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A Life Cycle Cost Analysis of Large-scale Thermal Energy Storage Technologies for Buildings using Combined Heat and Power

Kenneth Gaine
Dublin Institute of Technology, ken.gaine@dit.ie

Aidan Duffy
Dublin Institute of Technology, aidan.duffy@dit.ie

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K. Gaine, A. Duffy
Kenneth.Gaine@Student.Dit.ie
Aidan.Duffy@Dit.ie
Phone: 00 353 1 402 3934

Department of Civil and Building Services, School of Civil and Structural Engineering, Dublin Institute of Technology, Bolton Street, Dublin 1.

Abstract

Buildings account for approximately 40% of energy consumption and greenhouse gas (GHG) emissions in developed economies, of which approximately 55% of building energy use is for heating and cooling. The reduction of building-related GHG emissions is a high international policy priority. For this reason and because there are many technical solutions for this, these polices should involve significant improvements in the uptake of small-scale energy efficient (EE) systems.

However the widespread deployment of many technologies, must overcome a number of barriers, one of which is a temporal (diurnal or seasonal) mismatch between supply and demand. For example, in office applications, peak combined heat and power (CHP) thermal output may coincide with peak electrical demand in the late morning or afternoon, whereas heating is required early in the morning. For this reason, cost-effective thermal storage solutions have the potential to improve financial performance, while simultaneously reducing associated GHG emissions.

The aim of this paper is to identify existing thermal energy storage (TES) technologies and to present and asses the economic and technical performance of each for a typical large scale mixed development. Technologies identified include: Borehole Thermal Energy Storage (BTES); Aquifer Thermal Energy Storage (ATES); Pitt Thermal Energy Storage (PTES) and Energy Piles. Of these the most appropriate for large scale storage were BTES and ATES because of the site area required. A heat transfer analysis and system simulation of a variety of BTES system is carried out using Finite Element Analysis package (ANSYS) and energy balance simulation software (TRNSYS) to determine the optimal system technology and design. Financial models for each system are developed, which includes capital, installation, running, maintenance costs and losses. The costs of energy recovered from the storage area are estimated. It was found that a deep BTES was not suitable for daily storage and that a medium depth of 50 meters was the most feasible with running costs of €0.055 per kWh.

Keywords: Thermal energy storage; Combined heat and power; Life cycle cost; Borehole.

1 Introduction

A reduction in carbon emissions and lower running costs for buildings are a worldwide concern with many government policies implementing schemes to bring emissions and costs to a lower level. Groups such as the International Energy Agency (IEA) or the Intergovernmental Panel On Climate Change (IPCC) provide information leading to potential policies which have a high priority in many global energy supply initiatives which will involve significant increases in the uptake of small-scale energy efficient (EE). One such technology is known as Thermal Energy Storage (TES). This technology solves a problem, common to most other RES systems whereby it acts as a buffer between the mismatch in supply and demand of energy.

One of the disadvantages to any EE system is that it increases the initial capital cost of the building. However by increasing the energy efficient technologies in a building, the running costs over the life of the system are expected to decrease when compared to a more conventional non EE system thus justifying a higher initial cost. Capital costs can be decreased by integrating the building design and EE system to lower the loads of the system, hence reducing the capacity of the building services system.

The aim of this paper is to assess the technical and financial performance of the most appropriate TES system technology for a large scale commercial mixed use building using CHP. Site conditions are estimated and the TES system is examined under a number of deigns and loads.

2 Literature review

A TES system stores thermal energy which can be used at a later time; the thermal energy may be either be in the form of heat (at a higher temperature than the surrounding environment) or as coolth (at a lower temperature). The most common types of TES are diurnal systems which are used to store heat- usually during the night - so that it can be used during the day. An example of such system is a hot water cylinder in the home. This system takes one day to complete a cycle. The TES system can be designed to work on an annual or seasonal cycle also. However in order to store the energy needed to meet a seasonal load, a large volume is required. In a Seasonal Thermal Energy system (STES), waste heat from the building or, waste heat from industrial process and/or energy from solar gains during the summer are sent to the storage facility via a heat exchange system and stored there to be released in the winter. Also, after the heat is removed from the storage volume, it is now cooled and can be used for cooling during the summer. STES systems are usually underground, so that they can store the large amount of energy needed for heating or cooling for the year. These are known as Underground Thermal Energy Storage (UTES) systems.

2.1 TES Technologies

For large scale TES systems for buildings, UTES systems are preferred for a number of reasons:

- Valuable floor area is not needed;
- The ground is able to hold energy relatively constant all year round compared to other systems such as above ground tanks; and
- They are usually unobtrusive.

UTES systems can be classified into two types depending on the site conditions: Aquifer thermal energy storage (ATES); or Borehole thermal energy storage (BTES) system.

2.1.1 Aquifer Thermal Energy Storage (ATES)

An aquifer is a porous rock, clay or gravel that is usually deep below the surface, can hold or store water and allow water to be abstracted from it (Boyle). An ATES system transfers heat to and from the aquifer by means of manmade wells. The system uses two wells, an injection and extraction, or hot and cold well. The heat stored in the groundwater is extracted from the aquifer through the well and passed through a heat exchanger, for use in the building. The extracted groundwater is cooled during the process and is then sent back to the aquifer via the other well. This is known as an open loop or ‘pump and dump’ system. The excess heat from the building can be stored in the aquifer for the desired time. This raises the groundwater temperature of the aquifer and hence means less energy and fuels are used in the production of the heat in the winter.(David W.Bridger and Diana M.Allen 2005). Aquifers are typically 25% water and the larger the storage area, the larger the capacity and more economical it becomes. ATES systems have been used for projects ranging in thermal power from 50kW to 10,000kW and usually store at temperatures ranging from 10 ºc – 40 ºc. When storing higher temperatures, thermal losses through the bedrock, the sides and the top soil become significant. For high temperature storage, above 100 degrees Celsius, deeper wells of over 200 m are needed in order to reduce heat losses. This has a significant impact on the cost of the project and needs to be examined closely.

An example of an ATES system used for heating and cooling is used in Malmo, Sweden. The purpose of this system is to deliver free cooling for a district cooling system at a temperature of 6 degrees Celsius. The system uses 5 warm and 5 cold wells at a depth of 70 to 80 meters. In the aquifer, cold from the nearby sea and waste cold produced from the heat pump is stored from the winter to the summer. The system was installed in 2000 and has been successful, delivering 1300kW and a total of 3,900 MWh per year.

2.1.2 Borehole Thermal Energy Storage (BTES)

A BTES system is a closed loop type where many closely spaced vertical boreholes are placed usually 50-200 meters below the ground. The storage medium in this method is the ground itself, as opposed to the aquifer where it uses the flowing groundwater. A single U-Shape pipe in each borehole is installed in the ground and a fluid is pumped through the pipe to absorb or realise its energy to/from the ground. The pipes act as a large heat exchanger with the earth. (Pahud 2002). By having numerous boreholes over a large area, significant thermal energy storage is possible, however when one borehole is used, it is only suitable for heating or cooling on a small scale. Once the borehole is complete and the pipe is installed, the hole is then backfilled with a suitable high thermal conductivity grouting material such as water, sand or clay. This helps the heat transfer between the pipe and the earth.

The desirable ground characteristics for BTES are:

- a high specific heat and thermal conductivity value; and
- a low ground water flow rate

An example of a BTES is used for a district heating and cooling system in Canada. The Drake landing borehole field uses 144 boreholes of 150mm in diameter and 35 meters deep where installed as part of a district heating and cooling system. This BTES system is used to store heat at temperatures of up to 80ºC from solar.

3 Methodology

The uptake in EE systems are often hampered by a high capital cost but offer the user the potential of lower operating costs. To show if the potential lower operating costs are benificial, a life cycle cost ananlysis is used to determine if the EE system is economical. A thermal energy model was established to idenify the associated costs. The system chosen was a BTES system used store waste heat from a CHP machine to be used on a daily basis. The model comprised of two parts: to determine the heat transfer rate to the storage area under specific site conditions; and a second to simualate the thermal storage model over a number of years. The results from these tests where used to build a financial model showing the capital needed and estimate the running costs of each system.

3.1 Operating conditions/building services design.

Large scale-mixed developments often have a simultaneous heating and cooling load as well as a 24hr electrical load. This electrical load is met by the CHP. During the day time operation of the system, waste heat from the CHP is used to power an absorption chiller to provide the cooling load directly to the building via a chilled beam circuit. During the night, the waste heat is sent to the BTES area and a heat pump is used to control the temperature and compensate for losses. Operating conditions were obtained from case studies presented by (Gao 2008) and Pre-design guide (Hellstrom 2004). A building integrated CHP cooling circuit typically works on a 90°C/70°C circuit. The outlet 90°C water from the CHP is sent to the storage area every night from 8PM until the 8AM the following morning. This heat raises the ground temperature where it can be used on a daily or seasonal basis for heating. This model focuses on a daily storage design. The heating is met by using a chilled Beam circuit which operates at on a 40°C/60°C. Cool water enters the BTES system at a temperature of 40°C during the day where it absorbs the energy that was sent there the night previously by the CHP. The water returns close to 60°C to be used in the heating circuit. The heat pump is used to raise the temperature to the 60°C needed.

3.2 Numerical analsyses

The first analysis set up was to determine the average heat transfer rate using a FEA (Finite Element Analysis) package ANSYS. FEA models by (Lee and Lam 2008) have presented the various design tools and numerical models which have been developed. A single borehole with a single U-tube pipe was modeled using three dimensional implicit finite difference method under the site conditions and using operating conditions from design guides. The soil conditions used in the analysis are shown in table 1. Case studies (Paksoy 2007) show that the average depth used in BTES range from 20 to 250 meters. Three models where made using borehole depths of 20, 50 and 200 meters. 3D grids measuring 5 meter * 5 meter * (30meter, 70meter, 220meter) were made with single borehole drilled in the centre to the required depth. Space below the below the borehole was made to model the heat flow from all areas of the pipe. Specific inlet temperatures and flow rates shown in Table 2 were inputted into the analyses to simulate a 12 hour period. The outlet temperature and average soil temperature where recorded. Details of the analysis are shown in table 2 and the heat transfer rate to the storage volume was established under the site conditions.

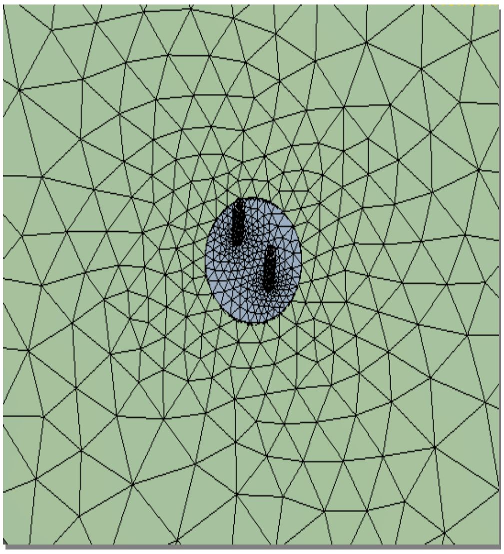

Figure 1: Total view of the borehole mesh.

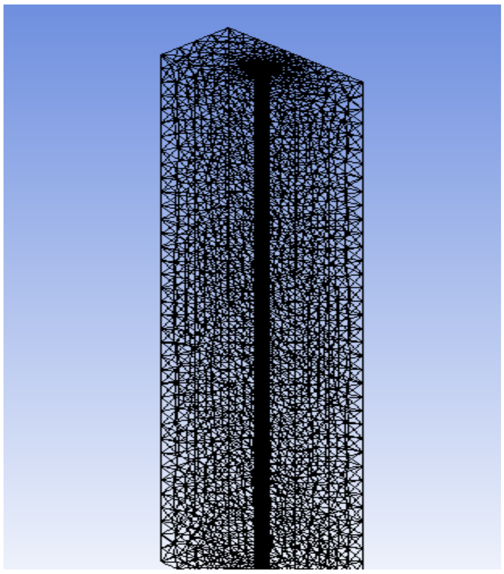

Figure 2: Close up view of the inlet and outlet of the borehole.

3.3 Thermal energy balance

A second simulation carried out for a number of different borehole quantities, depths, capacities and times. This was done using the Duct Storage Model (DST) model on TRNSYS version 16 as recommended in the Pre-design guide for thermal energy storage(Hellstrom 2004). This is a transient simulation package which has been developed over the last 35 years and has been presented in design guides. Flow rates and temperatures entering the system are assumed constant. The model is used to show the outlet temperature of the borehole field and the average ground temperature. Initial conditions of the ground are shown in table 1 and the following assumptions where made:

- The Soil mixture within the TES area is homogeneous and isotropic;
- The Specific heat and thermal conductivity of the storage medium are constant; and
- Groundwater flow is neglected.

Each system was modeled in 1000kWh increments of storing 1,000 kWh to 10,000kWh under the same operating conditions. The numbers of boreholes needed to store the given quantities of energy were determined numerically based on the average heat transfer rate from the results of the FEA analyses above.

Table 1: Soil Conditions

Soil Thermal Conductivity $W\ m^{-1}\ K^{-1}$	Soil Density $kg\ m^{-3}$	Soil Specific heat Capacity $J\ kg^{-1}\ K^{-1}$
1.8	1600	2200

Table 2: Analyses settings

Parameters	Values	Parameters	Values
Borehole diameter	0.08m	Average Heat transfer rate	109 wm^{-2}
Outer radius of Pipe	0.03m	Soil temperature end of year 1	59.75°c
Inner radius of Pipe	0.025m	Soil temperature end of year 5	61.2°c
Inlet temperature - charging	90°c	Soil temperature end of year 10	61.3°c
Inlet temperature – discharging	40°c	Soil temperature end of year 20	61.3°c
Inlet flow rate	0.3 $m^{-3}hr^{-1}$		
Storage volume	Various	Outlet temperature charging	57.3°c
Time period	12 hours	Outlet temperature discharging	54.2°c
Time step	0.02s		
Convergence - max/min iterations	100 / 20	Node qty	220,000

3.4 Financial model

A Life cycle cost (LCC) analyses of a project is used to determine if there is a future operational savings which will justify the initial capital cost.(Kneifel 2009). The capital and operating costs of a number of different BTES systems were therefore estimated for a large-scale mixed development, assumed cash flows determined and net present values (NPV) determined. Costing data was gathered from Irish boring and groundwork contractors for the installation.

3.4.1 Capital costs:

These are costs that are incurred at the initial stages of the project. They are the highest and biggest barrier to any EE system. For a BTES the capital costs include some of the following:

- Site investigation and testing;
- Design;
- Site preparation and set up;
- Drilling;
- Pipe work installation;

- Backfilling the borehole;
- Header and piping to energy supply centre; and
- Commissioning.

The total of these add up to give the capital costs associated with the BTES system. Industry quotations, rates and estimates were obtained and were applied to each system analysed. Piping from the borehole headers to the energy centre have been accounted for based on an average pipe length of 75 meters. Labor rates used are based on industry quotations and

3.4.2 Running costs.

These are the costs that are associated to with the day to day operation of the plant. For the BTES system, electrical energy is needed for pumping power to deliver and recover energy from the storage area. The pumping power required was calculated by obtaining the total equivalent length of pipe and calculated pressure drop in each system. An average industrial tariff for electricity of €0.12 per kWh in Ireland has been used to calculate the total running costs for the pumps. A fixed costs for maintaining the system included repairs, cleaning and controls. The controls of these systems are the highest cost associated with maintenance.

4 Results and discussion

The thermal energy model was simulated for different system configurations. It was observed that the average ground temperature rises from an initial value of 12 °C to approximately 60 °C after 18 months of operation due the night time charging and the outlet temperature from the day time operation was raised to approximately 60°C. From using the waste heat available, nearly 100% of the daily heating load was achieved. Based on a 20 year operation, the heating load can be achieved for approximately €0.055 per kWh.

4.1 Thermal energy balance results

Figure 2 shows the outlet temperature in red from the borehole field and the average soil temperature over a 20 year period in blue. The outlet temperature ranges from 57°c to 63°c daily as the inlet temperature changes from the 90°c input from the waste heat output from the CHP to 40°c input from the chilled beam heating circuit.

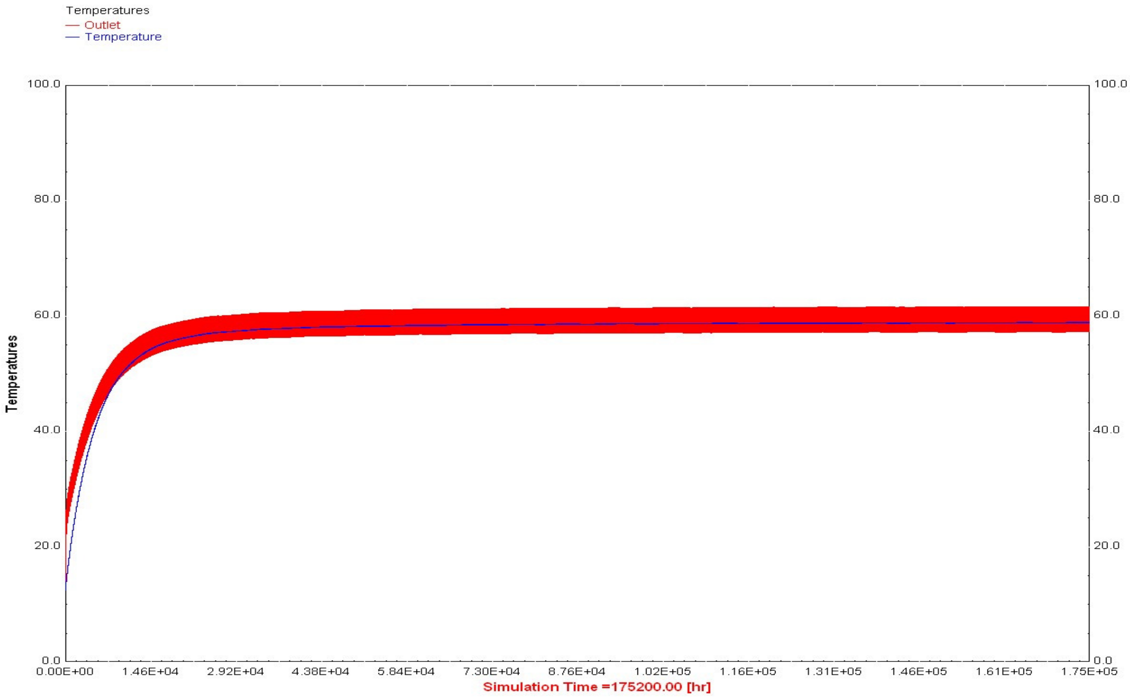

Figure 1: 20 year operation of 100no. 20 meter boreholes

Figure 3 and 4 shows the ground temperature and the outlet temperature of the 200 and 50 meter deep borehole configuration. It can be seen that the ground temperature has not risen to the 60°C needed for the heating circuit in the 200 meter system. Additional 'top up' boilers are therefore required resulting in extra heating costs. The shallow and medium system display similar results. Depending on the site area, for example, a large two or three story development may the ground area for the shallow system but a development in a more urban environment may benefit from the deeper system due to the high cost of ground area.

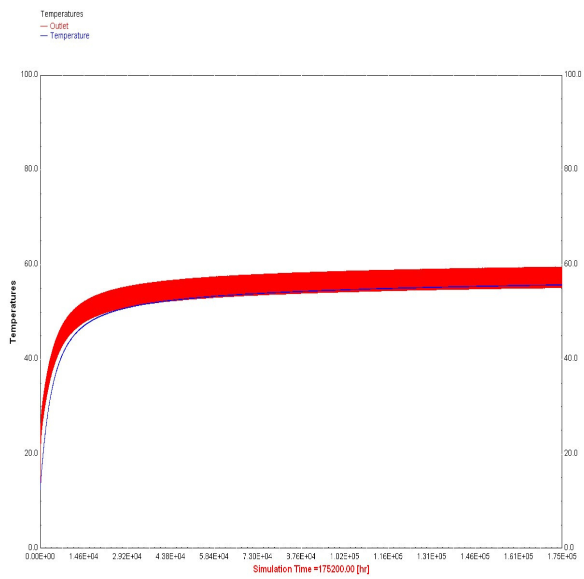

Figure 3: 20 year operation of 10no. 200 meter deep boreholes

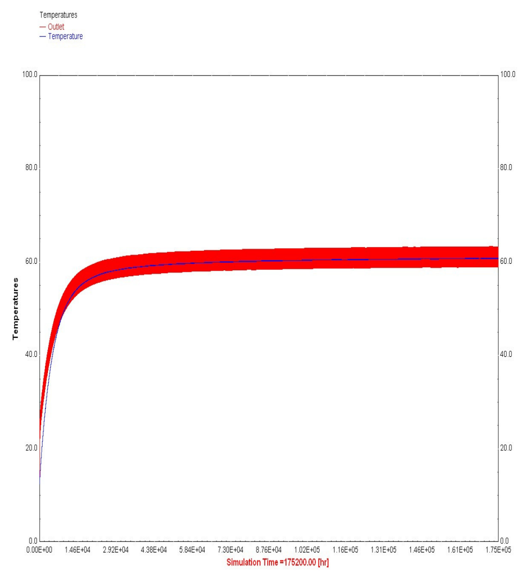

Figure 2: 20 year operation of 40no. 50 meter deep boreholes

4.2 LCC costs

Figure 5 is shows three different cost curves (€/kWh of stored energy) recovered from the storage area. It shows that for low quantities of energy stored, deep borehole systems are considerably more expensive than the shallow systems. This is due to its thermal performance and is not able to reach the needed ground temperature resulting in additional heating costs. But, above 4000kWh, 200 meter becomes prefarable to the shallow system.

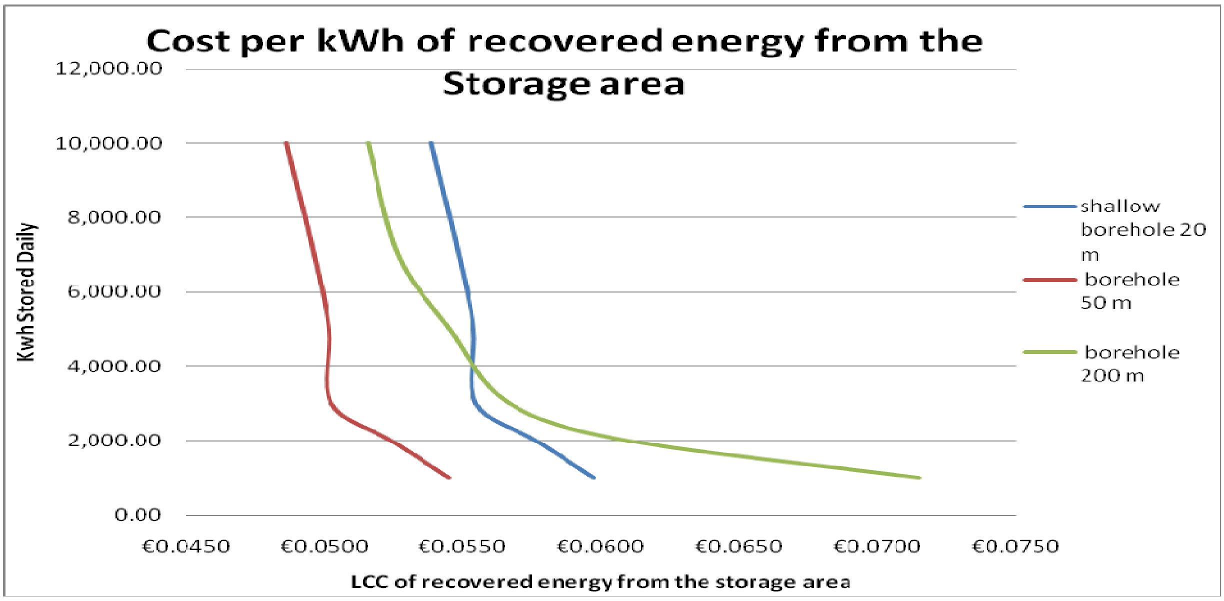

Figure 4: LCC of 20 year period per kWh of recovered energy from the storage area

5 Conclusion

Three different configurations of a BTES system have been examined to determine the LCC of recovering stored energy. Initial findings show that the deep BTES system has the highest LCC for small systems and becomes more favorable when storing large amounts. This was due to higher losses, a lower rate of heat transfer which resulted in additional costs to further raise water temperature. The medium system had the lowest LCC in all cases. The shallow system had higher installation costs mainly due to more pipe work installation to and from the energy centre and a larger ground area required.

This paper deals with various arrangements of the BTES system. Further analysis is being carried out to include ATES and energy piles. In addition to the extra systems, a seasonal analysis is being carried out on all systems. Worldwide costing data is also being gathered.

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