Comparative LCA of Two Thermal Energy Storage Systems for Shams1 Concentrated Solar Power Plant: Molten Salt vs. Concrete

Jubilee T. Adeoye, Yamrot M. Amha, Vahan H. Poghosyan, Khachatur Torchyan, and Hassan A. Arafat

***Abstract*—Thermal energy storage (TES) for concentrated solar power (CSP) is gaining popularity because it has the potential to increase the hours of electricity production from the CSP technology. In this Study, we conducted a comparative life cycle assessment (LCA) of two TES technologies (concrete and molten salt) for Shams-1 CSP plant in United Arab Emirates. Eco-Indicator 99 was employed to model the environmental impact per 800MWhe produced. Results obtained show that concrete TES has a greater environmental impact than molten salt TES, with fossil fuel being the largest impact contributor in both cases. A sensitivity analysis in which different scenarios were considered showed a reduction in environmental impact when waste recycling and transportation changes are incorporated. Based on the results obtained, incorporating molten salt TES in Shams 1 will have a lower environmental impact than the use of concrete TES.**

***Index Terms*—Concentrated solar power plant, concrete storage, life cycle assessment, molten salt storage, thermal energy storage.**

I. INTRODUCTION

Since the beginning of the industrial revolution, the atmospheric concentration of carbon dioxide has increased alarmingly by about 30%, due to human activities such as combustion of fossil fuels [1]. In Australia for example, electricity generation accounts for 45% of the carbon dioxide emission [2]. There is a need to reduce the quantity of CO_2 emission in order to mitigate its global warming effect. Hence, the development of renewable sources of electricity becomes relevant as the global requirement for electricity increases.

Electricity generation using Concentrated Solar Power (CSP) is a relatively new technology that utilizes solar thermal energy to produce electricity. In this system, highly reflective mirrors are employed to concentrate the Direct Normal Irradiance (DNI) of sunlight on receivers, through which Heat Transfer Fluid (HTF) is pumped. Afterwards, the HTF transfers the acquired heat to a steam generator to produce steam, which is used in a Rankine Cycle Steam Turbine for electricity generation [3].

Since the HTF is thermally stable and suitable for operations up to 400^{o}C [4], the temperature of the generated steam cannot exceed 380^{o}C. In order to increase the efficiency of the Rankine thermal cycle, CSP-natural gas hybridization can be used (Fig. 1). In this process, a booster heater is used to superheat the steam from 380^{o}C to 540^{o}C [5].

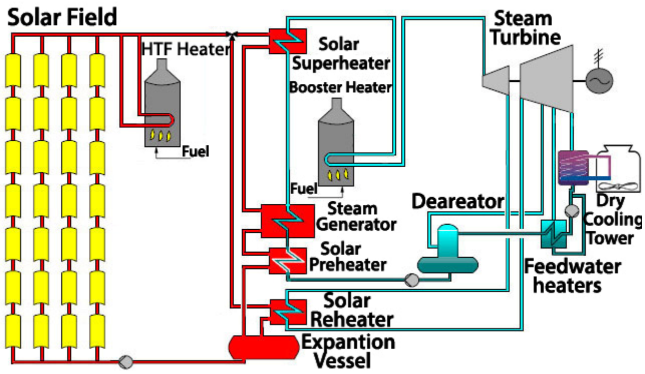

Fig. 1. Schematics of the hybrid CSP-natural gas plant [13]

The four configurations employed in CSP plants are Parabolic Trough, Solar Fresnel, Stand Alone Solar Dish, and Central Tower [3]. CSP mirrors are usually installed with a solar tracking system to ensure optimal capture of solar radiation [6]. Currently, the United States is the world leader in solar thermal power development, with 63% of the market share [7].

One disadvantage of CSP technology is that thermal energy generation is subject to daily fluctuations in solar radiation. In order to mitigate the effect of these fluctuations, the new direction is to install thermal energy storage (TES) systems. These systems store the excess thermal energy generated during the day so that it can be used at night when the sunlight energy is non-existent. Furthermore, the TES system will make the CSP system more efficient because daytime fluctuations in solar intensity can be compensated for by a regular supply of thermal energy from already stored energy [8]. In essence, the TES system acts like a battery for the CSP plant. Currently, there are only few commercial CSP plants with a TES system installed. Andasol 1,2, and 3 (in Spain), with a combined installed capacity of 150MW, are examples of plants that employ the Molten Salt TES system for energy storage [9]. Andasol 1 & 2 both have storage capacities for 7.5 full load hours daily, and individual net annual output of about 150 GWhe. Another promising

Manuscript received June 10, 2013; revised July 29, 2013.

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DOI: 10.7763/JOCET.2014.V2.139

alternative to molten salt TES is Concrete TES [10]. In this system, energy is stored within a concrete mass and utilized when needed. Currently, there are no commercial plants operating with concrete TES. However, there are several experimental setups for this system, such as the WESPE [11] and the WANDA [12] projects.

In line with the Abu Dhabi 2030 vision (UAE) of achieving 7% of total energy generation from renewables by the year 2020, the government of Abu Dhabi recently commissioned the Shams-1 100MW CSP-natural gas hybridization plant. Shams-1 is the largest operational single unit CSP plant in the world [6].

This plant covers 2.5 km^2 of land and utilizes over 258,000 mirrors for solar power generation using the parabolic trough system. Currently, there is no TES system in Shams-1. Therefore, the plant can only deliver electrical power generated from solar thermal energy to the grid during the day. In order to generate electrical energy at night, natural gas has to be used to heat up the HTF. However, there is a plan that future CSP plants with higher installed capacities will have TES systems that will enable them to operate up to 6000 full load hours annually [5].

In this study, we compare the environmental impacts of Concrete and Molten Salt TES systems for CSP plants, taking Shams-1 as a reference plant. This study will help in making decisions for future designs of the Shams-2 project and other commercial CSP plants. A professional LCA software, SimaPro v.7.0, was employed to conduct the impact assessment calculations.

II. System Description

A. Molten Salt TES

In this study, a two-tank indirect molten salt TES system was considered. The thermal energy storage material is a binary salt made up of 60% $NaNO_3$ and 40% KNO_3 with a freezing temperature of 220°C [14]. The heat transfer fluid (synthetic oil/Therminol VP-1), a mixture of 73.5% diphenyl oxide and 26.5% diphenyl, is made to run through the absorber tubes of the Solar Collector Assembly (SCA), where it is heated to 400°C. The HTF then carries the thermal energy directly to the steam generator for electricity production or into the heat exchanger where the thermal energy gained is exchanged with the cold molten salt (initial temp of 293°C), to raise its temperature to 393°C [15]. The hot molten salt is then pumped to the hot tank for storage. At night or during cloudy conditions, a reverse action occurs as the HTF flows through the heat exchanger, carrying the stored heat of the molten salt (380°C) to the steam generator for production of electricity. The cold molten salt is then pumped into the cold tank to start a new cycle (Fig. 2). In order to prevent the molten salt from freezing, heaters are installed in the cold tank to keep the temperature above 220°C. Fig. 3 shows the cross-section of the two-tank molten salt TES system and its design parameters.

Concrete TES employs a working principle similar to that of the Molten Salt TES. Furthermore, inlet and outlet temperatures of the HTF are similar in both TES systems [16]. However, the concrete TES differs from the molten salt system in that there are no heat exchangers in the concrete TES as shown in Fig. 4. Instead, direct heat transfer occurs between the HTF and the concrete via steel pipes embedded in concrete blocks (Fig. 5).

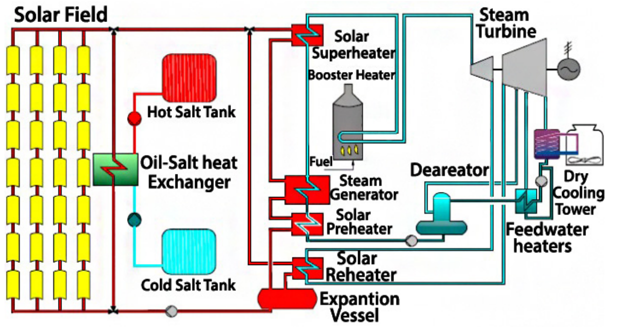

Fig. 2. Flow diagram of Molten Salt TES [13]

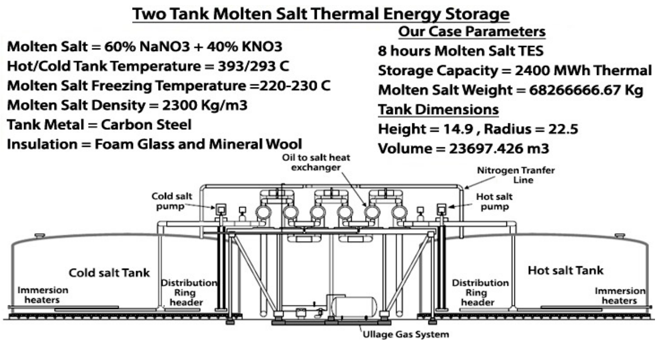

Fig. 3. Cross-section and parameters of two-tank Molten Salt TES Concrete TES [13]

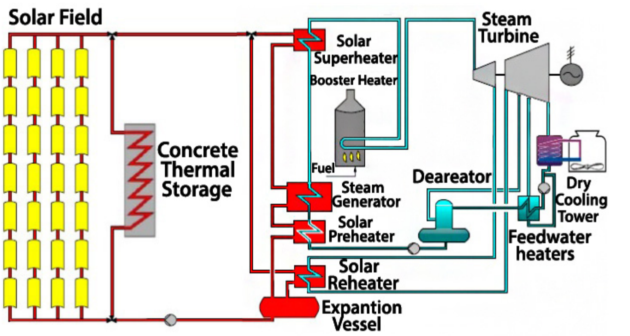

Fig. 4. Flow diagram of Concrete TES [13]

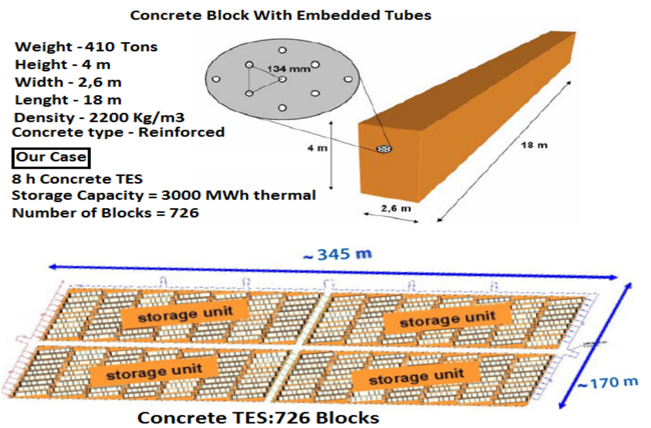

Fig. 5. Parameters of Concrete storage blocks imbedded with steel pipes [13]

Concrete TES is less efficient than molten salt TES due to high thermal losses in the system. Therefore, the concrete

TES usually requires a larger area of solar field to compensate for these losses.

III. Methodology

A. Goal Definition

The goal of this Life Cycle Assessment (LCA) is to compare the environmental impacts of Molten Salt TES and Concrete TES assuming that Shams-1 CSP plant (in UAE) is retrofitted to operate with a thermal storage system. Currently, Shams-1 has no energy storage capability. Hence, a hypothetical storage system will be designed for Shams-1 by scaling-up storage specifications from other plants such as Andasol 1 [17] and WANDA [11]. The study reflects the global environmental impact of installing a storage capability for Shams 1. That is, we took into consideration the additional solar field that will be needed for a specified storage capacity without taking into account the current energy production (Table I).

TABLE I: Inventory for the Additional Solar Field

Construction			
	Concrete Storage	Molten Salt Storage	
Flat Glass	1274	1019.20	kg
Copper	3.37	2.69	kg
Paint	11.2	8.96	kg
Concrete	9616.37	7693.09	kg
Reinforced Steel	3142.92	2514.34	kg
Chromium Steel	74.99	59.99	kg
Graphite	0.039	0.031	kg
Glass Tube, Borosilicate	4.26	3.41	kg
Aluminum Oxide	0.00062	0.0005	kg
Diphenylether73.5% & Phenol 26.5%	413.37	330.70	kg
Cast Iron	0.119	0.095	kg
Manganese	0.119	0.095	kg
Nickel	0.009	0.008	kg
Chromium	0.009	0.008	kg
Lubricating Oil	1.724	1.379	kg
Polyethylene, HDPE	1.038	0.831	kg
Area Used	414.41	331.53	m2
Maintenance			
Water	139566.12	111652.86	kg
Fuel, Diesel	25.41	20.16	kg

B. The Functional Unit

Defining the functional unit (FU) for this type of system presents a challenge because the two materials being considered have different properties. Hence, in order to allow for comparison, we have designed both systems for 8hrs full load electricity generation (100MW), which is defined as one cycle. We defined our FU as 800MWh electrical energy produced per cycle (one day).

The quantities of molten salt and concrete needed for 800MWh electrical energy production have been calculated based on previous studies, assuming a linear correlation [15]. For molten salt TES, the production of 100MW for 8 hours will require the storage of 2,400MWh thermal energy. For concrete TES, the production of 100 MW for 8 hours will require 3,000MWh thermal energy.

C. System Boundary

The system boundary of this LCA includes all activities from cradle to grave. Conceptually, this includes raw material extraction, manufacturing of system components, transportation, use, and disposal. The geographical boundary has been defined based on the location for product manufacture, use, and disposal. We have assumed that most of the system components are manufactured outside Abu Dhabi, while the use and disposal phases occur in Abu Dhabi. The disposal option chosen is landfilling, because it is the current predominant practice in Abu Dhabi. The TES has been designed for 30 years, which is also the expected life-time of Shams-1. As shown in Table II and Table III, the materials replaced within this period were taken into account based on the number of cycles for which they can be used [15].

TABLE II: Inventory for Concrete and Molten Salt Storages

Concrete Storage				
	Construction	Maintenance	Total	
Concrete	36766.16	0	36766.16	kg
Graphite Foil	4.38	0	4.38	kg
Stainless Steel	1302.01	0	1302.01	kg
Mineral Wool	493.53	987.06	1480.59	kg
Foam Glass	12.07	24.14	36.22	kg
Wood	7.97	0	7.97	kg
Diphenylether73.5% & Phenol 26.5%	312.76	312.76	625.51	kg
Nitrogen	0.05	0	0.05	kg
Area used	3.47	0	3.47	m2
Diesel Energy	3746.5	169066.7	172813.2	MJ
Electrical Energy	59.72	1756.27	1815.99	kWh
Molten Salt Storage				
	Construction	Maintenance	Total	
Concrete	1692.18	0	1692.18	kg
Molten Salt	8427.98	0	8427.98	kg
Stainless Steel	140.61	0	140.61	kg
Carbon Steel	446.75	0	446.75	kg
Mineral Wool	34.01	68.02	102.02	kg
Foam Glass	10.90	21.79	32.69	kg
Refractory Brick	80.15	160.30	240.44	kg
Nitrogen	141.23	0	141.23	kg
Area used	0.65	0	0.65	m2
Diesel Energy	3456.79	156800	160256.8	MJ
Electrical Energy	54.87	4751.73	4806.6	kWh

TABLE III: Life Cycle of Materials

	Expected Life (Cycles)	Equivalent factor
Concrete	10000	1
Graphite Foil	10000	1
Stainless Steel	10000	1
Mineral Wool	3650	3
Foam Glass	3650	3
Wood	10000	1
Diphenylether73.5% & Phenol 26.5%	7300	2
Molten Salt	10000	1
Carbon Steel	10000	1
Refractory Brick	3650	3

D. General Assumptions

Since Shams-1 is a new plant, there is no accurate information on its yearly hours of operation. However, Shams-1 is expected to generate 210 GWhe/yr [5]. This is equivalent to a capacity factor of 2100 hr/yr. For our analysis, we assumed that the plant operates 8 hours daily for 9 months in a year.

Some materials have been substituted because of lack of data in SimaPro as detailed below:

1) Therminol Vp-1 has been substituted with 73.5% diphenylether (w/w) and 26.5% phenol (w/w).
2) Sodium Nitrate salt has been substituted with the theoretical chemical reaction of Nitric Acid and Nitrate Hydroxide.

E. Base Case Scenario

The defined base case has the following characteristics:

1) For all materials produced in Europe, air transportation was assumed. Sea transportation was assumed for materials produced in the United States. All local transportation is by trucks.
2) The disposal scenario for the base case was assumed to be 100% landfilling.
3) The water used for cleaning the solar field mirrors is desalinated sea-water. Since the SimaPro database does not contain desalinated water, tap water was assumed and the energy required for desalination per unit volume was added.
4) The water and the materials used in the operation and maintenance phase are decoupled in order to avoid water land disposal, set as default by SimaPro.

IV. Results and Discussion

A. Base Case Scenario

In the base case scenario, most of the impact for both TES systems came from the manufacturing and construction phase rather than the operation, maintenance, and disposal phases.

The disposal phase is credited as the largest contributor to the carcinogen and ecotoxicity categories (Fig. 6 and Fig. 7). This is because the base case disposal scenario considered is landfilling, which results in carcinogenic emissions. Most of the impacts of the manufacturing and construction phases come from air transportation of materials. As for the operation and maintenance phases, the biggest impact can be traced to cleaning of mirrors.

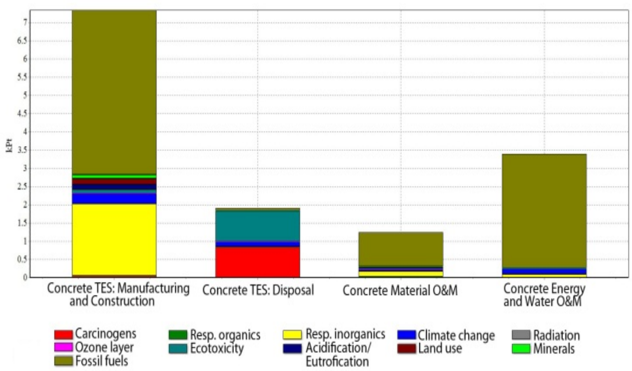

Fig. 6. Single score impact assessment of Concrete TES components

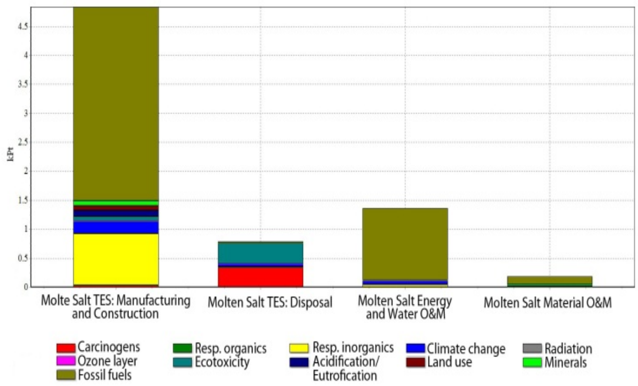

Fig. 7. Single score impact assessment of Molten Salt TES components

The base case environmental impact of the Molten Salt TES is 48.2% lower than the impact of the Concrete TES.

B. Sensitivity Analysis

In the base case scenario, the main environmental impact contributors were found to be transportation, water use and landfilling. Hence, we carried out a sensitivity analysis in which alternatives were considered for these three processes. Sensitivity analysis was carried out to test the robustness of the results obtained in the base case. The following scenarios were considered.

C. Material Recycling

In this scenario, we considered the recycling of steel, glass, polyethylene (PE), and polyvinylchloride (PVC) in the UAE. The energy required for dismantling the plant was considered in the analysis. However, the energy required for separating the dismantled materials was not taken into account.

D. Water Recycling

An on-site membrane bio-reactor (MBR) was considered for treatment of the water used in cleaning the mirrors. In this case, construction, operation, and maintenance of the MBR were considered. This almost eliminated the use of desalinated water.

E. Material Transportation

Production and transportation of materials from the local market and nearby countries was considered, instead of overseas markets.

F. Combined Scenario

A combination of all the three scenarios listed above was considered in order to model their cumulative effect.

G. Sensitivity Analysis Results

Detailed below are the changes in overall environmental impact due to the new considerations introduced in the sensitivity analysis cases.

1)Material Recycling Case

In the base case, all materials were landfilled at the end of life of the TES system. This resulted in a significant impact of carcinogens and ecotoxicity categories. In order to observe the change in environmental impact as a result of altering the disposal scenario, recycling in the UAE was taken into consideration for some materials. In this case, steel, glass, PE, and PVC were assumed to be recycled, based on the existing SimaPro recycling scenarios.

Since only a small portion of the materials was recycled, the change in the total impact is very small and can be said to be almost negligible (Fig. 8 and Fig. 9). With respect to individual impact categories, there is only a small percentage decrease in all categories (Fig. 10 and Fig. 11).

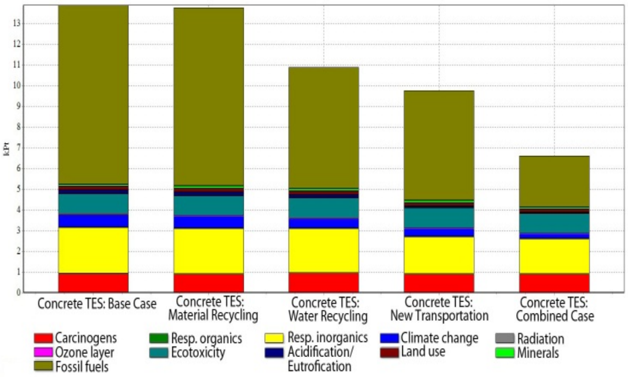

Fig. 8. Single score impact assessment comparison of all cases for Concrete TES

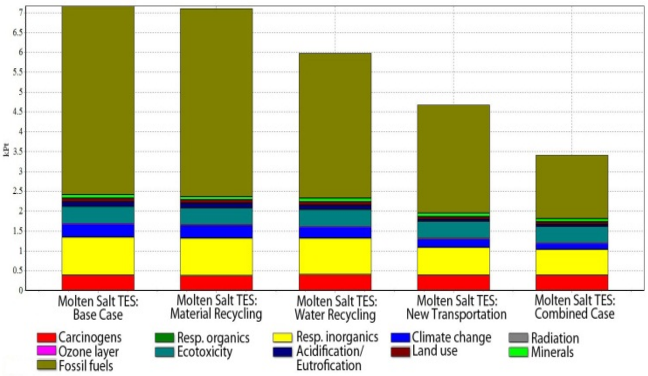

Fig. 9. Single score impact assessment comparison of all cases for Molten Salt TES

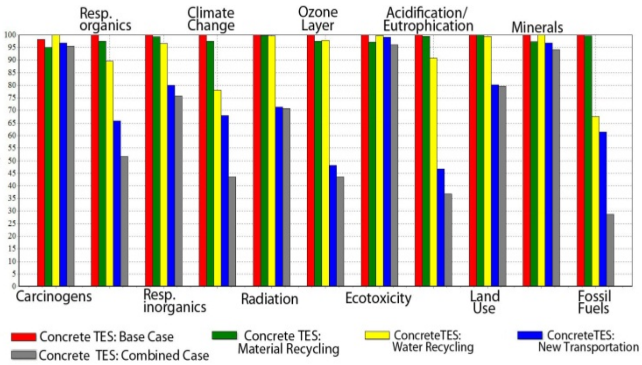

Fig. 10. Damage assessment comparison per category of all cases for Concrete TES

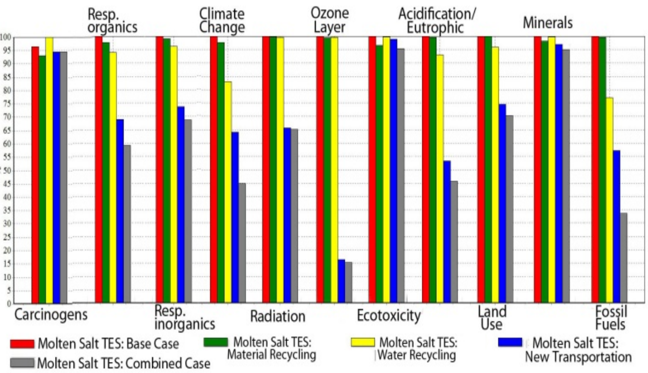

Fig. 11. Damage assessment comparison per category of all cases for Molten Salt TES

As a result of material recycling, a decrease in the mass of raw materials was observed in the inventory analysis. For example, glass recycling led to a drastic decrease in the mass of raw materials used, as every ton of glass recycled saved more than one ton of raw material needed to create new glass. The result also shows a negative flow of limestone (Fig. 12 and Fig. 13)

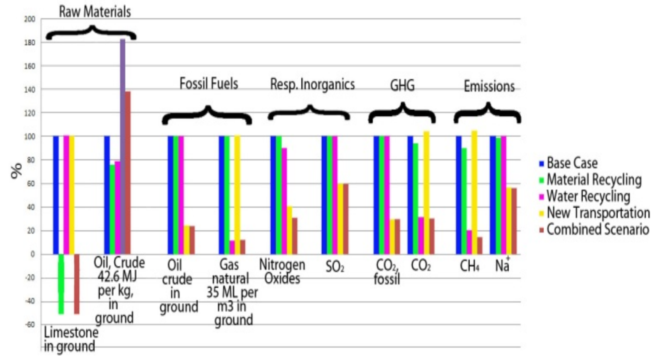

Fig. 12. Materials and emissions for Concrete TES

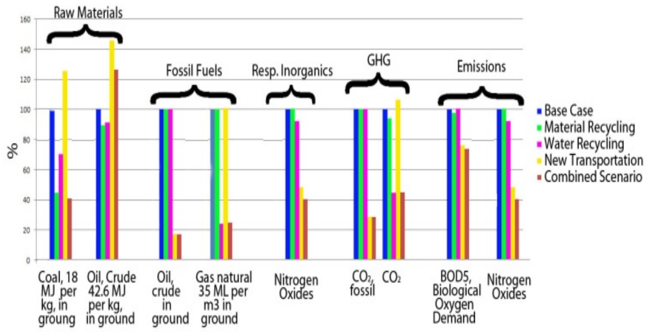

Fig. 13. Materials and emissions for Molten Salt TES

2) Water Recycling Case

In the base case, water was used for cleaning the mirrors. In order to understand the impact share of water in the system, we considered recycling the water used in cleaning the mirrors. For this reason, we designed an MBR plant to serve the CSP plant. The inventory for construction, operation and maintenance of the MBR plant, and collection of waste water are given in TABLE IV.

TABLE IV: INVENTORY FOR MBR

Construction			
	Concrete	MS	
PVC	0.35159	0.28127	kg
PVC pipes	0.20159	0.16127	kg
Cast Iron	0.00780	0.00624	kg
Bronze	0.00390	0.00312	kg
Stainless steel	0.05159	0.04127	kg
Polypropylene	0.00520	0.00416	kg
Area used	0.03086	0.02469	m2
Maintenance			
	Concrete	MS	
Potassium Hydroxide	0.03902	0.03121	kg
Hydrochloride	0.01777	0.01422	kg
Electricity	0.04270	0.03416	kWh

The results show that water recycling decreases the overall impact by 21.5% and 16.6% for Concrete and Molten Salt

TES, respectively (Fig. 8 and Fig. 9). Although the overall impact is decreased, the impact in carcinogens has increased in both cases due to the operation of the MBR plant. The categories which have experienced the largest decrease are fossil fuels consumption and climate change which decreased, respectively, by 32% and 22% for Concrete TES and by 23% and 16% for Molten Salt TES (Fig. 10 and Fig. 11). This has been achieved due to the energy saved by eliminating water desalination.

Water recycling decreased natural gas use, CO_2 emission, and methane emission because in the UAE, natural gas is used to produce electricity for water desalination (Fig. 12 and Fig. 13).

In general, water recycling leads to a reduction in total impact, despite the increase it causes in carcinogens.

3) New Transportation Case

In the base case, air transport of construction materials was the main contributor to fossil fuels and climate change. Hence, in this scenario, we considered sourcing raw materials from countries nearby, such as India (TABLE V). Therefore, the energy mix of India was taken into consideration. In addition, air transport was substituted by sea transport. Road transport was left unaltered.

TABLE V: TRANSPORTATION OF THE MATERIALS

	Base Case		New Case	
	Country	Distance (Km)	Country	Distance (Km)
Concrete	AE	120	AE	120
Graphite Foil	ES	7547	IN	2677
Stainless Steel	DE	6292	IN	2622
Mineral Wool	CH	6217	IN	2622
Foam Glass	CZ	5769	IN	2622
Wood	CH	6217	IN	3809
Diphenylether73.5% & Phenol 26.5%	US	16693	US	16693
Nitrogen	CH	6217	AE	280
Molten Salt	US	13208	US	16693
Carbon Steel	TR	3251	IN	2622
Refractory Brick	DE	6264	IN	2622
Flat glass	DE	6047.9	DE	9717
Copper	NL	6706	IN	2622
Paint	AE	280	IN	2622
Reinforced Steel	DE	6292	IN	2622
Chromium Steel	DE	6292	IN	2622
Graphite	DE	4870	IN	2777
Glass Tube, Borosilicate	DE	6292	DE	9784
Aluminum Oxide	DE	4783	IN	2622
Cast Iron	PL	4266	AE	280
Manganese	UA	2082	IN	2645
Nickel	NL	6706	IN	3012
Chromium	BG	3335	IN	2622
Lubricating Oil	TR	2417	AE	305
Polyethylene, HDPE	SE	4827	AE	305
PVC	-	-	AE	120
PVC pipes	-	-	AE	120
Polypropylene	-	-	AE	120
Bronze	-	-	DE	6022
Cast Iron	-	-	DE	6022

Result obtained showed that the change from air transportation to sea and road transportation cut down the total impact by 28.6% and 34.7% for Concrete and Molten Salt TES respectively (Fig. 8 and Fig. 9). This is due to a decrease in fossil fuel use and the associated CO_2 emission. Fig. 10 and Fig. 11 show the damage assessment per impact category for molten salt and concrete TES systems. It can be observed that the highest decrease occur in ozone layer and eutrophication categories, though these two categories account for a small shear of the total impact.

The change in transportation and energy mix caused an increase in the amount of coal and crude oil used as raw materials mainly because of the energy mix of India. On the other hand, it led to a decrease in the amount of crude oil as fossil fuel, NO_x, SO_x, CO_2, BOD5, and Sodium ion emissions (Fig. 12 and Fig. 13).

4) Combined Case

In this analysis, we considered a combination of all the three scenarios described above.

The result shows a decrease in the total impact by 52.5 % and 52.7% for Concrete and Molten Salt TES, respectively (Fig. 14). In both systems, the main contributors to the total impact are fossil fuels, climate change, ozone layer, and eutrophication (Fig. 15). Although the new transportation scenario increased the amount of coal used as raw material, in the combined case, the total amount of coal used decreased. This is due to the reduction in coal from the other two scenarios (Fig. 15). The combined scenario gives the largest decrease in the total environmental impact compared to all other scenarios.

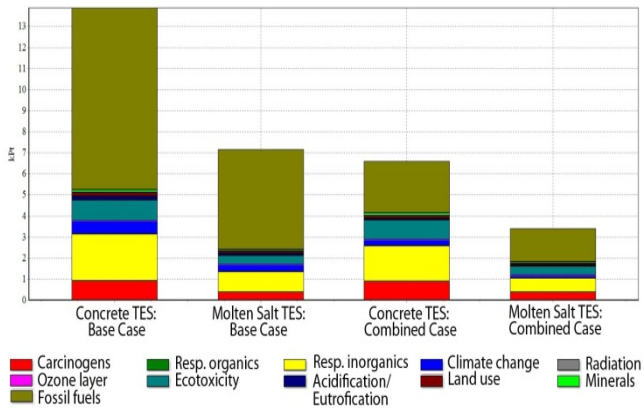

Fig. 14. Single score impact assessment comparison of base and combined cases for Molten Salt TES and Concrete TES

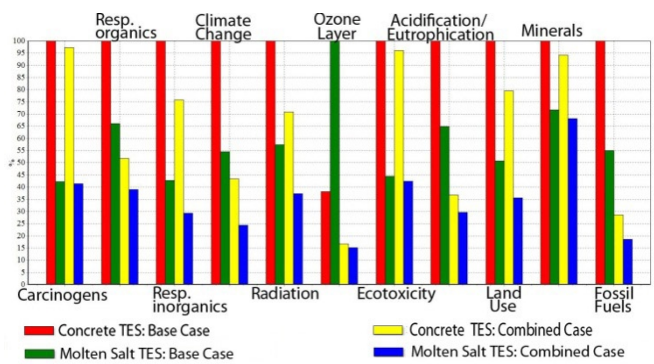

Fig. 15. Damage assessment comparison per category of base and combined cases for Concrete TES and Molten Salt TES

In some categories, the total impact change is the average of the impact changes from all the scenarios, while in others, it can be noticed that only one of the scenarios is responsible for the total change.

V. Study Limitations

TES for CSP plants is still a new technology and there are only a few commercial CSP plant with molten salt TES, while only pilot plants that use concrete TES exist. Therefore, we had to extrapolate the inventory for Andasol and WANDA in order to design a TES for UAE's Shams-1. By doing this, we have assumed a linear correlation between the storage capacity and the quantity of construction material. However, this linear relationship does not hold in all cases.

Some of the raw materials were not found in the SimaPro database and had to be substituted with similar materials.

Recycling is still a new concept in Abu Dhabi and we were only able to project the recycling of a small portion of the material flow. Therefore, the recycling analysis did not show us the overall impact of complete material recycling.

We excluded capital goods from our inventory due to limitation of data. In similar studies reviewed, this approach has been adopted [18], [19]. However, this is a critical limitation because capital goods have a significant contribution in the manufacturing phase of renewable energy infrastructure [18], [20].

VI. Conclusion

A comparative LCA was performed for two thermal energy storage systems for Shams-1 CSP plants in UAE; concrete TES and molten salt TES. Eco-Indicator 99 (EI99) was used to compare the environmental impact per 800MWhe. The results show that the concrete TES has a greater environmental impact than the molten salt TES. The biggest impact contributors in both cases were fossil fuel and respiratory inorganics. The sensitivity analysis showed that the impact can be reduced by employing a combination of transportation alternatives, on-site water recycling, and material recycling. Overall, we recommend molten salt as a more environmentally friendly thermal storage system for Shams-1.

Since the highest impact contributions for both TES systems come from the manufacturing & construction steps, of which transport of raw materials plays a significant role, it is highly recommended to minimize transportation by looking into local markets or countries nearby. Furthermore, the sensitivity analysis showed that the impact reduction occurred in the descending order of combined case, new transport scenario, water recycling, and material recycling.

Overall, there was a 53% and 50% reduction of impact between our base case and combined scenario for the concrete TES and Molten Salt TES respectively. Therefore, we recommend the implementation of the combined scenario in order to significantly reduce the environmental impact of the TES system.

Acknowledgment

The authors are grateful to Abdulaziz Al Obaidli, Senior Process Engineer, Shams-1 Power Company for his comments that helped improve this manuscript.

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