Supplementary information: A low-temperature glide cycle for pumped thermal energy storage

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This document presents a summary of the cost correlations employed in the calculation of the marginal energy cost (section 1) and marginal power cost (section 2) of the glide PTES system. Many of the correlations employed in section 2 were gathered from the work by McTigue *et al.* [1], which presents a techno-economic analysis of PTES with liquid stores. However, the original reference of each correlation is displayed in the corresponding tables.

1. CALCULATION OF MARGINAL ENERGY COST

The marginal energy cost is computed by adding the cost of the three or six tanks/pits, for single and double tank configurations respectively, plus water and insulation.

Each tank has a volume $V = m/\rho$, where the mass of water m depends on the specified energy storage capacity of the plant. The purchased equipment cost of the tanks can then be computed with correlations as a function of volume for each tank, compiled in Table 1. While their accuracy is limited to about ± 25%, these correlations still provide useful estimates. Steel tanks are made of carbon steel and are of the floating roof type, used when the vapour pressure of the stored liquid can cause substantial evaporation, which is the case here given the high temperature of the water. Several correlations are available and combined into an average value with standard deviation. The table also includes pits and concrete tanks. An additional multiplier of 1.4 [2] is applied to the tank correlations to obtain their installed cost. The pit cost equations already include installation costs. All of the equations have been updated to 2018 according to section 3.

Table 1. Correlations for installed costs of tanks and pits

Type	Purchasing cost functions ($, updated to 2018)	Volume (m^3)
Steel [3]	$12,586 \cdot V^{0.51}$	140-4,500
Steel [4]	$1.4 \cdot 10^{6.1385-0.7585 \log V+0.1749(\log V)^2}$	1,000-40,000
Steel [5]	$8,282 \cdot V^{0.55}$	50-8,000
Steel [6]	$11,255 \cdot V^{0.5018}$	750-2,650
Steel [6]	$3,013 \cdot V^{0.669}$	2,650-60,00
Concrete [2]	$1.4 \cdot \exp(9.44086 - 0.121103 \ln V + 0.04536(\ln V)^2)$	80-42,000
Pit [7]	$1.51 \cdot 10^6 + 41V$	10,000-500,000

The cost of water is estimated at 0.002 $/kg [8], low enough that any uncertainty in this value should not noticeably change the overall energy cost. The cylindrical tanks' aspect ratio is $H = 2R$, to minimise heat losses to the environment. They are insulated with a layer of glass wool, at a price of $c_{ins} = 3.6$ $/kg, with a density of $\rho_{ins} = 24$ kg/m^3 and thermal conductivity $\lambda_{ins} = 0.038$ W/m.K [9], [10], [11]. Setting an allowable fractional heat loss of $f = 1\%$ per day and given the aspect ratio of the tanks, the cost of insulation is

$$C = (c\rho\lambda)_{ins} \frac{8\pi R}{f(c_p\rho)_{\text{water}}} \tag{1}$$

2. CALCULATION OF MARGINAL POWER COST

The marginal power cost of the plant is constituted by the cost of the compressor, turbine, pump, motor-generator set and heat exchangers. The correlations employed are shown in Tables 2 to 6, respectively. Their year of publication is also listed, so that the CECI (see section 3) can subsequently be applied to update them to a 2018 basis.

Table 2. Compressor cost

Equation	Units	Year	Ref.
$250\ \dot{W}$	kW	2018	[12]
$\frac{1.051\times 39.5\dot{m}\beta\ln\beta}{0.92-\eta}$	kg/s	1995	[13], [14]
$\frac{1.051\times 39.5\dot{m}\beta\ln\beta}{0.92-\eta}\left(\frac{\rho_{in}}{\rho_0}\right)$	kg/s	1995	[14], [15]
$\frac{1.051\times 39.5\dot{m}\beta\ln\beta}{0.92-\eta}\left(1+\exp\left(0.01T_{out}-10\right)\right)$	kg/s, K	1995	[14]

Table 3. Turbine cost

Equation	Units	Year	Ref.
$1100\dot{W}^{0.81}$	hp	2009	[16]
$\frac{1.051\times 266\dot{m}\ln\beta}{0.92-\eta}\left(1+\exp\left(0.018T_{in}-1.207\times 26.4\right)\right)$	kg/s, K	1995	[14]
$\frac{1.051\times 266\dot{m}\ln\beta}{0.92-\eta}\left(1+\exp\left(0.018T_{in}-1.207\times 26.4\right)\right)\left(\frac{\rho_{out}}{\rho_0}\right)$	kg/s, K	1995	[14], [15]

Table 4. Cost of centrifugal pump, including motor

Equation	Units	Year	Ref.
$2,409.6+75.9\dot{W}$	kW	1998	[17]
$1,227.5+177.8\dot{W}$	kW	1990	[18]
$50,000+1,500\dot{W}^{0.8}$	kW	2009	[19]

Table 5. Cost of motor-generator set

Component	Equation	Units	Year	Ref.
Motor-generator	$5,000+110\dot{W}$	kW	2009	[19]
Generator	$40\dot{W}^{0.67}$	W	2017	[20]
Motor	$30\dot{W}^{0.7}$	W	2017	[20]

Table 6. Cost of carbon steel heat exchangers. The condenser cost was originally in euros but converted to US dollars by a factor of 1.33 for 2014.

Component	Equation	Units	Year	Ref.
Plate	$635.14A^{0.778}$	m^2	1986	[21]
Plate	$5000+450A^{0.82}$	m^2	2009	[19]
Air-cooled condenser	$705,000(A/3563)^{0.9}$	m^2	2014	[22]

3. CHEMICAL ENGINEERING COST INDICES

Table 7. Chemical Engineering Cost Indices [1]

Year	Index	Year	Index	Year	Index	Year	Index
1947	64.8	1965	104.2	1983	317.0	2001	394.3
1948	70.2	1966	107.2	1984	322.6	2002	395.6
1949	71.4	1967	109.7	1985	325.3	2003	402.0
1950	73.9	1968	113.7	1986	318.3	2004	444.2
1951	80.4	1969	119.0	1987	323.7	2005	468.2
1952	81.3	1970	125.7	1988	342.4	2006	499.6
1953	84.7	1971	132.2	1989	355.5	2007	525.4
1954	86.1	1972	137.2	1990	357.6	2008	575.4
1955	88.3	1973	144.1	1991	361.3	2009	521.9
1956	93.9	1974	165.4	1992	358.2	2010	550.8
1957	98.5	1975	182.3	1993	359.2	2011	585.7
1958	99.7	1976	192.0	1994	368.1	2012	584.6
1959	101.8	1977	204.1	1995	381.1	2013	567.3
1960	102.0	1978	218.8	1996	381.7	2014	576.1
1961	101.5	1979	238.7	1997	386.5	2015	556.8
1962	102.0	1980	261.1	1998	389.5	2016	541.7
1963	102.4	1981	297.0	1999	390.6	2017	567.5
1964	103.3	1982	314.0	2000	394.1	2018	603.1

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