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HYDROSTOR
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Attachment DA2.0-1: A-CAES – Historical Operational Data Summary

This memo has been prepared in response to California Energy Commission Staff's data adequacy recommendation in the technical area of Reliability, Appendix B(h)(3)(B)(v), and provides a summary of historical operational data for the Advanced Compressed Air Energy Storage (A-CAES) technology. As explained below, there is significant, demonstrable operational experience and history in all of the primary project elements, in addition to the included operational data from Hydrostor's commercial A-CAES facility in Ontario, Canada.

Hydrostor's Goderich (Ontario, Canada) Operations Data:

Hydrostor's Goderich A-CAES Facility is the world's first commercially contracted Advanced Compressed Air Energy Storage (A-CAES) facility. The plant is contracted by Ontario's Independent Electricity System Operator (IESO) for peaking capacity, ancillary services, and full participation in the merchant energy market to support grid reliability. While Goderich is relatively small, this achievement is a utility-scale commercial application of A-CAES technology that conforms to all interconnection, uptime, performance, and dispatch standards as set out by the IESO. Coupled with the proven delivery and supply chain for all A-CAES systems, the Goderich A-CAES Facility demonstrates the operational performance of the adiabatic process and the ability of A-CAES technology to fully participate in and deliver a range of valuable grid services to electricity markets.

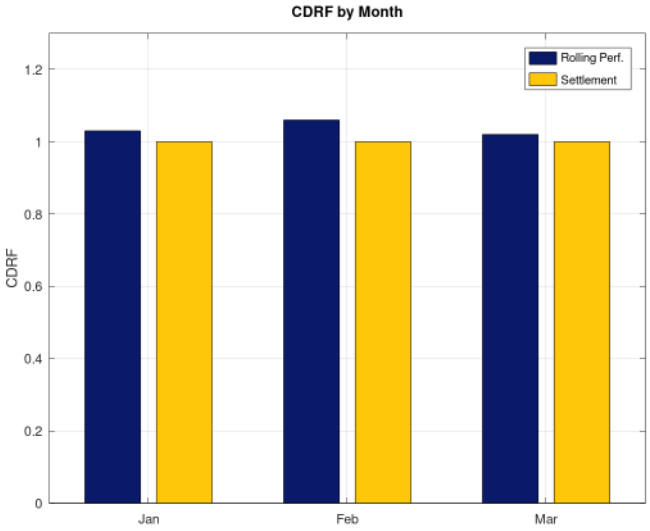
In its operational history, the project has cycled hundreds of times and is meeting its technical performance objectives, including receiving the maximum allowable score on the primary technical performance test with IESO. One performance objective for the Facility is measured by the Capacity Check Test (CCT), which is determined following a pre-defined test protocol. The CCT requires the facility to discharge for no more than four hours (Initial Discharge), recharge for no more than 8 hours, and then discharge again for no more than four hours (Secondary Discharge). The result is then the minimum of four scores. The facility was tested on June 25, 2020 where it achieved results exceeding the maximum allowable score, and therefore the maximum allowable score was assigned as the facility capacity: 1.75 MW. Table 1 presents the achieved scores. which were verified by the IESO and an Independent Engineer.

Table 1. Verified results from CCT test on June 25, 2020

Item	Description	Max under contract	Achieved Score
Initial Discharge Output	The full energy output over the four hours, divided by four hours	1.75 MW	1.773 MW; Passed
Allowable Recharge	The greatest energy consumption over any four hour consecutive period within the eight hour recharge window, divided by four hours.	1.75 MW	2.213 MW; Passed
Second Discharge Output	The full energy output over the four hours, divided by four hours	1.75 MW	1.765 MW; Passed

Worst Hour Output	The output for the single worst hour of output in the second discharge window, divided by 0.9.	1.75 MW	1.958 MW; Passed

The Cycling Deficiency Reduction Factor (CDRF) is the key reliability metric for Goderich. The CDRF effectively functions as a monthly performance indicator that provides a measure of how frequently the facility cycles when power market conditions indicate a storage asset ought to be cycled. It can be calculated continuously, but is settled at the end of the month using the real market conditions for that month. For example, in January 2021, the power market cost analysis indicated that a storage asset should have cycled 20 times, and the facility completed 20.4 full cycles, resulting in a CDRF of 1.02. The current CDRF value is monitored continuously by the operations team and energy managers to maintain a CDRF at or above 1.0. The plot on the right shows typical performance on this key contract parameter for some representative months, and clearly demonstrates that the facility is cycling the expected number of times in each month. Normally, this is about 20-22 times per month.



Operational Experience and History of Primary Project Elements

A-CAES utilizes standard equipment that has been rigorously deployed in a variety of other applications and industries (e.g. pipeline compressors and let-down stations) and is supplied exclusively by Tier 1 original equipment manufacturers (e.g. Baker Hughes, a global leading supplier of core equipment and an invested corporate partner on delivery of Hydrostor's systems). In addition, capital investments for A-CAES compares favorably per kWh when compared with other storage technologies. This is in part due to the combination of the well-established expertise and supply chains of the mining sector, and those of proven, bankable, industry-standard generating and process equipment which offer a compelling solution at scale.

Hydrostor's A-CAES technology has been specifically designed to rely only on a well-proven, reliable supply chain and the use of standard industrial equipment/construction approaches. A-CAES is based conceptually on the same basic design and process as traditional CAES with its multi-decade operating history. In addition, A-CAES technology incorporates two key improvements allowing it to be emissions-free and flexibly-sited: 1) the development of a proprietary thermal storage system that eliminates the need for a fuel source, and 2) the construction of

hydrostatically compensated, hard rock air storage caverns. Each of these also has operational precedent.

A-CAES air storage caverns – historical operations information:

The reliability of hydrostatically compensated air storage caverns in hard rock was independently assessed by experts who concluded that a mature design, construction, and operational environment were key components for below-ground hydrocarbon storage caverns in use today. Hydrostor's A-CAES cavern sizes and operational parameters are consistent with the sizes and operating parameters of hydrocarbon storage caverns in use today, and contain those same key components. This provides an abundance of real-world experience upon which to base the A-CAES cavern design, and to use in managing and mitigating subsurface issues as they are identified during development, site selection, and construction. In addition, approximately 200 hard rock storage caverns exist globally, storing hydrocarbons – the design and construction of which is directly analogous to air storage caverns. An enclosed document (*Enc. A. - Storage Cavern List.pdf*) provides reference data on 190 of these caverns.

Primary Process Equipment (Compressors, Turbines) – historical operations information:

All of the primary process equipment utilized in Hydrostor's A-CAES technology uses standard frame-size compressors or turbines, for which there are many decades of performance history across thousands of applications. Hydrostor's A-CAES design proposes mature and commercially available rotating and static equipment technologies. These mature equipment technologies have been employed successfully in a variety of industrial applications worldwide and have significant operating history. In addition, the technologies support the implementation of parallel trains to enable a scalable plant size in increments of 100 MW with low levels of design and supply risk. Technical details regarding these established equipment are provided below:

- Compressors:
  - The compressors of this scale are commonly used in the air separation industry.
- Turbines:
  - The turbines used in A-CAES are those commonly used in steam power production applications. Each of the vendors consulted has confirmed the suitability of the use of their steam-oriented equipment for the air application. There are thousands of steam turbine examples installed around the world.

A-CAES thermal storage – historical operations information

Hydrostor's thermal storage system uses conventional equipment with strong track records of safe and effective operations around the world. The core of the thermal storage system is the shell and tube style heat exchangers, millions of which are installed and in-use globally, operating in a predictable and safe manner. The thermal fluid (water in this case) is kept in storage tanks that also have significant precedent for reliable and safe operations. See, *Enc. B - IO - Spherical Tank Review.pdf* and *McDermott brochure for the hortonsphere at the hyperlink provided here:*

https://www.mcdermott.com/getmedia/3e01d2b7-392b-40fa-88ef-4c82fde83149/hortonsphere-2020-digital.pdf.aspx

Enclosures

Storage Cavern List

HYDROSTOR

Country	Area	Title	Storage type	Stored products	Detail	Working Volume (m^3)	Qty Caverns	Cavern Depth	P mean (bar)	Water Curtain	Cavern Access	Construction Cost (U/G)	Construction Duration (years)	General Contractor	Owner Operator	Contracting Strategy	GK Involved
AUSTRALIA			Mined cavern	Liquefied hydrocarbons	Propane	135 000	1	127	6.4	Y	SHAFT		5	WALTER CONTRUCTION GROUP			Y
BELGIUM	FLEMISH	ANTWERPEN	Mined cavern	Liquefied hydrocarbons	Butane; Propane	10 700	2			N	SHAFT				DISTRIGAS		
CANADA	ONTARIO	DOW HCSD	Mined cavern	Liquefied hydrocarbons	Butane; Ethylene; Propane; Propylene	667 800	10			Y					DOW CHEMICAL CANADA LTD		
CHINA	SHANDONG	HUANG DONG	Mined cavern	Liquid hydrocarbons	Crude oil		1			Y	DECLINE						
CHINA			Mined cavern	Liquefied hydrocarbons	Butane; Propane	520 000	2	65; 125	1.2; 7	Y	DECLINE	$ 22 500 000.00	5	CHIYODA/NCC		EPC	Y
CHINA			Mined cavern	Liquid hydrocarbons	Crude oil	150 000	2			Y	DECLINE		3	RAILWAY BUREAU			Y
CHINA			Mined cavern	Liquefied hydrocarbons	Butane; Propane	250 000	2	111; 142		Y	DECLINE		3	RAILWAY BUREAU			Y
CHINA			Mined cavern	Liquefied hydrocarbons	Butane; Propane	229 000	2	55; 115	2; 7.5	Y	DECLINE	$ 19 000 000.00	3	LGEN		EPC	Y
CHINA	GUANDONG	ZHUHAI	Mined cavern	Liquefied hydrocarbons	Butane, Propane	370 000	1			N	DECLINE			PB	BP		
CHINA			Mined cavern	Liquefied hydrocarbons	Propane; Butane; Mixed LPG	570 000	3	128		Y	DECLINE		3	CREC			Y
CHINA			Mined cavern	Liquid hydrocarbons	Crude Oil	3 000 000	4	72-98		Y	DECLINE			RAILWAY BUREAU			Y
CHINA			Mined cavern	Liquid hydrocarbons	Crude Oil	3 000 000	3			Y	DECLINE			RAILWAY BUREAU			Y
CZECH REPUBLIC	CENTRAL BOHEMIA	HAJE PRIBRAM	Mined cavern	Natural gas	Natural gas	600 000	5			Y	SHAFT		2		CPP/TRANSGAS		
FINLAND	EGENTLIGA	KERNI	Mined cavern	Liquid hydrocarbons	Diesel oil		3			N					STATE		
FINLAND	KYMI	KOTKA	Mined cavern	Liquid hydrocarbons	Crude oil		2			N					SHELL FINLAND		
FINLAND	SOUTH WEST FINLAND	NAANTALI	Mined cavern	Liquid hydrocarbons	Crude oil	253 400	2			N					NESTE OY		
FINLAND	PIRKANMAA	NOKIA	Mined cavern	Liquid hydrocarbons			2			N							
FINLAND	NORTH OSTROBOTHNIA	OULU	Mined cavern	Liquid hydrocarbons	Gasoline	17 000	2			N					KEMIRA OY		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquid hydrocarbons	Diesel oil		14			N					NESTE OY		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquefied hydrocarbons	Butane	116 290	1			Y					NESTE OY		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquefied hydrocarbons	Propane	300 000	3			Y					NESTE GAS		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquid hydrocarbons	Crude oil	3 350 000	13			N					NESTE OY		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquid hydrocarbons	Light Fuel oil	1 360 000	5			N					NESTE OY		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquid hydrocarbons	Light Condensate	105 000	1			N					NESTE OY		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquefied hydrocarbons	Butane	163 000	1	100		Y	DECLINE				BOREALIS POLYMERS		
FINLAND	UUSIMAA	PORVOO	Mined cavern	Liquid hydrocarbons	Heavy Fuel Oil	410 000	2			N					NESTE OY		
FINLAND	SATAKUNTA	RAUMA	Mined cavern	Liquid hydrocarbons	Diesel oil	200 000	2	43		N	DECLINE				TEBOIL		
FINLAND	HELSINKI	SALMISAARI	Mined cavern	Liquid hydrocarbons	Diesel oil		6			N					STATE		
FINLAND	HELSINKI	SALMISAARI	Mined cavern	Liquid hydrocarbons	Fuel oil	200 000	3			N					STATE		
FINLAND	LAPLAND	TORNIO	Mined cavern	Liquefied hydrocarbons	Propane	83 000				Y					NESTE OY		
FINLAND	SAVONIA	VARKAUS	Mined cavern	Liquid hydrocarbons	Diesel oil		6			N					STATE		
FRANCE			Mined cavern	Liquefied hydrocarbons	Propane	80 000	1	112	6	Y	SHAFT		4				Y
FRANCE			Mined cavern	Liquefied hydrocarbons	Propane	130 000	1	132	7.3	N	DECLINE		4				Y
FRANCE			Mined cavern	Liquefied hydrocarbons	Butane; Propane	306 000	3	100; 65	6; 1.7	Y	DECLINE	3 688 000.00 €	4	SAINRAPT/SKANSKA		RATES CONTRACT	Y
FRANCE			Mined cavern	Liquefied hydrocarbons	Propane	98 000	1	142	5.5	Y	SHAFT	16 100 000.00 €	4	FOUGEROLLES BALLOT		RATES CONTRACT	Y
FRANCE			Mined cavern	Liquefied hydrocarbons	Butane; Propane	64 000	2			N	SHAFT			F&S			Y
FRANCE			Mined cavern	Liquefied hydrocarbons	Propane	8 000	1	143	6.5	N	SHAFT	3 501 000.00 €	4	PASCAL			Y
INDIA			Mined cavern	Liquefied hydrocarbons	Propane	127 600	1	162	5	Y	SHAFT		4	L&T		EPC	Y
INDIA			Mined cavern	Liquid hydrocarbons	Crude Oil	2 000 000	2	50-110		Y	DECLINE	$ 180 000 000.00		SKEC/KCT		EPC	Y
INDIA			Mined cavern	Liquid hydrocarbons	Crude Oil	2 500 000	2			Y	DECLINE	$ 250 000 000.00		SKEC/HCC		EPC	Y
INDIA	ANDRA PRADESH	VISAKHAPATNAM	Mined cavern	Liquid hydrocarbons	Crude Oil	1 000 000	2			Y	DECLINE	$ 172 000 000.00		HCC	EIL for ISPRL	EPC	
ITALY			Mined cavern	Liquefied hydrocarbons	Propane	45 730	3			N	SHAFT						Y

Storage Cavern List

HYDROSTOR

Country	Area	Title	Storage type	Stored products	Detail	Working Volume (m^3)	Qty Caverns	Cavern Depth	P mean (bar)	Water Curtain	Cavern Access	Construction Cost (U/G)	Construction Duration (years)	General Contractor	Owner Operator	Contracting Strategy	GK Involved
JAPAN	OCHI	KIKUMA	Mined cavern	Liquid hydrocarbons	Crude oil	1 500 000	7			Y	DECLINE				JOGMEC		
JAPAN			Mined cavern	Liquid hydrocarbons	Crude oil	1 750 000	3			Y	DECLINE			KAJIMA			Y
JAPAN			Mined cavern	Liquefied hydrocarbons	Propane	800 000	1	160		Y	DECLINE			SHIMIZU/KAJIMA/JGC			Y
JAPAN	KAGOSHIMA	KUSHIKINO	Mined cavern	Liquid hydrocarbons	Crude oil	1 750 000	3			Y					JOGMEC		
JAPAN			Mined cavern	Liquefied hydrocarbons	Propane; Butane	900 000	2	150		Y	DECLINE		8	OBAYASHI/TAISEI/CHIYODA			Y
NORWAY	OSLO	EKEBERG OLJELAGER	Mined cavern	Liquid hydrocarbons	Diesel oil; Gasoline; Jet Fuel	136 000	17			N					HYDROTEXACO, SHELL, ESSO, STATOIL		
NORWAY	NORDLAND	GLOMFJORDEN	Mined cavern	Other products	Ammonia		1			N							
NORWAY	TROMS	HARSTAD	Mined cavern	Liquid hydrocarbons	Crude oil		1			N							
NORWAY	PORSGRUNN	HEROYA	Mined cavern	Other products	Ammonia	47 700	1			N					NORSK-HYDRO		
NORWAY	TRONDHEIM	ILSVIKA	Mined cavern	Liquid hydrocarbons	Crude oil					N							
NORWAY	BERGEN	KARSTO	Mined cavern	Liquefied hydrocarbons	Propane	275 000	2			N					STATOIL		
NORWAY	SORLANDET	KRISTIANSAND	Mined cavern	Liquid hydrocarbons	Crude oil					N							
NORWAY	BERGEN	MONGSTAD	Mined cavern	Liquefied hydrocarbons	Butane; LPG Mix; Propane	180 000	3			Y					STATOIL		
NORWAY	BERGEN	MONGSTAD	Mined cavern	Liquid hydrocarbons	Crude oil; Diesel oil; Gasoline; Other products	925 000	15			N					STATOIL		
NORWAY	BERGEN	MONGSTAD	Mined cavern	Liquid hydrocarbons	Crude oil; Other products	1 480 000	9			N					STATOIL		
NORWAY	BERGEN	MONGSTAD	Mined cavern	Liquefied hydrocarbons	Refrigerated propane	30 000	1			Y					STATOIL		
NORWAY	BERGEN	MONGSTAD	Mined cavern	Liquefied hydrocarbons	Propane	30 000	1			Y					STATOIL		
NORWAY	TRONDELAG	NAMSEN	Mined cavern	Liquid hydrocarbons	Diesel oil					N							
NORWAY	TONSBERG	OSEBERG	Mined cavern	Liquid hydrocarbons	Crude oil	950 000	5			N					NORSK HYDRO A.S.		
NORWAY	OSLO	RAFNES	Mined cavern	Liquefied hydrocarbons	Propane	100 000	1			Y							
NORWAY	ROGALAND	SOLA	Mined cavern	Liquid hydrocarbons	Crude oil	220 000				N							
NORWAY	SOTRA ISLE, WEST COAST	SOTRA	Mined cavern	Liquid hydrocarbons	Crude oil	900 000	6			N					STATOIL		
NORWAY	SOTRA ISLE, WEST COAST	SOTRA	Mined cavern	Liquefied hydrocarbons	Butane; Propane	163 000	4			Y					STATOIL		
NORWAY	ROGALAND	STAVANGER	Mined cavern	Liquid hydrocarbons	Crude oil					N							
NORWAY	WEST COAST	STURE	Mined cavern	Liquid hydrocarbons	Crude oil	800 000	4			N					NORSK HYDRO		
NORWAY	VAIDAKA	STURE	Mined cavern	Liquefied hydrocarbons	Propane	65 000	1			N					STATOIL		
NORWAY	TRONDELAG	TRONDHEIM	Mined cavern	Liquid hydrocarbons	Gasoline; Kerosene		3			N					A.S. NORSKE ESSO		
PORTUGAL			Mined cavern	Liquefied hydrocarbons	Propane	83 000	1	137	7	Y	DECLINE	11 200 000.00 €	3	LEMMINKAINEN		RATES CONTRACT + TARGET PRICE	Y
SAUDI ARABIA	ASIR	ABHA	Mined cavern												SAUDI ARAMCO		
SAUDI ARABIA	AL-QASSIM	BURAIDAH	Mined cavern												SAUDI ARAMCO		
SAUDI ARABIA	TIHAMAH	DJEDDAH	Mined cavern												SAUDI ARAMCO		
SAUDI ARABIA	AL-MADINAH	MEDINA	Mined cavern												SAUDI ARAMCO		
SINGAPORE			Mined cavern	Liquid hydrocarbons	Crude oil; LPG; Naphtha; Propylene; Condensate; Marine fuel oil	1 500 000	5	119		Y	SHAFT	$ 275 000 000.00	7	HDEC		EPC/GBR	Y
SOUTH KOREA	GYEONGSANG	GOJE	Mined cavern	Liquid hydrocarbons	Crude oil	690 000									KNOC (KOREAN NATIONAL OIL CORPORATION)		
SOUTH KOREA	GYEONGSANG	GOJE	Mined cavern	Liquid hydrocarbons	Crude oil	320 000									KNOC (KOREAN NATIONAL OIL COMPANY)		
SOUTH KOREA	GYEONGSANG	GOJE	Mined cavern	Liquid hydrocarbons	Crude oil	130 000									KNOC (KOREAN NATIONAL OIL COMPANY)		
SOUTH KOREA	GYEONGGI	GURI	Mined cavern	Other products	Other products	229 000									KNOC (KOREAN NATIONAL OIL COMPANY)		
SOUTH KOREA			Mined cavern	Liquefied hydrocarbons	Butane; Propane	480 000	2	110; 130	1.7; 6.3	Y	SHAFT	$ 300 000 000.00	3	LGEN		EPC	Y
SOUTH KOREA			Mined cavern	Liquefied hydrocarbons	Propane	270 000	1	115	5.5	Y	DECLINE		3	SKEC		EPC	Y
SOUTH KOREA			Mined cavern	Liquefied hydrocarbons	Butane; Propane	309 000	2	60; 115		Y	DECLINE		3				Y

Storage Cavern List

HYDROSTOR

Country	Area	Title	Storage type	Stored products	Detail	Working Volume (m^3)	Qty Caverns	Cavern Depth	P mean (bar)	Water Curtain	Cavern Access	Construction Cost (U/G)	Construction Duration (years)	General Contractor	Owner Operator	Contracting Strategy	GK Involved
SOUTH KOREA			Mined cavern	Liquefied hydrocarbons	Propane	420 000	1	137		Y	DECLINE		3				Y
SOUTH KOREA			Mined cavern	Liquid hydrocarbons	Diesel oil; Bunker-C	251 000	2	10		Y	DECLINE		3	HYUNDAI			Y
SOUTH KOREA			Mined cavern	Liquefied hydrocarbons	Butane; Propane	550 000	2	63; 119	1.7; 5.5	Y	DECLINE		4	SKEC			Y
SOUTH KOREA			Mined cavern	Liquefied hydrocarbons	Butane; Propane	296 000	2	60; 114	1.1; 6.2	Y	DECLINE		3	JUNGWOO			Y
SOUTH KOREA	YEONGNAM	ULSAN	Mined cavern	Liquid hydrocarbons	Crude Oil					Y	DECLINE			SKEC		EPC	
SWEDEN	LYSEKIL	BROFJORDEN	Mined cavern	Liquid hydrocarbons	Crude oil	1 598 950	1			N							
SWEDEN	GASTRIKLANG	GÄVLE	Mined cavern	Liquid hydrocarbons	Crude oil		5			N							
SWEDEN	GOTEBORG	HISINGEN	Mined cavern	Liquid hydrocarbons	Crude oil	2 800 000	9			N							
SWEDEN	BLEKINGE	KARLSHAMM	Mined cavern	Liquefied hydrocarbons	Propane	48 000	1			Y					EON SVERIGE (SYDKRAFT AB.)		
SWEDEN	BLEKINGE	KARLSHAMM	Mined cavern	Liquefied hydrocarbons	Propane	145 000	1			N					EON SVERIGE (SYDKRAFT AF)		
SWEDEN	GOTEBORG	KOPPARTRANS	Mined cavern	Liquid hydrocarbons	Crude oil	180 000	3			N					SHELL-HJARTHOLMEN		
SWEDEN	GOTEBORG	KOPPARTRANS	Mined cavern	Liquid hydrocarbons	Crude oil	300 000	3			N					SHELL-HJARTHOLMEN		
SWEDEN	STOCKHOLM	LOUDDEN	Mined cavern	Liquid hydrocarbons	Diesel oil; Heavy oil	200 000	2			N					STOCKHOLM HARBOUR AUTHORITY		
SWEDEN	GOTALAND	LYSEKILL	Mined cavern	Liquefied hydrocarbons	LPG Mix	12 000				Y					SCANRAFF		
SWEDEN	SCANIA	MALMÖ	Mined cavern	Liquefied hydrocarbons		200 000				Y					SYDGAS		
SWEDEN	OSTERGOTLAND	NORRKOPPING	Mined cavern	Liquid hydrocarbons	Crude oil; Heavy oil	1 200 000	5			N							
SWEDEN	STOCKHOLM	NYNÄSHAMN	Mined cavern	Liquid hydrocarbons	Crude oil; Gasoline; Heavy oil; LPG	950 000	5			N					AB NYNAS-PETROLEUM		
SWEDEN	SODERMANLAND	OXELÖSUND	Mined cavern	Liquid hydrocarbons	Crude oil	954 000	7			N							
SWEDEN	LYSEKIL	SCANRAFF	Mined cavern	Liquefied hydrocarbons	Propylene	20 000	1			N							
SWEDEN	HALMSTAD	SKALLEN	Mined cavern	Natural gas	Natural gas	9 000 000	1								LRC DEMO AB (Joint venture between GDF and Sydkraft)		
SWEDEN	SODERMANLAND	SODERTALJE	Mined cavern	Liquid hydrocarbons	Heavy oil		1			N							
SWEDEN	SODERMANLAND	SOLNA	Mined cavern	Liquid hydrocarbons	Heavy oil		1			N							
SWEDEN	GOTALAND	STENUNGSUND	Mined cavern	Liquefied hydrocarbons	Propane; Butane	190 000	4			Y					BOREALIS		
SWEDEN	GOTALAND	STENUNGSUND	Mined cavern	Liquefied hydrocarbons	LPG	500 000	1			Y							
SWEDEN	GOTALAND	STENUNGSUND	Mined cavern	Liquefied hydrocarbons	Propylene	12 000	1			Y					ESSO CHEMICALS		
SWEDEN	GOTALAND	STENUNGSUND	Mined cavern	Liquefied hydrocarbons		140 000	2			Y					ESSO CHEMICALS		
SWEDEN	SKANE	STIDSVIG	Mined cavern	Liquefied hydrocarbons	LPG	200 000	1			Y							
SWEDEN	MEDELPAD	SUNDSVALL	Mined cavern	Liquid hydrocarbons	Diesel oil; Gasoline; Heavy oil		5			N							
SWEDEN	MEDELPAD	SUNDSVALL	Mined cavern	Liquefied hydrocarbons	Propane	58 600	1			Y					FORTUM SVENSKA		
SWEDEN	GOTEBORG	TORSHAMMEN	Mined cavern	Liquid hydrocarbons	Crude oil	530 000	6			N							
SWEDEN	VASTERBOTTEN	UMEA	Mined cavern	Liquid hydrocarbons	Diesel oil; Gasoline		1			N							
SWEDEN	VASTMANLAND	VASTERAS	Mined cavern	Liquid hydrocarbons	Heavy oil		1			N							
TAIWAN	WESTERN TAIWAN	MOIALI	Mined cavern	Liquefied hydrocarbons	LPG Mix	50 000	1								CPC		
UNITED KINGDOM			Mined cavern	Liquefied hydrocarbons	Butane; Propane	240 000	2	165; 179	3.5; 9	N	SHAFT		4				Y
USA	ILLINOIS	ALTON	Mined cavern	Liquefied hydrocarbons	Propane	15 900	1			N	SHAFT						
USA	DUPAGE	AURORA	Mined cavern	Liquefied hydrocarbons	Propane	7 950	1	63		N	SHAFT				WARREN PETROLEUM CORP.		
USA	ILLINOIS	AUX SABLE	Mined cavern	Liquefied hydrocarbons	Isobutane; Propane	7 155	8			N	SHAFT				AUX SABLE LIQUID PRODUCTS		
USA	MARYLAND	BALTIMORE	Mined cavern	Liquefied hydrocarbons	Propane	23 848	1	107		N	SHAFT			F & S	BALTIMORE GAS & ELECTRIC CO.		
USA	NEW JERSEY	BAYWAY	Mined cavern	Liquefied hydrocarbons	Butane; Propane	72 345	5			N	SHAFT				CONOCO PHILLIPS		
USA	TEXAS	BRECKENRIDGE	Mined cavern	Liquefied hydrocarbons	LPG	7 950	2	76		N	SHAFT			F & S	WARREN PETROLEUM CORP.		
USA	OHIO	BUTLER	Mined cavern	Liquefied hydrocarbons	Propane	26 550	1	114		N	SHAFT			F & S	CINCINNATI GAS & ELEC		
USA	KENTUCKY	CALVERT CITY	Mined cavern	Liquefied hydrocarbons	Propane; Propylene	43 750	2	117		N	SHAFT			F & S	WESTLAKE GROUP		

Storage Cavern List

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Country	Area	Title	Storage type	Stored products	Detail	Working Volume (m^3)	Qty Caverns	Cavern Depth	P mean (bar)	Water Curtain	Cavern Access	Construction Cost (U/G)	Construction Duration (years)	General Contractor	Owner Operator	Contracting Strategy	GK Involved
USA	MISSOURI	CARTHAGE	Mined cavern	Liquefied hydrocarbons	Propane	30 210	1	100		N	SHAFT			F & S	WILLIAMS ENERGY SERVICES		
USA	KENTUCKY	CONSTANCE	Mined cavern	Liquefied hydrocarbons	Propane	26 553	1	122		N	SHAFT			F & S	CINCINNATI GAS & ELECTRIC CO.		
USA	ILLINOIS	CROSSVILLE	Mined cavern	Liquefied hydrocarbons	Propane	7 950	1			N	SHAFT			F & S	WARREN PETROLEUM CORP.		
USA	ALABAMA	DEMOPOLIS	Mined cavern	Liquefied hydrocarbons	Butane	22 737	1	101		N	SHAFT			F & S	BP		
USA	ALABAMA	DEMOPOLIS	Mined cavern	Liquefied hydrocarbons	Propane	34 000	1	101		N	SHAFT			F & S	BP		
USA			Mined cavern	Liquefied hydrocarbons	Butane; Propane; Ethane	47 700	3	175; 175; 422		N	SHAFT			F & S			Y
USA	OKLAHOMA	DRUMRIGHT	Mined cavern	Liquefied hydrocarbons	Propane	35 775	1	123		N	SHAFT						
USA	ILLINOIS	EOLA	Mined cavern	Liquefied hydrocarbons		7 950	1			N	SHAFT			F & S	WARREN PETROLEUM CORP.		
USA	ILLINOIS	FARMINGTON	Mined cavern	Liquefied hydrocarbons	Propane	65 190	1			N	SHAFT			F & S	WILLIAMS		
USA	MISSOURI	FLORISSANT	Mined cavern	Liquefied hydrocarbons	Propane	124 815	2	116		N	SHAFT			F & S	LACLEDE GAS COMPANY		
USA			Mined cavern	Liquefied hydrocarbons	Propane	37 840	2			N	SHAFT						Y
USA	NEW JERSEY	GIBBSTOWN	Mined cavern	Other products	Ammonia	28 600	1	104		N	SHAFT			F & S	Dupont Facility Services		
USA	PENNSYLVANIA	GREENSBURG	Mined cavern	Liquefied hydrocarbons	Butane; Propane	45 315	2	104		N	SHAFT			F & S	TEPPCO		
USA	NEBRASKA	GREENWOOD	Mined cavern	Liquefied hydrocarbons	Propane	52 470	1	99		N	SHAFT			F & S	WILLIAMS ENERGY SERVICES		
USA	INDIANA	GRIFFITH	Mined cavern	Liquefied hydrocarbons	Propane	39 750	1	183		N	SHAFT			F & S	DOME PETROLEUM CORP./ BP		
USA	INDIANA	GRIFFITH	Mined cavern	Liquefied hydrocarbons	Empty	55 650	1	105		N	SHAFT			F & S			
USA	OHIO	HAMILTON	Mined cavern	Liquefied hydrocarbons	Propane	30 370	1			N	SHAFT				CINCINNATI GAS & ELEC.		
USA	Indiana	HAMMOND	Mined cavern	Liquefied hydrocarbons	Ethane; Propane	63 600	2	160		N	SHAFT			F & S	BP AMOCO		
USA	ILLINOIS	HARTFORD	Mined cavern	Liquefied hydrocarbons	Propane	12 720	1			N	SHAFT				CONOCO		
USA	INDIANA	HUNTINGTON	Mined cavern	Liquefied hydrocarbons	Propane	12 750	1	139		N	SHAFT				DOME PETROLEUM		
USA	WEST VIRGINIA	HUNTINGTON	Mined cavern	Liquefied hydrocarbons	Butane		1			N	SHAFT						
USA	IOWA	IOWA CITY	Mined cavern	Liquefied hydrocarbons	LPG Mix; Propane	68 370	2	221; 143		N	SHAFT			F & S	WILLIAMS ENERGY SERVICES		
USA	ILLINOIS	KANKAKEE	Mined cavern	Liquefied hydrocarbons	Propane	23 850	1	63		N	SHAFT				PHILIPPS PETROLEUM		
USA	KENTUCKY	KENTON	Mined cavern	Liquefied hydrocarbons	Propane	26 553	2			N	SHAFT				CINCINNATI GAS & ELEC. & KENTON		
USA			Mined cavern	Liquefied hydrocarbons	Butane; Propane; Isobutane	38 637	3	149		N	SHAFT						Y
USA	ILLINOIS	LICK CREEK	Mined cavern	Liquefied hydrocarbons			1			N	SHAFT						
USA	OHIO	LIMA	Mined cavern	Liquefied hydrocarbons	Butane; Propane; Propylene	76 797	3	151		N	SHAFT			F & S	PREMCOR REFINING GROUP		
USA	NEW JERSEY	LINDEN	Mined cavern	Liquefied hydrocarbons	LPG Mix	63 595	3	98		N	SHAFT			F & S	ESSO STANDARD OIL COMPANY		
USA	PENNSYLVANIA	MARCUS HOOK	Mined cavern	Liquefied hydrocarbons	Butane; Isobutane; Propylene	301 900	5	110; 110; 76		N	SHAFT			F & S	SUNOCO		
USA	MINNESOTA	MENTOR	Mined cavern	Liquefied hydrocarbons	Propane	52 470	1	156		N	SHAFT			F & S	AMERADA HESS		
USA	OHIO	MIDDLETOWN	Mined cavern	Liquefied hydrocarbons	LPG Mix; Propane; Butane	371 000	9	119		N	SHAFT			F & S	TEXAS EASTERN TRANSMISSION CORP.		
USA	GEORGIA	MILNER	Mined cavern	Liquefied hydrocarbons	Propane; Butane	86 651	2	104		N	SHAFT			F & S	DIXIE PIPELINE CO.		
USA	ILLINOIS	MONEE	Mined cavern	Liquefied hydrocarbons	Butane; Isobutane	51 675	2	149		N	SHAFT			F & S	TEPPCO		
USA			Mined cavern	Liquefied hydrocarbons	Ethane	14 310	1	550		N	SHAFT			F & S			Y
USA	Illinois	MORRIS	Mined cavern	Liquefied hydrocarbons	Propane		1	320		N	SHAFT			F & S	KINDER MORGAN ENERGY		
USA			Mined cavern	Liquefied hydrocarbons	Propane	12 720	2	89		N	SHAFT			F & S			Y
USA	WEST VIRGINIA	NEIL	Mined cavern	Liquefied hydrocarbons	Propane; Butane	238 481	2	153		N	SHAFT			WSP	MARATHON ASHLAND		
USA	MARYLAND	NOTCH CLIFF PLANT	Mined cavern	Liquefied hydrocarbons	Propane	23 500	1			N	SHAFT				BALTIMORE GAS & ELECTRIC		
USA	NEBRASKA	OAK STORAGE	Mined cavern	Liquefied hydrocarbons	Propane	22 700	3	89; 90; 145		N	SHAFT			F & S	METROPOLITAN UTILITIES DISTRICT		
USA	INDIANA	OAKLAND CITY	Mined cavern	Liquefied hydrocarbons	Propane	24 600	1			N	SHAFT				TEPPCO		
USA	OKLAHOMA	PONCA CITY	Mined cavern	Liquefied hydrocarbons	Propane	47 700	1	107		N	SHAFT			F & S	CONOCO PHILIPPS		
USA	INDIANA	PRINCETON	Mined cavern	Liquefied hydrocarbons	Propane	24 645	1			N	SHAFT				TEXAS EASTERN PRODUCTS		

Storage Cavern List

HYDROSTOR

Country	Area	Title	Storage type	Stored products	Detail	Working Volume (m^3)	Qty Caverns	Cavern Depth	P mean (bar)	Water Curtain	Cavern Access	Construction Cost (U/G)	Construction Duration (years)	General Contractor	Owner Operator	Contracting Strategy	GK Involved
USA	VIRGINIA	RAVENSWORTH	Mined cavern	Liquefied hydrocarbons	Propane	44 000	3	122		Y	SHAFT			F & S	WASHINGTON GAS LIGHT		
USA	WYOMING	RAWLINS	Mined cavern				1	130		N	SHAFT						
USA	ILLINOIS	ROBINSON	Mined cavern	Liquefied hydrocarbons	Butane	222 582	1	198		N	SHAFT			WSP	MARATHON PETROLEUM CORP.		
USA	OKLAHOMA	SEMINOLE	Mined cavern	Liquefied hydrocarbons	Propane	17 100	1	94		N	SHAFT			F & S	SINCLAIR OIL AND GAS CO.		
USA	INDIANA	SEYMOUR	Mined cavern	Liquefied hydrocarbons	Butane; Isobutane	97 785	2	127		N	SHAFT			F & S	TEPPCO		
USA	INDIANA	SEYMOUR TERMINAL	Mined cavern	Liquefied hydrocarbons	Propane	79 500	1			N	SHAFT			F & S	SILGAS INC.		
USA	KENTUCKY	SILOAM	Mined cavern	Liquefied hydrocarbons	Butane; Propane	56 286	3	116		N	SHAFT			F & S	MARKWEST HYDROCARBONS		
USA	SOUTH CAROLINA	TIRZAH	Mined cavern	Liquefied hydrocarbons	Propane	222 600	1	127		N	SHAFT			F & S	SUBURBAN PROPANE, L.P.		
USA	SOUTH CAROLINA	TIRZAH	Mined cavern	Liquefied hydrocarbons	Propane	59 625	1			N	SHAFT			F & S	CAROLINA PIPELINE CO.		
USA	OHIO	TODHUNTER	Mined cavern	Liquefied hydrocarbons	Propane	27 200	1			N	SHAFT				DAYTON POWER & LIGHT		
USA	OHIO	TODHUNTER	Mined cavern	Liquefied hydrocarbons	Butane; Isobutane; Other products; Propane	227 750	6			N	SHAFT				TEPPCO		
USA	OHIO	TOLEDO	Mined cavern	Liquefied hydrocarbons	Propane; Propylene	27 030	2			N	SHAFT			F & S	BP		
USA	MARYLAND	TOWSON	Mined cavern	Liquefied hydrocarbons	Propane	23 850	1			N	SHAFT				BALTIMORE GAS & ELEC.		
USA	OKLAHOMA	TULSA	Mined cavern	Liquefied hydrocarbons	Propane	36 570	1			N	SHAFT			F & S	SUNOCO INC.		
USA	ILLINOIS	TUSCOLA 1	Mined cavern	Liquefied hydrocarbons	Propane	137 375	2			N	SHAFT			F & S	DOME PETROLEUM CORP.		
USA	ILLINOIS	TUSCOLA 2	Mined cavern	Liquefied hydrocarbons	Propane	23 848	1			N	SHAFT			MC LEAN GROVE & CO	DOME PETROLEUM CORP / BP		
USA	NEW YORK	WATKINS GLEN	Mined cavern	Liquefied hydrocarbons	Propane	181 400	1			N	SHAFT			F & S	TEPPCO		
USA	LOUISIANA	WEEKS ISLAND	Mined cavern	Liquid hydrocarbons		11 130	1			N	SHAFT				SPR		
USA	INDIANA	WHITING	Mined cavern	Liquefied hydrocarbons	Butane	47 700	1	163		N	SHAFT			F & S	BP		
USA	ILLINOIS	WILLIAMS	Mined cavern	Liquefied hydrocarbons	Propane	65 190	1			N	SHAFT				WILLIAMS		
USA	ILLINOIS	WOOD RIVER	Mined cavern	Liquefied hydrocarbons	Butane; Propane	112 410	2	122		N	SHAFT			F & S	SHELL OIL CO.		
USA	ILLINOIS	WOOD RIVER	Mined cavern	Liquefied hydrocarbons	Propane	12 720	1	163		N	SHAFT			F & S	CONOCOPHILLIPS		
USA	ILLINOIS	WOOD RIVER	Mined cavern	Liquefied hydrocarbons	Propane	34 980	2	122		N	SHAFT			F & S	BP (Amoco Chemical)		
USA	WEST VIRGINIA	CATLETTSBURG	Mined cavern	Liquefied hydrocarbons	Butane	36 000	1			N	SHAFT			PB	MARATHON PETROLEUM CORP.		

including A/G

11 Phase 2 Further Work

11.1 Analogues and Precedents - Pressurised Hot Water Storage

An investigation of referenced pressurised liquid storage applications in industrial settings has been carried out. The purpose of this is to provide context to the recommendations made in this report and ensure that the recommended storage conditions are not unique and the storage type is at a sufficient TRL.

For specific safety aspects of operating pressurised hot water storage systems refer to the Safety Assessment Report [Ref. 9] for the outcomes of the HSE review and comparative MAR assessment.

A review of referenced, installed storage options has been carried out and these are presented in the below bubble chart Figure 11.1 for comparison with the intended Hydrostor design (shown by the green bubble).

The storage options are compared in terms of the three key parameters of interest:

- size / volume (m3) - indicated by the size of the bubbles;
- design pressure (bara) - on the y-axis; and
- design temperature (°C) - on the x-axis

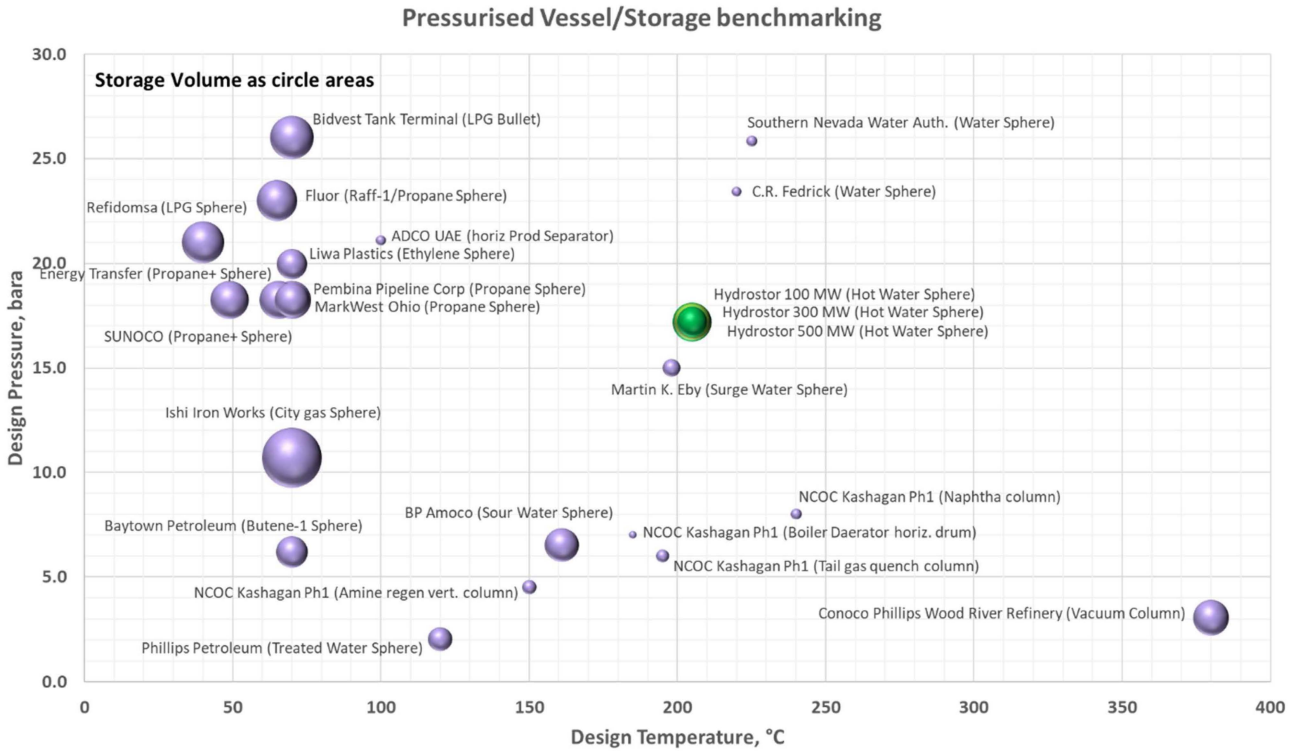

Figure 11.1 Analogues Bubble Chart

In terms of system analogues, it should be noted that the required storage conditions sit comfortably within the normal operating envelope of a conventional steam system i.e. typically LP steam at 5 bara and 160°C, HP steam at 42 bara and 265°C.