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Silica Sand as Thermal Energy Storage for Renewable-based Hydrogen and Ammonia Production Plants

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Due to rising climate change concerns, developing renewable energy and low-cost utility-scale energy storage technologies has become critical to reducing environmental impacts. Thermal energy storage (TES) systems offer scalable, efficient, and low-cost methods for energy storage, yet commercially have mainly been limited to use in concentrating solar power plants. With increasing renewable energy developments, the commercialisation of standalone TES systems has become vital. A few recent studies began exploring sand's use as a TES material. Sand, particularly Silica Sand, provides an abundant, thermally stable, and low-cost method for storing thermal energy at temperatures as high as 1,200 °C. When there is insufficient electricity to meet demand, the stored heat could be discharged from the silica sand and converted into electricity by driving an electric power system. The silica sand in the Sultanate of Oman was found to be ultra-pure (>98 wt% SiO_2); a composition National Renewable Energy Laboratory (NREL) has proven to have ideal thermal properties for its use as a TES system. NREL has also proposed a standalone sand-TES concept, which offers ample storage capacities, longer discharging hours and meagre cost compared to other commercial energy storage technologies. This research analyses the economic benefit of utilising this sand TES system in maintaining the full-day operation of a 500 MW solar-based green ammonia production plant in Duqm-Oman and compares it to commercial lithium batteries. The result shows that using silica sand as a TES system significantly reduced the unit production cost of green hydrogen and green ammonia by 59 % and 48 %, compared to the use of lithium-ion batteries, where the green hydrogen and green ammonia lifetime normalized costs fell to 0.60 US$/kg$H_2$ and 0.16 US$/kg$NH_3$. The sand TES system is thus a promising solution for intermittent renewable energy storage. The low cost and abundance offered through a sand TES system will contribute to ramping up renewable energy projects, thus driving down the costs of clean energy and renewable energy-based products.

1. Introduction

The intermittent nature of renewable energy sources creates challenges in maintaining the constant operation of renewable energy-powered plants and therefore hinders the penetration of renewable energy resources into the country's energy mix, particularly in fossil-fuel-dependent countries.
TES systems offer scalable, long-duration and standalone energy storage that is superior to other energy storage technologies (Ma et al., 2020). These systems store thermal energy as sensible heat, latent heat, or chemical energy that can be re-converted into electricity during the night. Commercially, however, TES systems have been limited to CSP plants (Diago et al., 2018). The molten salt system is the most proven TES technology to extend operation beyond sunlight hours. The drawbacks of this method, however, include the salt mixture's upper operation limit (565 °C) along with its high melting point (120-220 °C), which bounds the maximum power cycle efficiency and increases the risk of salt freezing in the pipeline during winter (Diago et al., 2018).
Alternative TES materials are under development to eliminate salt systems issues. Phase change materials offer high densities for energy storage as latent heat, yet candidate material development is still ongoing (Diago et al., 2018). Thermochemical energy storage concepts are similarly in early development (Diago et al., 2018). Particle-TES systems, instead, which involve storing energy as sensible heat in solid particles, are gaining increased attention (Poulose et al., 2022). Particle-TES systems exhibit an excellent ability to store and dispatch

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thermal energy at operating temperatures above 1,000 °C, thereby supporting high-efficiency power cycles which lead to overall TES systems levelized cost of electricity (LCOE) reduction and allow for grid-scale standalone system development (Ma et al., 2020).
For standalone TES systems, particle flowability, abundance, stability and energy density are the governing factors for selecting particles for use as energy storage media (Ma et al., 2020). A few studies explored using sand as an energy storage medium (NREL, 2020). Sand's high operating temperature potential, abundance and low-cost present a commercially attractive solution for energy storage. In a recent study by NREL, high-purity silica sand (99.65 % SiO_2) offered operating temperatures as high as 1,200 °C and underwent no thermal degradation (NREL, 2020). From a commercial-scale perspective, however, such high operating temperatures impose technical containment challenges. Therefore, NREL authors proposed a detailed design of a commercial-scale containment storage silo to overcome these challenges (Ma et al., 2020). NREL also economically compared the use of this sand-TES system to power various power cycles and concluded that the use of this sand-TES system to power a Brayton Combined Power Cycle – adapted from a Combined Gas Power Cycle, was the most economically superior method (Ma et al., 2020). As shown in Figure 1, the concept by which a sand-TES system operates is simple (Ma et al., 2020): (1) A high-temperature device uses renewable electricity to heat the stored silica sand particles to a temperature of 1,200 °C, (2) during the night, these stored hot sand particles are sent to a fluidised-bed heat exchanger to transfer this heat to a thermal working fluid, and (3) this thermal fluid is then used to drive a combined gas power cycle to re-produce electricity. Finally, the cooled sand at 300 °C is moved to the transfer silo and recycled.

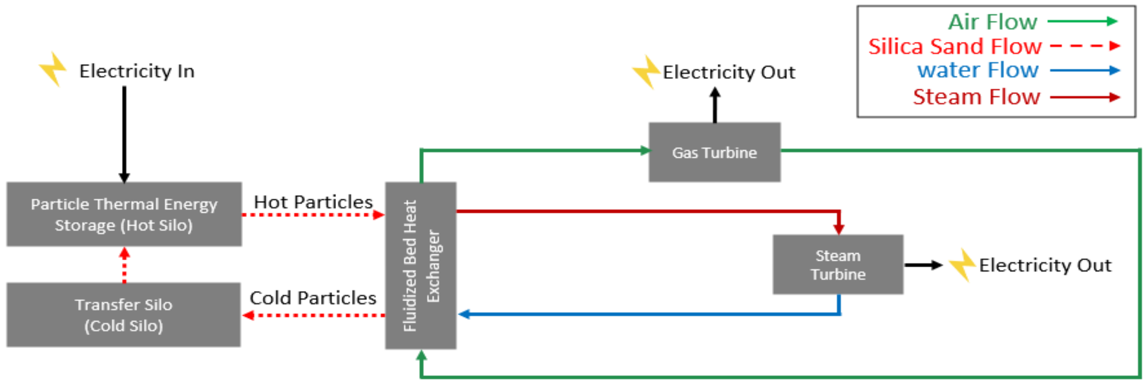

Figure 1: A standalone TES system integrated with a combined gas power cycle (Ma et al., 2020)

With the rapid rise in green hydrogen plants in Oman, implementing standalone silica-sand TES systems would offer an efficient and low-cost method to maintain constant operation of these plants beyond sunlight hours. So far, no study has analysed the economic potential of using silica sand to power green hydrogen plants. This work will investigate the use of NREL's sand-TES system to power a 500 MW green hydrogen/ammonia plant in Duqm – Oman, and economically compare it to the use of lithium-ion batteries; conventional method used for energy storage in hydrogen plants. The results from this study aim to incentivise the development of commercial sand-TES systems for use in renewable-based plants.

2. Methodology

The methodology for assessing the economic potential of using a silica-sand TES system for the operation of a green hydrogen/ammonia plant involved:
Step 1: Determining the composition of silica sand across different regions in Oman.
Step 2: Identifying the thermo-physical properties of this sand and thus assessing its suitability as a TES system.
Step 3: Conducting a cost comparative case study to assess the economic benefit of using silica sand as an energy storage system instead of batteries.

3. Silica sand TES system

Oman's silica sand composition and its potential for use as a TES system are discussed hereafter.

3.1 Oman's silica sand composition

Minerals Development Oman conducted a recent analysis on silica sand deposits in Oman (Qidwai, 2020). As show in Table 1, five locations in the Sultanate were identified to have abundant resources of silica sand, with purities exceeding 98 wt% SiO_2 (Qidwai, 2020). To coduct the composition analysis, each sample was collected after removing the top layers exposed to the atmosphere and stored in sealed containers during transportation. The samples were then first examined using a scanning electron microscope (SEM) to determine the silica-sand granulometry and any required preparation technique, following which they were later analysed using a Laser Elemental Spark Analysis (LESA) (Qidwai, 2020).

3.2 Silica sand thermophysical properties

NREL recently conducted a thermophysical properties analysis of silica sand samples with a composition of ~99.65 wt% SiO_2 (NREL, 2020). The particles' thermal stability was tested by subjecting the samples to two thermal tests: (1) subjecting the sand particles to 1,200 °C for 500 h; (2) cycling the silica sand between 300 °C and 1,200 °C for 25, 50, and 100 times. Results indicated no thermal degradation of the silica sand particles with negligible changes in particle distribution and crystallographic structure, concluding that silica sand in the range of this purity would be optimum for use in a TES system. Oman's silica sand has similar SiO_2 composition (Table 1) compared to the tested sample by NREL, which the NREL sand sample is reported with the thermophysical data as shown in Table 2 (NREL, 2020). The thermophysical data in Table 2 will be used in the case study described hereafter.

Table 1: Oman's silica sand composition

Sample No.	Name of the deposit	Resources Low (ton)	Resources High (ton)	SiO_2 %
1	Salil	5×10^6	> 10×10^6	> 98
2	Al-raqi	0.7×10^6	> 1.4×10^6	> 98
3	Abu-Tan	6.4×10^6	> 10×10^6	> 98
4	Wadi Baw	1.8×10^6	> 4.17×10^6	> 98
5	Hawf	5.3×10^6	> 10×10^6	> 98

Table 2: Silica sand thermophysical properties (NREL, 2020)

Sample Type	Composition	Density (kg/m^3)	Capacity (J/kg.°C)	Potential Operating Temperature (°C)
Silica Sand	99.65 % SiO_2	2,650	1,128	1,200

4. Case study – green ammonia plant

A case study is used to demonstrate the economic benefit of using silica sand as a TES system. A PV-based 500 MW green hydrogen/ammonia plant is taken as the case study, as shown in Figure 2. The installation of a silica sand TES system or lithium-ion battery system is compared in the case study for storing electricity from the daytime to be used in the nighttime. The storage system in the case study was compared in terms of the required electricity to be stored and the unit production cost of hydrogen and ammonia.

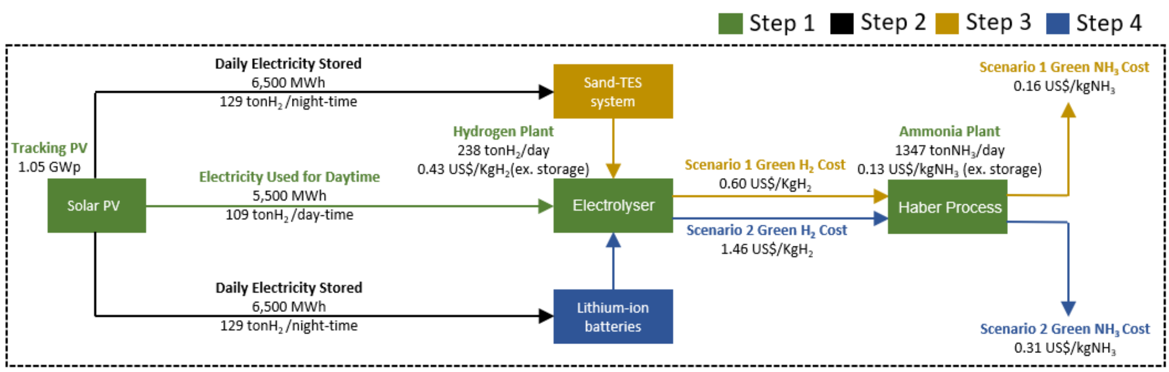

Figure 2: 500 MW green ammonia plant with energy storage system

4.1 Step 1: green ammonia plant design

The plant's design specifications are summarised in Table 3. To generate 1 kg H_2, 50.5 kWh_e of electricity and 9 L water are assumed, whereas 1 kg NH_3 requires 0.8 kg N_2 and 0.18 kg H_2 (IEAGHG, 2017). The required PV plant capacity and No. of electrolysers can be calculated from Eq(1), retrieved from (ONSS, 2020), along with the data in Table 4. The green hydrogen/ammonia plant costs (excluding the energy storage cost) normalised over the plant's hydrogen and ammonia capacity can then be calculated using Eq(2), Eq(3) and Table 4 data.

$$\text{Capacity Factor (\%)} = \text{Actual Energy Generated (MWh)} \,/\, \text{Nominal Capacity (MW)} * \text{Time Period (h)} \quad (1)$$

$$\text{CAPEX (US\$)} = [P_{nominal} * \text{PV plant Cost}] + [\text{No. of Electrolys.} * \text{Electrolys. Cost}] + [_{NH_3} \text{ plant Cost}] \quad (2)$$

$$\text{Normalised Plant Cost (US\$/kg)} = (\text{CAPEX} + \text{OPEX}) / (\text{kg of product/y} \times \text{Plant lifetime(y)}) \quad (3)$$

Table 3: 500 MW green ammonia plant design specifications.

Parameter	Required daily electricity generation (MW)	Hydrogen capacity (t H_2/d)	Ammonia capacity (t NH_3 /d)	Plant Lifetime (y)
Green NH_3 plant	500	238	1,347	25

Table 4: Normalised H_2/NH_3 plant cost data (excluding energy storage technology cost)

Data	CAPEX			OPEX
	PV plant	Electrolyser	Ammonia Plant	
Design	Capacity Factor 47.7 %[a]	Efficiency 78 %; 2.1 MW/ton H_2[a]	-	-
Cost	0.7 x 10^6 US$ / 1 MW_p[a]	6 x 10^6 US$ / 20 MW electrolyser[a]	1,394 US$/ton$NH_3$[b]	3% * capex[a]

(a) ONSS (2020), (b) IEAGHG (2017)

4.2 Step 2: Determining the required daily storage of electricity

From Oman's National Spatial Strategy, Duqm's daily solar profile indicates that the guaranteed sunlight hours are between 7 am – 6 pm, i.e. 11 h (ONSS, 2020). However, since the green ammonia plant operation should continue for 24 h, some of the electricity produced during the daytime should be stored for use at nighttime (in a sand TES system or lithium-ion batteries). The power generated in the daytime will be used during the daytime for H_2 production and partially stored for the plant operation at nighttime. Eqs (4) and (5) are used to calculate the H_2 that will be produced during the daytime and the nighttime (and subsequently NH_3).

$$\frac{\text{t } H_2}{\text{daytime}} = \left(\frac{\text{sunlight h}}{\text{24 h/d}}\right) \times (\text{500 MW x 24 h/d}) \quad (4)$$

$$\frac{\text{t } H_2}{\text{nighttime}} = \left(\frac{\text{non-sunlight h}}{\text{24 h/d}}\right) \times (\text{500 MW x 24 h/d}) \quad (5)$$

4.3 Step 3: silica sand as the energy storage system (Scenario 1)

In the first scenario, the electricity stored during the day for hydrogen production during the night is stored in silica sand-TES systems. The amount of sand required to store the nighttime electricity needed by the 500 MW hydrogen/ammonia plant can be evaluated using Eq(6) and Eq(7), retrieved from (Ma et al., 2020). Table 5 includes the sand TES's combined gas power cycle design parameters. Based on the data shown in Table 6, the production cost of the silica sand set-up can be calculated using the scale-factor method in Eq(8), retrieved from (Sinnot and Towler, 2020). The lifetime normalised cost of green hydrogen or green ammonia when silica sand is used as the energy storage can then be calculated using Eqs(3) and (9).

$$\Delta E = (MW_t * t_{storage}) / \eta \quad (6)$$

$$\Delta E = m_s * C_p(T_f - T_i) \quad (7)$$

$$C_2/C_1 = (Q_2/Q_1)^{0.6} \quad (8)$$

$$\text{Storage Cost (US\$/kg)} = (\text{silica sand TES system or battery cost}) / (\text{kg product/y} * \text{Plant lifetime (y)}) \quad (9)$$

Table 5: TES power plant design parameters (Ma et al., 2020)

Parameter	Efficiency (%)	Storage Duration (h)	Inlet temp (°C)	Outlet temp (°C)	ΔT (°C)
Combined Power Cycle	52.5	13	1,200	300	900

Table 6: References data to calculate the cost of a silica sand TES system through the scale-factor method

Equipment	Sand cost	Fluidised-bed heat exchanger cost	Gas turbine	Steam turbine
Reference Cost	480 US$/ton[a]	4.58 M US$ for 255 MWe plant in 2014[b]	500-700 US$/kW[c] Asm. 60% MWe	670-1,140 US$/kW[d] Asm. 40% MWe

(a) Ma et al. (2020), (b) Stenberg et al. (2020), (c) Deal et al. (2010), (d) USDE (2016)

4.4 Step 4: Lithium-ion batteries as the energy storage system (Scenario 2)

In the second scenario, the electricity stored during the day for hydrogen production during the night is stored in lithium-ion batteries instead of a silica-sand TES system. In a recent study by NREL, the cost breakdown for a lithium-ion battery is illustrated in Table 7. Based on this data, the cost of lithium-ion batteries required to maintain the green hydrogen/ammonia plant's constant operation during nighttime can be calculated through Eq(10). The lifetime normalised cost of green hydrogen and green ammonia when lithium-ion batteries are used as the energy storage method can then be calculated using Eqs(3) and (10).

$$\text{Total Lithium-ion battery storage cost} = \text{Electricity Stored for night use (kWh)} * \text{Battery cost (US\$/kWh)} \quad (10)$$

Table 7: Utility-scale lithium-ion battery cost, 10-h storage duration (NREL, 2021)

Parameter	Battery Cost	Balance of system	Installation Cost	Total cost
Lithium-ion battery (US$/kWh)	224	73	48	345

5. Results and discussion

The use of silica sand as an electricity storage system for the continuous operation of green ammonia plants was significantly superior to the use of lithium-ion batteries, as discussed hereafter.
To meet the daily H_2 and NH_3 production targets in Table 3, the 500 MW plant was computed to require a tracking PV plant capacity of 1.05 GWp and 25 electrolysers of 20 MW capacity each. The normalised cost of the green ammonia plant (excluding energy storage cost) was also computed and summarised in Table 8. As shown in Table 9, the total daily electricity produced is 12,000 MWh – 5,500 MWh of which is used during the day for H_2 production and the other 6,500 MWh stored (in sand TES systems in scenario 1 or in lithium batteries in scenario 2) and used at night. The amount of H_2 produced during the day and night is thus shown in Table 9.

Table 8: Normalised cost of the green hydrogen and ammonia plant (excluding energy storage cost)

Normalised Cost	PV plant	Electrolyser	Ammonia Plant	CAPEX	OPEX	Total Cost
Hydrogen Plant (US$/kg$H_2$)	0.35	0.071	-	0.42	0.012	0.43
Ammonia Plant (US$/kg$NH_3$)	0.062	0.013	0.057	0.13	0.002	0.13

Table 9: Electricity Stored and H_2 produced during the daytime and nighttime

Parameter	Daily electricity generation	Daytime Operation		Nighttime Operation	
		Electricity used	H_2 Produced	Electricity used	H_2 produced
NH_3 plant	12,000 MWh	5,500 MWh	109 t H_2/daytime	6,500 MWh	129 t H_2/nighttime

The mass of silica sand required to store the 6,500 MWh of electricity at nighttime was calculated. This computed amount and critical design parameters of the combined gas power cycle are shown in Table 10. The unit production costs of hydrogen and ammonia were then computed. As shown in Figure 2, when using silica sand as a TES system, the unit production cost of hydrogen and ammonia was lower by approximately 58 % and 47 %, compared to when using lithium-ion batteries. As a result, the sand TES system scenario costs were as low as 0.60 US$/kg$H_2$ and 0.16 US$/kg$NH_3$. These significantly lower production costs result from the inexpensive and recyclable feedstock used in the construction and operation of a sand-TES system, as compared to the use of rare and expensive resources for the constructuion of lithium-ion batteries.

Table 10: Sand TES system power cycle parameters and required mass of sand

Sand TES System	Storage Duration (h)	Electric Load (MW_e)	Thermal Load (MW_t)	TES capacity (MWh_t)	Mass of Sand (t)
Data	13	500	952	23,583	154,562

6. Conclusion

The study involved analysing the economic potential of exploiting silica sand's high operating temperatures to store electricity in a green hydrogen/ammonia plant and comparing this to the use of lithium-ion batteries. The sand-TES system was found to significantly reduce the unit production cost of green hydrogen and ammonia by 59 % and 48 %, compared to the use of lithium-ion batteries. The low cost, abundance, and high thermal stability of silica sand, along with the simplicity of operation offered by a sand-TES system are vital factors that incentivise silica sand's use in powering renewable-based plants beyond sunlight hours. Recommendations for future work involves testing the thermophysical properties of Oman's silica sand rather than relying on NREL's data as well as constructing a pilot set-up to test Oman's silica sand thermal storage properties under the Sultanate's realistic environmental conditions**.**

Nomenclature

$C_{1,}$ – known item cost
CAPEX – Capital expenditure
ΔE – TES capacity, MWh_t
m_s – mass of silica sand, kg
η – Power Cycle Efficiency, %
Q_1 – known capacity
SEM – scanning electron microscope
TES – Thermal energy storage
C_2 – Unknown item cost
C_p – Specific Heat Capacity, J/kg.°C
LESA – Laser Elemental Spark Analysis
NREL – National Renewable Energy Laboratory
OPEX – Operational expenditure
Q_2 – known capacity
$T_{i,f}$ – entry and exit power cycle temperatures, °C
y – number of years

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