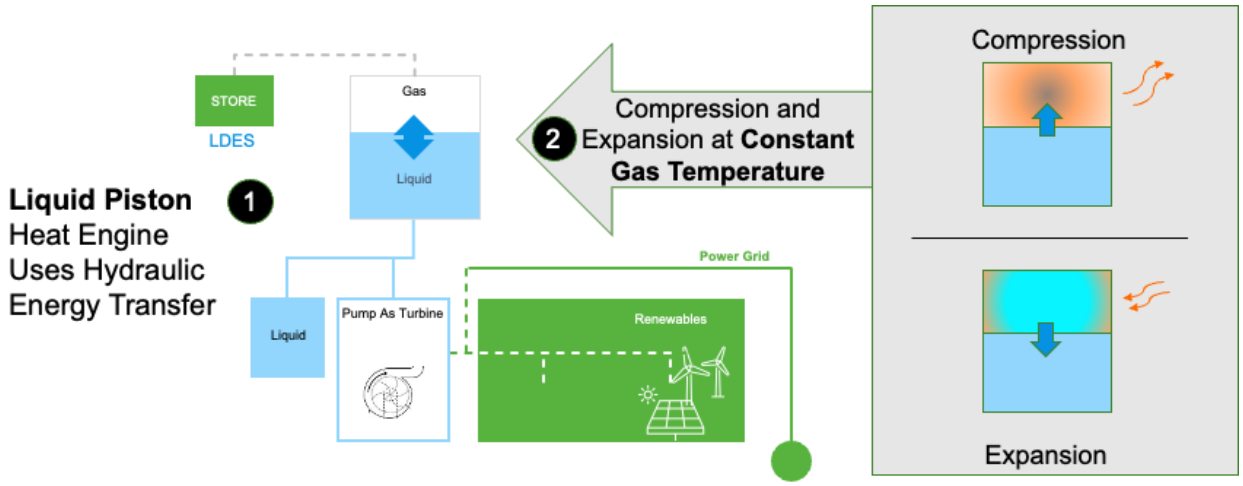
Inherent Benefits of Liquid Piston Relative to Mechanical Piston for Isothermal Compression

In order to understand the advantages of liquid pistons for gas compression it is first important to clarify the rationale for isothermal compression as it relates to storing energy as compressed gas potential energy, and to efficiency in general. True isothermal compression and expansion represents the most efficient means of transferring shaft work into potential energy of the gas[1]. At first glance this may seem counterintuitive to those familiar with the first law of thermodynamics that states that internal energy of a system changes in direct relation to the work that is done on or by the system, and the heat transfer in or out of the system[2]. If heat is transferred out of the compression device this would appear as a loss of energy. The key to understanding this is to properly define the system boundaries when considering the first law. As long as the heat energy can be transferred back and forth into the compression/expansion process at the rate needed to maintain the temperature, the thermodynamic system is actually the compression vessel, the storage vessel and the atmosphere itself all together. The heat is not transferred out of the system, it remains within to be recovered.



Essentially we are using the atmosphere as an infinite sink to avoid putting energy into raising the temperature of the gas and thereby reducing the burden on the incoming energy to counteract the pressure rise associated with temperature increase. Importantly though, we are also using it as an infinite heat source during expansion. To the extent that we approach this

[1] Investigation of a compressed air energy storage system:Flow and heat transfer numerical modeling in a liquid piston
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[2] Experimental investigation of internal air flow during slow piston compression into isothermal compressed air energy storage
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theoretical maximum by minimizing temperature rise, we will approach this most efficient process[3].
Theoretically, if the process were adiabatic (no heat transfer from the compression vessel) instead of isothermal and the increase in temperature was able to be retained indefinitely, there would be no advantage as the heat energy would be available to recover along with the potential energy. In practicality, this heat will escape the system through the storage vessel over time and the total energy of the stored compressed gas will decrease accordingly[4]. The energy we put in will not all be there when we need it back. In this adiabatic case, the system is defined as the compression vessel and the storage vessel, because the heat that escapes during storage cannot be recovered quickly and therefore remains outside of the system. Without the ability to compress and expand isothermally, heat must be stored and reintroduced or added in the form of fossil fuels. Storing low grade heat for very long is quite challenging and therefore limits the duration of storage.

The liquid piston is important to this isothermality for several reasons and has some additional contributions to efficiency that we will discuss subsequently. The favorable geometry for a pressure vessel that comprises the compression chamber in terms of heat transfer is a long thin tube because the surface area to volume of contained gas is maximized and so the ability of the vessel to transfer heat to ambient through the vessel walls is maximized[5]. The practical ability to perform compression in a long thin tube with a mechanical piston is realistically limited to single digit L/D ratios. Additionally, the speed of the advancing piston has an effect on heat transfer rate both in terms of time for heat transfer and in terms of impact on gas flows which in turn affect the ability of the gas to transfer heat to the tube wall[6]. The piston speed in a liquid piston can be much slower than a mechanical piston that must cycle rapidly through its short travel, and it can be varied by controlling the liquid pump delivery rate during the cycle. The unique conformal nature of a liquid piston also permits variations in the cross section of the compression vessel which can be exploited to enhance heat transfer via induced air

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[3] Review on Liquid Piston technology for compressed air energy storage
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turbulence[7]. The liquid provides a secondary benefit as an additional heat transfer path from the liquid/gas interface and through the tube walls as well.

In addition to the contribution of liquid pistons to isothermal compression, there are other advantages. A liquid piston does not have the sliding friction that a mechanical piston requires for sealing, nor does it bypass gas through a sealing surface[8]. It is, however, susceptible to dissolution of the gas into the liquid which is affected by many variables such as temperature, pressure and miscibility of the two fluids…though there are methods to mitigate this. The final contribution of the liquid piston to the overall efficiency of the process is the inherently more efficient process of pressurizing a liquid in a pump relative to pressurizing a gas with a conventional compressor. The higher density of a liquid permits more of the motor work to be imparted to the liquid and also makes the sealing task easier.

Liquid piston technology has been around since at least 1906[9] and was used in some Stirling cycle applications as well, but is not commonly found today. The resurgence in interest in this technology is being driven by its application to compressed air energy storage which is deemed to be one of the few long duration storage approaches that is viable at a large scale[10] and which has been in existence since the early 20th century[11]. It has been demonstrated that liquid piston technology produces a 19% efficiency gain[12] over traditional gas compression and many forms of enhancement have been tested and quantified. Round trip efficiencies have been shown to increase to 70%[13], removing one of the constraints to large scale deployment. Two compressed air storage plants have been in operation for many years and the basic principles and

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effectiveness are well understood[14]. The liquid piston and near isothermal compression process now provide a path to adoption just as global demand for storage accelerates.

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