an inlet water temperature of 85°F. Because peak summer power is the most expensive due to the use of either batteries and/or simple cycle gas turbines with the latter also being one of the most carbon intensive forms of power, the time shifting of electric use to improve peak hour efficiency can reduce both cost and CO2 emissions, even if it were to require more total power. The next section provides an example calculation.

The other advantage of a GABESS will be that it will reduce the size of the BTES. This is because greater diurnal temperature heat rejection can be achieved with the ASHP than with the dry cooler, and therefore not as many boreholes and not as much BTES total volume is needed. This reduces cost and improves economic viability.

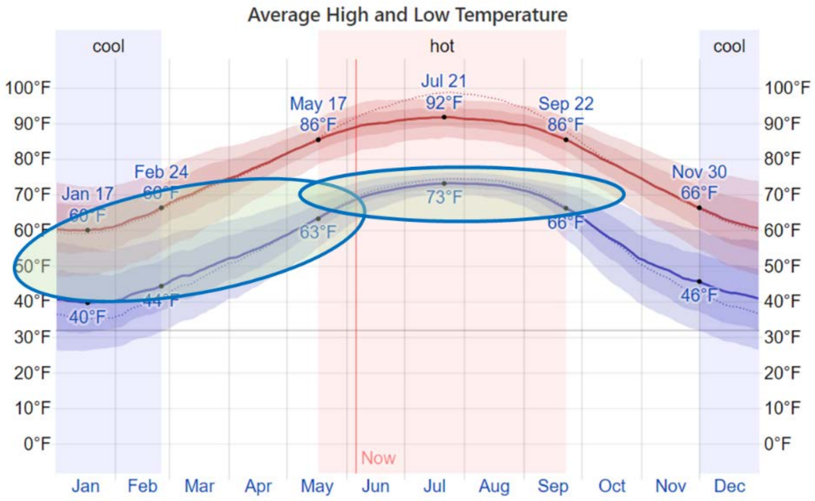

Figure 4: Albany Georgia average high and low temperatures with shading for 25th/75th and 10th/90th percentile bands. The circles show the extensive hours available in late winter and spring for charging the cold BTES, as well as the potential for diurnal charging at high ASHP COP.

Hybrid systems of GABESS with some of the design elements of the existing system could provide even better performance. For example, much smaller dry-coolers could provide BTES cooling when air temperatures are below about 50 °F, while the ASHP would provides BTES cooling whenever the temperature is between about 50°F and 75°F to maximize its efficiency. Because most daylight hours would have either the ASHP or the WSHP operating, or both, a small PV array sized to a portion of the demand of the ASHP would likely always be consumed on-site by some combination of equipment, further reducing CO_2 emissions from the operation of the ASHP. On-site PV would be a good approach for a GABESS in which the utility does not control the charging of the GABESS with the ASHP.

7. GABESS Can Provide Round Trip Efficiency of Greater than 200%.

Summer utility loads peak at the end of the daylight hours when air temperatures are high, and most buildings still have their normal cooling set point. As solar photovoltaic and wind generation increases, the value of electrochemical batteries (BESS) increases to store grid electricity and deliver it to meet peak demand. GABESS is a more effective “battery” than BESS and can have a roundtrip efficiency of >200%, compared to a BESS at 90% or less.

The purpose of a BESS for summer peak demand is to provide power for building cooling loads, which are what is driving the peak. The batteries are typically discharged near the hottest hours of the day, or shortly thereafter. This is when an air-cooled building cooling system is operating at its least efficient.

For the business-as-usual (BAU) case of air-cooled building cooling, assume that there are multiple buildings that together have a cooling load of 50 MW-th. Suppose the BAU air-cooled systems are operating at an average COP of 3.5 across the hottest hours. That means that the BESS must supply 50/3.5 = 14.3MWh/hr of electricity. To recover 14.3MWh of electricity at a 90% round trip efficiency means that a total of 15.9MWh must be generated and delivered at another time.

For GABESS we can assume that the water temperature to the WSHP is about 65°F resulting in a COP of about 8. Therefore, the electrical demand is 50/8 = 6.3MW resulting in a peak load reduction of 8MW and that is only 6.3/14.3 = 44% of the BAU case. This has enormous economic value to any electric utility. To calculate the load required to charge the BTES, assume that we can run the ASHP at half load to maximize its efficiency at a ratio of 2 hours of ASHP run time for every hour of WSHP run time. This can produce a storage COP of 17. So, to store the needed 50MW-th would require 50/17 = 2.9MWh, or perhaps 3.2MWh including losses. This time shifted the energy needed for building cooling and built load during off-peak hours, both of which are valuable to the utility.

Battery efficiency at the point of use (POU) can be defined as energy not generated at the POU divided by energy stored. The BESS delivered14.3MWh of electricity to the POU which was therefore "not generated" at that hour, while 15.9MWh of electricity was stored for a round trip efficiency of 90%. Applying this same definition to the GABESS, 14.3-6.3MW = 8 MW of electricity was not consumed (generated) at the POU compared to the BAU case. 3.2MW were used to "charge" the GABESS. Therefore 8/3.2 = 250% round trip efficiency at the POU. The actual efficiency may not be this high because of differences in COPs and the pump power need but will still easily be greater than 200%. This provides huge value from the electric grid operator's perspective, in addition to the 1-44% = 56% reduction in actual peak hour demand.

Furthermore, as utility peak load management tools are deployed, the remaining peak duration increases. While this is an economic problem for BESS, it is a non-issue for GABESS which delivers cooling load reduction across every hour of cooling demand.

Most BESS systems are currently sized for 4 hours and have a capital cost as given in Figure 5.

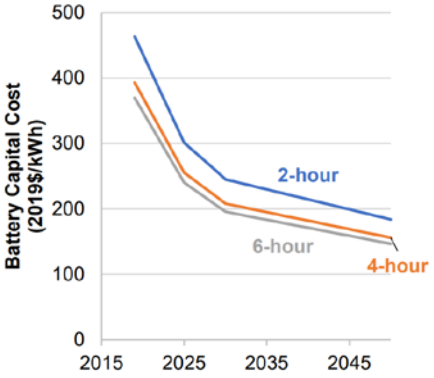

Figure 5: Battery Capital Cost without operating cost or the cost of energy to charge the BESS (Cole 2020)

The complex interaction of large-scale GABESS deployment on the long-term asset mix and cost of grid operation are beyond the scope of this paper and can only really be calculated by use of utility grid asset modeling software, technically called grid expansion modeling.

8. How to Model GABESS in Utility Power Planning Models

In utility grid asset modeling, new proposed systems must be large enough to make a measurable change in the grid performance characteristics. Thus, to measure the value of GABESS it needs to be modeled as a cumulative grid-scale asset, not as a single system for a building or group of buildings. The size must be large enough to displace other existing and potential assets. A likely representative approach would be to assume the equivalent of 10,000 to 100,000 residential buildings a year are converted, after an initial startup period.

The actual building mix will be some combination of residential, commercial, and some industrial loads. However, the load required by 10,000 residential buildings with an average peak load of 5 tons (17.5 kW-th) of heating or cooling at an average COP of 4 would be 4.4 kW electrical demand, or a 44MW block of grid planning demand. This would be a good size block and achievable in most small states. In larger more populace states, like Texas, California, New York, Illinois, Pennsylvania, etc. Blocks of 80 – 150MW per year may be more appropriate and would still be easily achievable.

GABESS will be challenging to model because it affects so many elements of a grid asset model. However, there is existing work that can be used to quickly approximate the characteristics of GABESS which can then be used in grid asset planning software to help assess the financial value and operational impact.

There is a large body of work on how ASHPs affect utility grid loading which can be modified as a first order GABESS approximation. Summer ASHP impact is already modeled for the efficiency improvement of a new ASHP on summer total energy use and demand. ASHPs in the very coldest hour of the winter peak are somewhere between very low efficiency (COP of less than 2) and simple straight electric resistance heat (COP = 1). GABESS modeling could make use of these studies to model the impact of GABESS using a few simplifying assumptions, based on physics. GHPs in general, and GABESS in particular, can be modeled as having a COP of 4 (1 unit electricity, 4 units of heat). This can be compared to the COP of ASHPs based on air temperature. Thus, at the winter peak, GHP systems will reduce peak demand by about 75% compared to ASHPs operating at a COP of 1 for strip heat. For most of the cold weather periods (for example January and February), a reduction of 50% could be appropriate reflecting an average ASHP COP of 2. For spring and fall heating conditions, a zero to 25% reduction could be used based on air temperatures which could have the ASHP operating at a COP of 3 to 4.

Summer changes can be similarly modeled. At peak summer hours, air temperatures are at a maximum and air-cooled building cooling systems efficiency is greatly reduced. GHP and GABESS systems are water-cooled which provides both the benefit of lower temperature and using water instead of air to remove the heat from the refrigeration equipment. The net result is that at peak hour, GHP system typically run with about half the power requirement of air-cooled systems cutting peak demand by roughly 50%. During the daily on-peak period of about 8 hours, the cooler water temperatures compared to hotter air temperatures are still going to provide about a 25% or greater reduction in total energy use.

One option for modeling would be to use these first-order winter and summer load estimates to shape a grid asset which is represented as negative load and would help quantify the full grid value of these reductions in key high-load intervals.

An analysis of grid avoided costs over multiple decades can be performed in which the grid model takes up these blocks of negative load and re-optimizes the grid assets to minimize grid cost. Then a comparison to the grid model “base case” is made (one without the GABESS blocks). The changes are quantified and the value of the addition of the GABESS blocks is calculated which includes changes in the required grid assets (e.g., a reduction in capital cost if fewer BESS are installed), changes in asset operations (if less natural gas or coal is required to be burned), whether transmission line additions can be avoided, and how much less grid CO_2 is emitted from coal and gas power plants. The calculation of the value of CO_2 not emitted from converted fossil fuel building heating systems is another value that must be captured but will usually not be obtained from the grid asset model. However, if it has been calculated as part of an ASHP electrification study, then the value would be the same.

The evaluation of avoided-costs over a 20-year time frame is a valuable technique for evaluating GHP systems including GABESS because it helps identify the value to the grid of GHP technology. From that value, the incentives and/or utility investments can be justified. Utility investment can be an important tool for achieving decarbonization. Utilities can only invest in projects that benefit all ratepayers. Thus, if a GABESS or GHP system is evaluated as a building energy cost reduction alone, not all ratepayers benefit, so incentives are hard to justify. But if that same system is shown to reduce future grid capital and operating costs, then it benefits all ratepayers and so justifies utility capital investment or incentives. It also justifies recovering that investment from all ratepayers through their electric rates, instead of from the building owner alone.

The approach of extrapolating GHP system performance compared to ASHP is a simple method for evaluating the cost benefits of load changes for hour-by-hour heating and cooling of buildings. But it does not inform the impact, costs, and benefits from the charging of the GABESS. There are three elements to this part of the evaluation, the first is the GABESS charging strategy, the second is how the preferred generation mix of the grid changes, and the third is arbitrage (buy low, sell high).

BESS are a relatively new grid asset the modeling of which utilities are just beginning to master. They are hard to model in part because of the number of variables: How large in capacity; How large in Energy; When and how much to charge and discharge at what times; How to capture the financial value of the grid ancillary services; etc. GABESS has all these same challenges and more. The GABESS size is ultimately set by the need of the building (or the buildings of a DES), but there are a range of conditions that make the GABESS performance variable. For example, with less diurnal chilling of a GABESS it will operate at a higher temperature, resulting in a larger peak load, but less charging energy. Conversely, doing extra diurnal chilling will cut peak load further. The best operating mode one week may be different than another week. Hypothetically a grid facing calm, cloudy, mildly hot weeks may find it is better to use the former operating mode (minimal night cooling), but on weeks with record hot temperatures, it may be best to use the latter method (maximum night cooling), potentially even if the charging energy is derived from a coal plant, in order to build reserve margin by lowering upcoming peak hour demand with a colder GABESS. This latter example demonstrates that GABESS provides the grid operator a discretionary tool to increase weather-related grid reliability when deemed valuable to do so. As such, GABESS can also be a quantifiable grid planning margin asset.

GABESS provides the ability for continuous storage of excess power generation over days, weeks, or even months. Consequently, this GHP technology can enable greater deployment of low-CO_2 power, including solar, wind, nuclear, and geothermal. All of these are characteristically of lower value in spring and fall because grid electric demand is low.

GABESS addresses that challenge and builds grid value instead of incurring grid costs from curtailments.

Arbitrage by storing low-priced power from off-system is a 3rd benefit of GABESS charging. In the case of GABESS, the arbitrage is not from reselling the stored power at a higher price, but from not needing to self-generate or import expensive on-peak power. By reducing peak demand, a utility may also be able to sell their own excess peak power generation excess capacity and/or energy.

Mechanically, GABESS in charging mode is simply motors that can be started/stopped almost instantly and operated across a range of load levels. For the most part, the building comfort levels controls the discharge mode of GABESS, but the charging mode may be best controlled by the electric utility. And in such cases, the GABESS provides several grid ancillary services. A large installed base of GABESS allows the utility to use the charging mode to provide frequency control by varying the load, which could include ramp-up (as the sun rises) and ramp-down (as wind velocities slow, even on a minute-to-minute basis). Large quantities of GABESS can be started and stopped in less than a minute, effectively providing spinning reserve. Lastly, the variable speed motors are driven by power electronics which have a power factor of 1. This is generally beneficial at the distribution level although not technically a grid ancillary service.

9. Alternative BTES Arrangements

To date, BTES borehole arrangements are simple vertical loops, they are arranged in a purely radial manner, and all of the boreholes are the same depth. All of these could be examined for opportunities for optimization. Furthermore, this paper has focused on large systems for either large buildings/campuses or DES, but single home GABESS is also potentially viable.

Thermal losses from BTES arrays are a recognized problem. The use of GHPs in the GABESS reduces those losses because the temperature of the BTES is closer to the undisturbed ground temperature, but the losses will still be a concern. Several ways to drill and complete the boreholes could be evaluated to reduce losses:

- By drilling the boreholes that are farther from the center to greater depths, the heat/cold losses from inner boreholes will be captured by the outer boreholes. The ideal depth versus radial distance will be an optimization that depends on borehole spacing, conductivity, BTES temperature, and other factors. This approach reduces bottom losses.
- Like the idea of deeper outer boreholes, using a non-conductive grout in the upper few feet of the BTES boreholes (especially those in the center) would reduce thermal losses out the top by preventing heat transfer from the upper plastic pipes of the borehole.
- Drilled boreholes are typically vertical because they are cheaper, and that is what is most advantageous, thermally, for traditional GHP systems. For GABESS, it is likely that drilling either angled boreholes toward the center or drilling vertical wells with a deviation in the lower half to take the outer boreholes under one or more of the inner boreholes, would reduce bottom losses.
- BTES designs place insulation between the top of the boreholes and the ground surface to reduce top losses. But since GHPs are being used, it would also be possible to capture those losses instead by using “slinky” type heat exchange to change the ground temperature above the BTES, either above or below the insulation layer.

- An entirely different arrangement would be suitable for locations with minimal available surface area and could combine many of the above ideas as well. This arrangement would be a BTES with angled boreholes drilled down and outward from a compact surface footprint. The boreholes on the outside would be deeper. Those on the inside would be both shallower and completed with non-conductive grout at the top of the boreholes. A trench-type slinky around the outside of the wellbores would contain and minimize shallow losses.
- Another challenge for a BTES is the slow rate at which the ground can absorb the energy during charging. Drake Landing used a tank to extend solar thermal charging past daytime hours. Alternatively, the upper portion of the boreholes could be used the same way by incorporating water volumes or especially with phase change materials that would change temperature more quickly than the ground, thus allowing higher rates of energy storage and recovery over shorter periods of time. This might be of particular value in a utility-controlled arbitrage charging scheme.

The arrangement of boreholes in a radial manner is effective for thermal energy efficiency design, but if the greatest value driver is the grid, then other arrangements may be preferred. This could also be true for very large BTES systems in which the radius is too large for a single radial run of connected boreholes.

- An outer ring of wellbores could be connected as a conventional GHP to cut losses from the side of the BTES dramatically. This could also be used to provide the small amount of cooling in a strongly heating dominant service, or heating in a strongly cooling dominant one.
- The center of the BTES provides the coldest or hottest return water to the building. It is conceivable to use the center of the BTES only for maximum peak load management by changing the connection of the boreholes to each other. For example, if the very center of a cold-storage BTES was frozen and chilled below the freezing point, it could be used to provide 42°F (5°C) water used in many commercial building cooling systems without a compressor, taking the peak hour load close to zero. A very hot center BTES could be used in a similar way to provide heating for fan coils.
- Other ways of breaking the BTES into different zones could also be useful from a grid management perspective, especially for very large BTES arrays. There are many possible combinations, and the intent is not to describe every permutation, but rather to show that this idea exists and can be optimized depending on the location. For example, suppose a BTES is built with an inner radial flow zone, and an outer radial flow ring, which surrounds the inner zone, like a donut. During peak hours, the BTES would be operated with the inner ring which would be maintained colder by the diurnal and seasonal storage. During off-peak hours, the outer ring would provide the cooling. Because the outer ring will deliver warmer water, it will require more grid power, but that power is worth less. Partial arc arrangements may be able to serve similar functionality.

GABESS can also provide a way to significantly cut the cost of single-building GHP systems, including single family residential while creating dispatchable distributed grid assets. Four-to-six ton (15-21 kw-th) GHP compressors are a common size for homes in the US. The rule of thumb is often reported that about one vertical borehole is needed for each ton of space conditioning. It is the cost of the four to six vertical wellbores that is such a barrier to GHP deployment at the residential level. This is also the type of building layout where DES are difficult to justify because of the wide separation between energy consumers. Because GABESS can provide active thermal energy management of the borehole temperatures, fewer boreholes would be required. A simple 1-ton split unit heat pump could provide the grid energy storage to a smaller bore field. A 1-ton split heat pump with very high COPs in both heating and cooling can be found on-line for under $1000, including the indoor air handler unit. A refrigerant to water heat exchanger would be far cheaper than the indoor air handler unit and provide an even higher COP for the overall unit. Utilities already have signaling technologies to prevent an A/C unit from turning on for load management. That same technology could be used to signal the split unit to store energy. Such a simple arrangement of existing technology could provide huge grid cost and CO_2 benefit to a utility and to the ratepayers as a whole, and therefore justify economic incentives for their installation.

10. Deep Decarbonization Problem Summary

Deep decarbonization of global energy for building heating and cooling faces at least 8 major problems:

1) Planned decarbonization of building heating increases electric load and generally exacerbates the mismatch between solar and wind generation and load. For example, peak residential heating load occurs in the early morning before the sun is up, and often when wind velocities are minimal.
2) Air Source Heat Pumps (ASHP) are the generally discussed mechanism for electrification of building heat, but in numerous studies they create a larger, even massive, winter peak, even in regions that would otherwise be summer peaking. This is because as air temperature drops, three effects occur. i) The building needs more heat. ii) The ASHP produces less building heat for every kwh of electricity it consumes. iii) The capacity of the ASHP drops requiring larger heat pumps and eventually most ASHP switch to straight electric resistance heating.
3) ASHPs operate the same as normal air conditioners, and so must work against the hot air temperatures of summer.
4) There can be no fundamental change in the way energy is used because of the laws of physics. There is simply little energy available for building heat in very cold winter air, and all air-cooled refrigeration equipment (chillers) use more power as air temperatures increase.
5) Replacement of highly dispatchable fossil-fired power plants is required for CO_2 reduction with those that are not well-suited to load following, including solar, wind, geothermal, and nuclear. The first two are variable generation over diurnal and seasonal patterns, the latter two are best operated at full output in every hour to minimize their delivered energy cost ($/MWh). The problem is that grid load does not match either pattern, and so there must either be curtailments (cost inefficiencies) or storage (capex increase).
6) Meeting the winter peak and the summer peak with ASHP demands very expensive time shifting of electric generation and delivery (i.e., storage). Combined with the limits imposed by physics, ASHPs must inevitably drive-up the overall cost of the power delivery system as well as the monthly energy costs for buildings. This disproportionately affects the less wealthy whether they are individuals or countries, thus creating both social justice and economic barrier to deployment and so to deep decarbonization of global energy use.

7) Storage for even 4 hours is extremely expensive and projected to remain so at over \$200/MWh for the uncharged battery alone. See Figure 5. (NREL 2020) No economically viable widely available storage mechanism exists for storage longer than a few hours. A technically viable long-term (i.e., seasonal) power-to-power storage mechanism is yet unproven.
8) Replacement of gas heating with electric heating eliminates the need for each nation's natural gas utilities. As this happens, the cost of service grows exponentially for the remaining customers to recover the cost of the installed assets, creating a so-called "death spiral" of increasing costs. Beyond the cost increases suffered by those of lower economic standing in society, there will be political pressures to adopt hydrogen as a replacement fuel because there does not currently seem to be another investment option for natural gas utilities. It seems unlikely that any corporation will quietly accept a low-carbon future that results in the corporation minimal long-term future earning potential.

These barriers are not a complete list but illustrate the magnitude of the problem that must be addressed for the decarbonization of building heating and cooling.

11. Deep Decarbonization with GABESS Solution Summary

The problems named above are all addressed by GHPs in general. GHP systems incorporating thermal storage via the GHP boreholes (GABESS) turn many of the problems into benefits and help accelerate decarbonization because the more buildings that are converted, the lower the cost of power can go. When GHPs and/or GABESS are the basis of a District Energy System (DES) the benefits can be even larger. With ASHPs, the discussion is about the societal cost to decarbonize buildings, including increasing the cost of power on the grid to do so. GHPs, and especially GABESS changes the discussion to how grid cost are decreased, and the financial benefits can be returned to building owners as financial incentives to convert or participate in a DES. The problems in the previous section are addressed as follows:

1) GHP's operate against the ground temperature, which is cooler in summer and warmer in winter, especially compared to the peak hours in those two seasons. Thus, GHPs reduce both the total amount of electricity required over the heating and cooling seasons and especially cut the peak demand. This lowers the cost of providing electricity overall.
2) Storing excess grid energy in the geothermal borehole system reduces the number (cost) of boreholes because the boreholes operate at a more favorable temperature through active temperature management. As a result, it also increases the efficiency of the GHP system (less power for the same heating or cooling effect). Long-term (seasonal) energy storage for both heating and cooling in BTES systems has already been demonstrated as technically viable for multi-month storage.
3) Building heating and cooling energy use is fundamentally changed and reduced by taking advantage of time-shifting and physics to heat when it is not cold and to cool when it is not hot as well as to use water as a heat transfer mechanism instead of air.
4) Because seasonal storage is possible, all low-carbon power generation technologies can be deployed at their maximum beneficial operating point because the GHP BTES provides a mechanism for continuously storing heating or cooling energy without the need of expensive batteries. Furthermore, the ability to store off peak energy continuously on a seasonal basis enables greater and faster deployment of low-carbon power sources.

5) The electric power levels and durations used to create the BTES hot or cold storage can be controlled by the utility to maximize benefits which can change between low-cost power, high storage efficiency, excess green power, or managing coming peak demand periods to increase weather related resiliency and planning margin.
6) GABESS dispatchability allows the utility to use the GABESS as an ancillary services technology enabling ramping in both directions or as “spinning reserve” that can either come on-line or drop off over a matter of seconds.
7) Whether for large facilities, individual homes, or DES, the basic principle is to deliver energy to the building via underground pipes. That is the exact business model of natural gas utilities. The only change is from delivering flammable methane to a burner tip to delivering cool to warm liquid water in a closed-loop for use in a heat pump. In short, GHPs provide a pathway for natural gas utilities to participate in a low-carbon future while providing ratebase capital investment for shareholders and expertise for reliable energy infrastructure.
8) The conversion to low-carbon building heating and cooling is accomplished with a reduction in grid cost, which provides both environmental and social justice for communities and nations with lower economic means because it provides an affordable path to decarbonization.

12. Conclusion

GABESS is an evolution of existing ideas about using BTES to achieve cost and CO_2 reductions compared to other building heating and cooling technologies, including conventional GHPs. It is an approach which uses only proven and widely available technology. At this point, no operating systems have been built, and none are in active development beyond early-stage discussion. GABESS is a grid-focused approach, and its largest economic value will be derived and must be monetized from the grid benefit that it provides to the grid and its many electric ratepayers. It is a technology that can provide grid benefits in any climate with any mix of generation technologies and can provide that benefit to small and large stand-alone buildings as well as to groups of buildings via District Energy Systems.

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