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Technical Report
NREL/TP-5500-64429
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Summary

This study lists material composition data for two concentrating solar power (CSP) plant designs: a molten-salt power tower and a hypothetical parabolic trough plant, both of which employ a molten salt for the heat transfer fluid (HTF) and thermal storage media. The two designs have equivalent generating and thermal energy storage capacities. The material content of the salt-HTF trough plant was approximately 25% lower than a comparably sized conventional oil-HTF parabolic trough plant. The significant reduction in oil, salt, metal, and insulation mass by switching to a salt-HTF design is expected to reduce the capital cost and LCOE for the parabolic trough system.

The report relies primarily on data generated through two prior studies undertaken with WorleyParsons Group that estimated the material content of a molten-salt power tower [1] and oil-HTF parabolic trough plants [2]. New analysis is provided with regard to the material composition of the power tower solar field and the sizing of a salt-HTF trough solar field and HTF system. The overall embodied mass of the salt-HTF trough plant was slightly below that of the salt tower design. The similarity in the total mass of the two designs, combined with the inherent similarity in how the two plants would operate, suggests that salt-HTF trough plants could be competitive with molten-salt power towers if the technical hurdles of deploying salt in the solar field can be overcome. The potential cost and complexity of freeze protection and freeze recovery technology are viewed as having the greatest impact on the viability of salt-HTF troughs. The development of acceptable flexible connections that are compatible with molten salt has also been a challenge.

CSP plants are composed mainly of steel, glass, concrete and aggregate materials, which are abundantly available from domestic sources. This is true for most locations in the world where CSP plants might be deployed and is an attractive attribute of the technology with regards to its impact on the local economy. In the U.S., we estimate that 90% by mass and 79% by value of the commodity materials utilized in a CSP plant can be supplied by domestic sources.

Background and Motivation

The availability of critical materials is a concern for many renewable energy technologies. In general, CSP technologies do not rely on rare earth metals, lithium, or other materials viewed as having potentially restricted supply. Indeed, CSP plants are constructed mainly from steel and glass, which are abundant worldwide and frequently supplied by local sources. Consequently, the material composition, life-cycle cost, material source location, and economic impact of CSP plants could have a role in limiting or enhancing CSP deployment.

The cost of solar photovoltaics (PV) has dropped dramatically in recent years, and utility-scale PV now represents the lowest-cost method of generating solar power [3]. In response to this new reality, CSP's role in the solar-generation marketplace has switched from being the lowest-cost energy provider to being the technology that can provide dispatchable, high-value power based on the inclusion of thermal energy storage (TES). Quantifying the value of energy storage is complex and depends on the specifics of the grid into which the power is to be dispatched. Recent studies by NREL indicate that capacity value of CSP systems could be the key to their continued deployment [4], [5].

In addition to the advantage provided by thermal energy storage, CSP plants tend to have a much higher content of locally sourced materials than PV plants. That translates into greater benefit to the economy of the host country. This report seeks to further the understanding of that aspect of CSP plant design by building on previous assessments of the material content of state-of-the-art CSP plants [1], [2], and assessing the fraction of those materials likely to come from domestic suppliers. The report looks exclusively at plants that use solar salt as the HTF and thermal storage media: a molten-salt power tower and a hypothetical molten-salt parabolic trough plant.

The inclusion of thermal energy storage is viewed as an essential aspect to the commercial viability of CSP plants in the U.S. In addition, overall cost for the technology must continue to decline to be competitive with alternative generation methods. In late 2013, NREL updated its estimate of CSP technology costs for the U.S. Department of Energy. Consistent with other sources, the results show that molten-salt power tower systems have a significantly lower cost compared to the oil-HTF trough systems that were taken as the baseline technology in 2010 (Figure 1). These values were used to update the DOE SunShot program estimates for CSP cost [6].

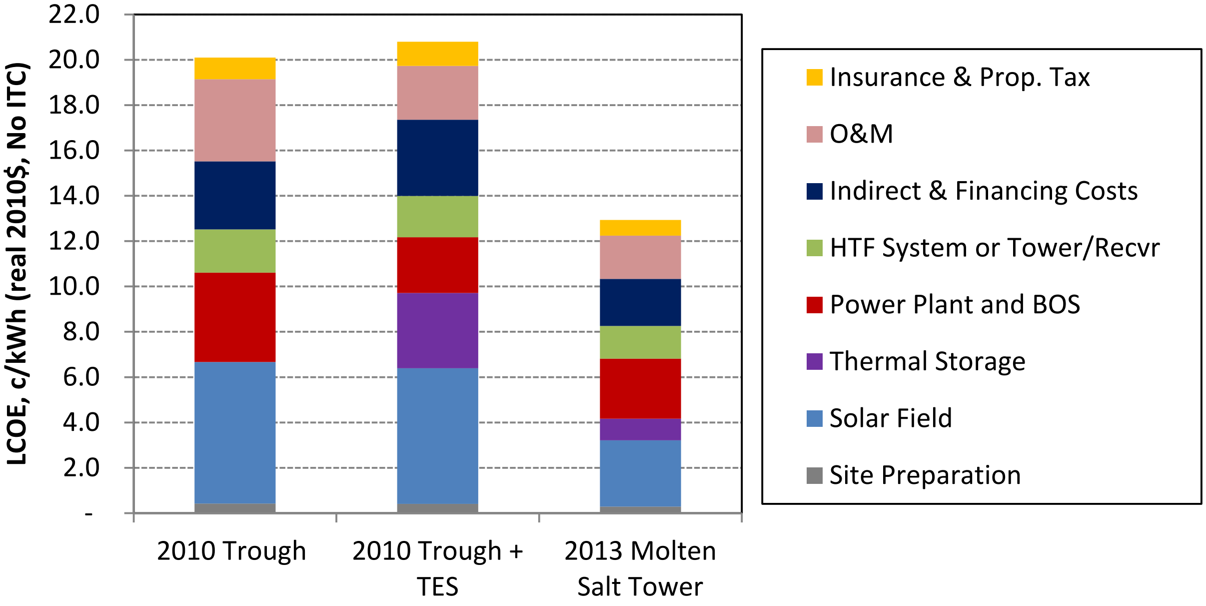

Figure 1. Estimated levelized cost of energy from CSP technologies in the U.S. The values assume no investment tax credit and are shown in real 2010 dollars. Assumptions are listed in Appendix A.

The analysis depicted in Figure 1 reveals that molten-salt power towers offer a significant advantage in cost versus the traditional oil-HTF parabolic trough design. Several factors contribute to this:

- Power towers can achieve higher operating temperatures (approx. 565°C versus 390°C), which allows more efficient thermal-to-electric conversion in the power cycle;
- By using molten salt as the HTF and thermal storage media, the power tower system eliminates the need for oil-to-salt heat exchangers, thereby increasing TES efficiency and lowering equipment costs;

- The higher operating temperature of power tower systems allows the TES system to span a wider temperature range, which greatly increases the energy storage per tonne of salt and reduces salt requirements per $\mathrm{MWh_{th}}$ of storage.

Furthermore, while the 2010 trough cost numbers assumed a wet-cooled power plant, the 2013 tower values are based on the use of dry cooling. This switch reduces the water requirements for plant operation by 90% or more [7], which is viewed as an essential element of deployment in the drought-stricken Southwest. The cycle-efficiency penalty for switching to dry cooling is lower for a power tower because of its higher operating temperature. The power tower advantages listed above are contingent on the ability to use a high-temperature HTF, such as solar salt, rather than oil as the HTF in the receiver. If trough systems could deploy the same or a similar molten-salt HTF, they could also take advantage of these attributes.

Various teams have explored the potential of using molten salt as the HTF in a parabolic trough plant [8] - [9], and the 5-MW Archimede facility in Sicily is testing molten salt in troughs [10]. These industry studies have predicted that molten-salt HTF plants could reduce the LCOE of parabolic trough technology by approximately 15%. However, the challenge of dealing with extensive piping and receiver networks filled with molten salt have proven difficult to overcome, the major issues being the needed development of reliable flex-joints for the rotating troughs and the risk associated with potential freezing of the HTF network.

Approach

At present, the most common CSP technology is the parabolic trough utilizing a synthetic-oil HTF and operating at a solar-field outlet temperature of about 390°C, which is the maximum operating temperature of these oils. These plants have been deployed with TES in the form of a two-tank, indirect system that utilizes molten salt as the storage media, see Figure 2.

Figure 2. An oil-HTF parabolic trough plant with molten-salt TES tanks under construction.
Photo courtesy Solar Millennium AG

In contrast, the use of molten salt as the HTF with direct storage leads to greater efficiency and lower cost. In the present analysis we assume the power tower and parabolic trough plants employ this design. Solar salt, a blend of 60wt% sodium nitrate and 40wt% potassium nitrate, is the HTF and thermal storage media. Solar Salt is used in the Archimede molten-salt parabolic trough pilot test. The use of Solar Salt allows a straightforward comparison with molten-salt power towers and oil-trough plants using indirect TES with Solar Salt. Other salts might be better suited as the solar field HTF, but if direct TES is cost prohibitive some of the advantages of the molten-salt trough plant design are lost.

The subsystems of a power tower plant using this design are depicted in Figure 3. This design is employed at Gemasolar in Spain and Crescent Dunes in the U.S. A molten-salt parabolic trough plant would have the same subsystems that are depicted in Figure 3. An overview of the two plant designs is presented in Table 1.

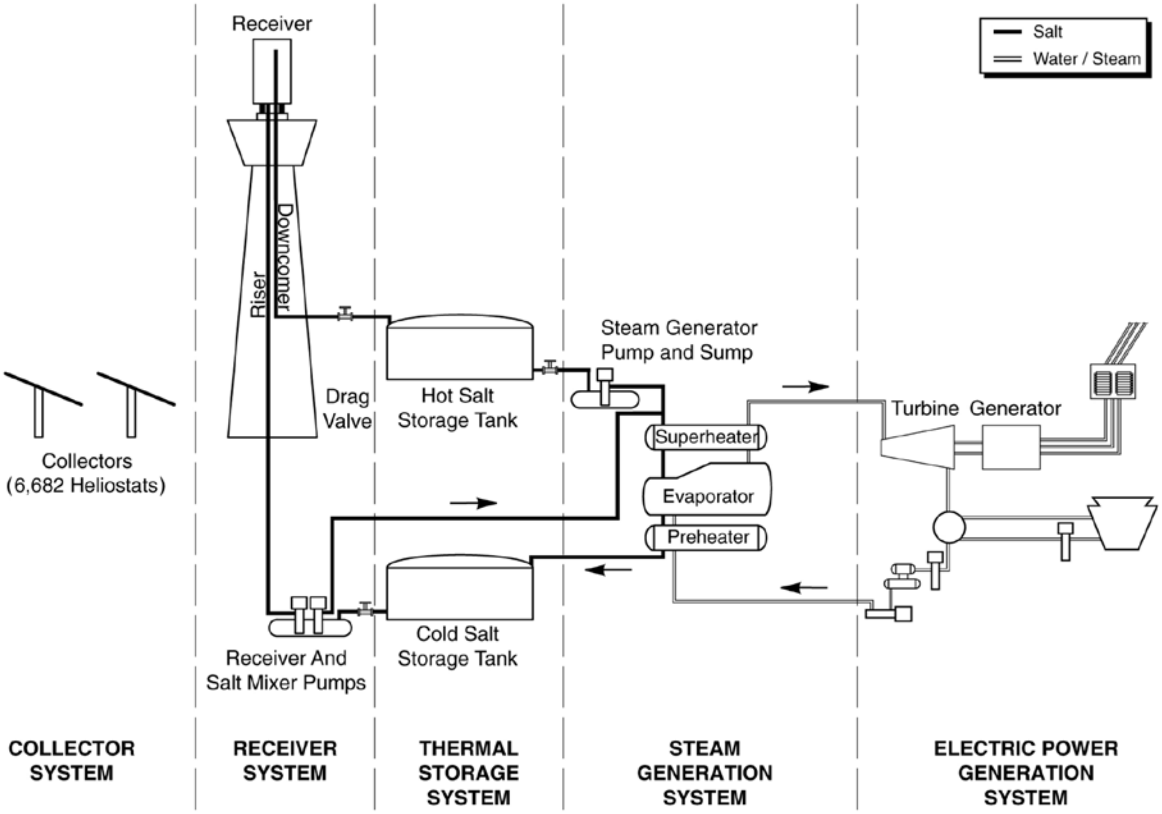

Figure 3. Schematic of a molten salt power tower showing major subsystems [7].

Table 1. CSP plant specifications use in this analysis.

Plant Property	Parabolic Trough	Power Tower
Nameplate Capacity (net)	103 MW_e	102 MW_e
Thermal Storage (operating time at nameplate capacity)	6.3 hours	6 hours
Solar Multiple	2.1	1.9
Solar Field Aperture Area (m^2)	981,000	1,061,000
Receiver outlet and Hot Tank temp.	500°C	574°C
Cold Tank temperature	293°C	290°C
Turbine inlet temperature	490°C	565°C
Heat Transfer Fluid	Solar salt	
Storage Fluid	Solar salt	
Thermal Storage System	Direct “2-tank” system	
Power Cycle	Superheated steam Rankine cycle with reheat and dry cooling	
Power cycle gross efficiency	0.395	0.412
Location	southwest Arizona	southwest Arizona

Molten-Salt Parabolic Trough Plant

A parabolic trough plant using solar salt as the HTF was developed in NREL’s System Advisor Model (SAM) version 2014-01-14. The starting point for the design was the dry-cooled parabolic trough plant modeled by WorleyParsons in 2010 for NREL’s parabolic trough cost and life cycle assessment studies [2], [11]. This starting design was modified in SAM by setting the solar field HTF to Solar Salt. This change causes SAM to automatically shift the thermal energy storage system to a direct 2-tank system because the thermal storage fluid now matches the field HTF. The power block operating temperature and TES temperatures were raised to the values noted in Table 1. A target solar-field exit temperature of 500°C was selected based on prior analysis [12] [13]; this temperature is well within the operating bounds of Solar Salt. Other system variables, such as power block startup temperature and field freeze protection temperature were also raised.

The Solar Collector Assembly (SCA) was left at the SAM library value for the EuroTrough ET150, which was used in the prior analysis. However, the number of SCAs in a loop was expanded to six to accommodate the higher temperatures and properties of Solar Salt. The model assumes use of Schott’s PTR80 for the solar receiver. The PTR80 has been proposed for use with large-aperture troughs (aperture > 5.5 m) such as the ET150 and SkyTrough. Receiver selection is an important consideration with high-temperature, large aperture troughs. A receiver diameter that is too large will lead to excessive heat loss, while one that is too small can negatively impact intercept factor and HTF pressure drop. In the present case, the estimated average heat loss at design conditions was raised from 190 W/m to 500 W/m, reflecting the higher average operating temperature of the receiver [14]. This value is used for initial system sizing; during a simulation, SAM calculates heat loss from the receivers based on fundamental heat transfer models developed by Forristall (see [15]), thereby accounting for greater heat loss at the higher operating temperatures.

The gross power block efficiency was raised to 0.395, representative of the improvement one may expect when turbine inlet temperature is increased to 490°C [12]. The dry-cooling conditions were left unchanged from the prior WorleyParsons-study assumptions.

A comparison of the conventional oil-HTF trough plant and the new salt-HTF trough plant is informative. Table 2 shows a high-level comparison of the two plants. Power block and thermal storage capacity are equivalent. The most obvious changes are a slight decrease in the solar aperture area and a drastic decrease in TES mass. These changes result from the increased power block efficiency and the larger temperature differential across the TES system. The cost impacts of these changes would be a large drop in TES cost per kWh_{th}, a slight drop in absolute solar field cost, and an increase in power block cost due to the higher operating temperature, which necessitates more robust materials.

Table 2. Oil-HTF and salt-HTF trough plant comparison. Both plants are dry cooled.

Plant Property	Oil-HTF Trough	Salt-HTF Trough	Change
Nameplate Capacity (net)	103 MW_e	103 MW_e	-
Thermal Storage (op. time at full capacity)	6.3 hours	6.3 hours	-
Solar Field Aperture Area	1,063,000 m^2	981,000 m^2	-8%
SCA per loop	4	6	
Number of loops	325	200	
Receiver outlet	393°C	500°C	+107°C
Hot Tank temperature	388°C	500°C	
Cold Tank temperature	300°C	290°C	
TES temp. differential	88°C	210°C	+239%
TES salt mass	58,180 MT	22,120 MT	-62%
Power cycle gross efficiency with dry cooling	0.355	0.395	+11%
Location	southwest Arizona	southwest Arizona	
Estimated annual generation	388,000 MWh	395,000 MWh	

One change that is not obvious from the general SAM outputs is a significant decrease in HTF system size (and cost). This results from the different physical properties of the two HTFs. The impact is summarized in Table 3. Even accounting for the need to use stainless steel rather than carbon steel for the hot header piping, the switch to a salt HTF leads to a substantial decrease in HTF system cost due to the lesser amounts of steel, HTF, and insulation that are required. There is also an approximately threefold decrease in the amount of energy required for the HTF pumps.

Table 3. Impact of HTF on solar field header properties based on SAM's header piping model [15].

Plant Property	Oil-HTF Trough	Salt-HTF Trough
Primary header diameter	1.0287 m (40.5 in)	0.5334 m (21.0 in)
Hot header material	carbon steel	stainless steel
Cold header material	carbon steel	carbon steel
Carbon steel mass (MT) in headers	3017	807
Stainless steel mass (MT) in headers	-	404
Header pipe surface area (m^2)	33,000	15,000
HTF volume in headers (m^3)	6,500	2,400
Approximate HTF value in headers	$21M	$4.4M
Annual HTF pumping energy	6100 MWh	2200 MWh

A missing component in this analysis is the risk associated with potential salt freezing and the cost of mitigating that risk. Abengoa Solar reported that conventional heat-tracing/freeze-recovery costs could negate much of the potential capital cost savings in a salt-HTF System [16]. Fraunhofer reported similar findings [13]. A low-melting salt would provide a clear advantage in this regard, assuming one maintains high-temperature thermal stability and reasonable cost. As yet no formulation has emerged as a satisfactory candidate and most research still assumes Solar Salt or some related nitrate/nitrite salt variation as the leading contender for use in a salt-HTF trough facility. Researchers at Fraunhofer suggest that residual, otherwise unusable, energy from a thermocline storage system could provide freeze protection energy [17]; however, freeze-recovery hardware would likely still be required. One path is to use a low-melting (but more expensive) salt as the HTF and retain Solar Salt as the TES media. However, unless a salt with a near-ambient melting point is developed, this approach may be ineffective as heat tracing may still be deemed necessary.

It is important to note that, unlike water, molten salts contract when freezing and expand when thawing. Thus, the act of freezing generally does not damage the piping systems. It is the thawing process that must be carefully controlled to avoid any permanent deformation on the piping and receivers.

Molten-Salt Power Tower Plant

The molten-salt power tower conceptual design (see Figure 3) was taken directly from NREL's prior analysis that was performed with WorleyParsons [1]. This included development of a SAM model representing the plant, which was updated to SAM 2014-01-14 in this work. The previous work developed a heat & mass balance of the major HTF, feedwater and steam generation systems to establish design flow, temperature and pressure parameters for the associated equipment and piping. A process flow schematic of the major plant systems is provided in Figure 4.

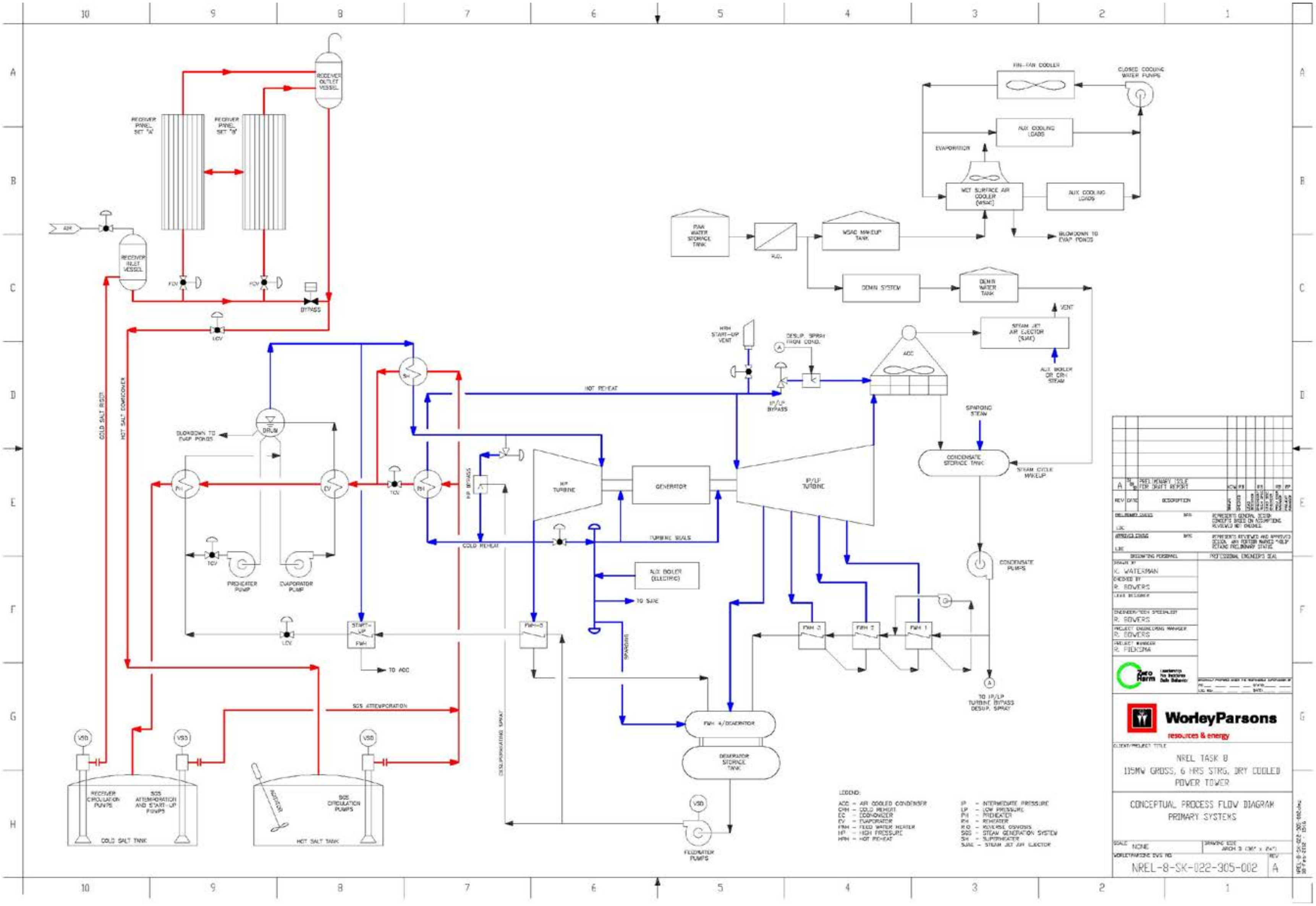

Figure 4. Process flow diagram for the molten-salt power tower plant [1].

For the receiver design, NREL provided the thermal-transfer capacity, panel quantity, diameter, and height of the solar receiver and also the panel tube diameter, wall thickness, and solar absorption length. Tube quantities per panel were calculated from these data, and structures were designed to support the panel tubes and headers. An additional structure attached to the top of the tower was designed to support the panels, boom crane, salt inlet vessel, salt outlet vessel, salt overflow vessel, and other auxiliary receiver equipment. A concrete tower was designed based on the seismic criteria and typical soils found in the Tucson, AZ area. The weight of the receiver and equipment, salt piping, heat tracing, insulation, instrumentation, and wiring was calculated to determine the design load on top of and inside of the concrete tower. The tower and receiver included stairs, platforms, and elevators for personnel and equipment.

The prior WorleyParsons analysis did not include material data for the solar field. In the present work NREL estimates the mass of the solar field assuming deployment of BrightSource Energy's LH-2.2 heliostat. This design is used at the Ivanpah Solar Electric Generating System in southern California, and represents a modern, high-production-volume design. Approximately 173,000 heliostats are installed at the 3-tower site (Figure 5). The LH-2.2 design uses two glass panels, each 230 cm x 330 cm, for a total reflector area of 15.2 m^2. The unit is constructed primarily of steel and glass. NREL estimated the weight of the heliostat, including the mounting pylon, based on published information related to the structural design, e.g., [18], [19], [20] and inclusion of a representative 2-axis drive system. The heliostat pylons are physically driven into the ground and do not use concrete foundations. The solar field mass composition is presented in the following section.

Figure 5. LH-2.2 heliostats at Ivanpah.

Photo by Gilles Mingasson/Getty Images for Bechtel. Used with permission.

Plant Materials

The total mass of materials associated with the two molten-salt plant designs is shown in Table 4. A listing by subsystem is provided in Table 5. The values for the conventional oil-HTF parabolic trough plant are also shown for comparison. As noted in the previous discussion, these plants are nominally the same capacity and generate approximately the same amount of energy per year. The material savings associated with the switch from an oil-HTF to a molten-salt HTF is clearly shown, with the majority of the savings coming from the change in fluid requirements, i.e., oil vs. molten salt.

Differences in the structure of the two prior WorleyParsons analyses lead to some inconsistencies in how the data are reported. For example, the original analysis of the oil-HTF parabolic trough plant included the steam generator train and power block in the same subsystem [11]. This was separated in the power tower analysis [1], following the convention established in previous power tower studies [21]. Because the salt-HTF trough plant operates at conditions more similar to the molten-salt power tower, the material values for the power tower design were used for the power block and steam generator subsystems in the salt-HTF trough plant. Similarly, the TES system for the salt-HTF trough plant was scaled linearly from the power tower TES data, based on the amount of required salt estimated within the two SAM models.

Table 4. Comparison of materials content (in MT) of three different nominal 103 MWe CSP plants with 6 hours of thermal storage.

Material (metric tonnes)	Oil-HTF Trough	Salt-HTF Trough	Salt Power Tower
Carbon Steel, Iron and Zinc	30,804	26,367	28,107
Stainless Steel	1,918	2,283	1,010
Alloy Steel	1	261	335
Copper	140	334	427
Silver	1	1	1
Ferronickel	11	10	-
Aluminum	441	333	287
Insulation	2,755	2,169	1,277
Glass	12,211	11,261	10,055
Plastics	508	400	617
Glue	12	11	-
Paint	233	215	-
Oils and lubricants	4,600	95	95
Sodium nitrate (solar salt)	40,100	16,301	10,451
Potassium nitrate (solar salt)	26,700	10,867	6,967
Nitrogen	18	-	-
Concrete and brick	66,661	59,088	78,829
Cement	49	-	-
Asphalt	7,960	7,347	3,879
Crushed Stone and Gravel	53,081	49,087	46,889
System Total	248,204	186,431	189,227

Table 5. Material content (in MT) for an oil-HTF Trough Plant (top), a molten-salt-HTF Trough Plant (middle), and a molten-salt Power Tower Plant (bottom).

Oil-HTF Parabolic Trough Plant Material (metric tonnes) / System	Site Improvements	HTF System		Solar Field	Power Plant & Steam Generator Systems		TES	Sum for Power Plant
Carbon Steel, Iron and Zinc	68	3,640		18,652	5,093		3,351	30,804
Stainless Steel	2	22		899	26		969	1,918
Alloy Steel	1							1
Copper	1	6		63	67		2	140
Silver				1.2				1
Ferronickel				11				11
Aluminum		56		18	366		1	441
Insulation		564		175	87		1,929	2,755
Glass		-		12,200	11		-	12,211
Plastics	264			24	126		95	508
Glue				12				12
Paint				233				233
Oils and lubricants		4,600		-	-		-	4,600
Sodium nitrate (solar salt)		-		-	-		40,100	40,100
Potassium nitrate (solar salt)		-		-	-		26,700	26,700
Nitrogen		18						18
Concrete and brick	413	5,920		30,200	20,028		10,100	66,661
Cement (exclusive of concrete)					49			49
Asphalt	7,960	-					-	7,960
Crushed Stone and Gravel	52,300	781					-	53,081
System Total	61,008	15,608		62,489	25,853	-	83,246	248,204

Salt-HTF Parabolic Trough Plant Material (metric tonnes) / System	Site Improvements	HTF System		Solar Field	Power Plant Systems	Steam Generator System	TES	Sum for Power Plant
Carbon Steel, Iron and Zinc	63	570		17,216	4,907	2,794	817	26,367
Stainless Steel	2	426		830	67	254	705	2,283
Alloy Steel	1	-		-	249	8	3	261
Copper	1	6		58	185	68	16	334
Silver	-	-		1.1	-	-	-	1
Ferronickel	-	-		10	-	-	-	10
Aluminum	-	26		17	257	7	27	333
Insulation	-	260		162	53	27	1,667	2,169
Glass	-	-		11,261	-	-	-	11,261
Plastics	244	-		22	115	15	5	400
Glue	-	-		11	-	-	-	11
Paint	-	-		215	-	-	-	215
Oils and lubricants	-	-		-	95	-	-	95
Sodium nitrate (solar salt)	-	-		-	-	-	16,301	16,301
Potassium nitrate (solar salt)	-	-		-	-	-	10,867	10,867
Nitrogen	-	-		-	-	-	-	-
Concrete and brick	381	4,049		27,875	12,213	10,080	4,491	59,088
Cement					-	-	-	
Asphalt	7,347	-		-	0	-	-	7,347
Crushed Stone and Gravel	48,273	534		-	280	-	-	49,087
System Total	56,311	5,871		57,677	18,421	13,253	34,898	186,431

Molten-Salt Power Tower Plant Material (metric tonnes) / System	Site Improvements	Tower	Receiver	Solar Field	Power Plant Systems	Steam Generator System	TES	Sum for Power Plant
Carbon Steel, Iron and Zinc	103	2,811	384	16,584	4,907	2,794	524	28,107
Stainless Steel	3	97	137	-	67	254	452	1,010
Alloy Steel	1	5	70	-	249	8	2	335
Copper	1	2	40	121	185	68	10	427
Silver	-	-	-	1.0	-	-	-	1
Ferronickel								
Aluminum	-	2	4	-	257	7	17	287
Insulation	-	40	88	-	53	27	1,069	1,277
Glass	-	-	-	10,055	-	-	-	10,055
Plastics	399	1	14	70	115	15	3	617
Glue								
Paint								
Oils and lubricants	-	-	-	-	95	-	-	95
Sodium nitrate (solar salt)	-	-	-	-	-	-	10,451	10,451
Potassium nitrate (solar salt)	-	-	-	-	-	-	6,967	6,967
Nitrogen								
Concrete and brick	624	53,033	-	-	12,213	10,080	2,879	78,829
Cement								
Asphalt	3,879	-	-	-	0	-	-	3,879
Crushed Stone and Gravel	46,609	-	-	-	280	-	-	46,889
System Total	51,619	55,991	737	26,832	18,421	13,253	22,374	189,227

Water Consumption

Water consumption during material manufacturing, plant construction, plant operations, and decommissioning & deconstruction were estimated for oil-HTF parabolic trough plants [2]. Water consumption during operations was also estimated for a molten-salt power tower [1]. The summary results of these two studies are shown in Table 6. Burkhardt et al. [2], examined embedded water consumption in more detail, including, for example, water consumed offsite in support of O&M activities at the plant. The power tower study included only mirror washing, steam cycle makeup water, and auxiliary cooling water consumption.

Table 6. Water consumption by different plant designs. Use in manufacturing and construction is a one-time occurrence. Use of dry cooling reduces water consumption during operations by approximately 90% or more [7]. Total generation assumes annual generation multiplied by a 30-year plant life.

Plant type	Annual Gen. (MWh)	Water Consumption (L/kWh)			Ref.
		Manu. and Construct.	Operations	Decomm. & deconstruct.	
Oil-HTF trough (wet cooled)	426,700	0.50	4.2	0.0076	[2]
Oil-HTF trough (dry cooled)	438,800	0.53	0.55	0.0079	[2]
Molten-salt Tower (dry cooled)*	539,700	n/a	0.23	n/a	[1]

* Data for a dry-cooled, molten-salt trough plant were not estimated, but are expected to be similar to that for a dry-cooled, molten-salt power tower.

Material Value and Embodied Domestic Jobs

The dollar value of the primary materials in the plants is estimated based on market prices for the different commodities. These values are obtained from various sources including: USGS yearbook reports [22], online commodity brokers, trade publications, etc. Values are adjusted to the 2013 cost year using the Chemical Engineering Plant Cost Index (CEPCI). In addition, an estimate is made of the fraction of the U.S. domestic supply represented by the mass required in each nominal 100-MW_e plant.

The number of domestic jobs associated with each commodity is estimated using the Bureau of Economic Analysis (BEA) input-output industry accounts (http://bea.gov/iTable/index_industry_io.cfm). These accounts are used to estimate the jobs tied to a specific value of activity in a given industry. BEA's industry accounts are used extensively by policymakers and businesses to understand industry interactions, productivity trends, and the changing structure of the U.S. economy. Two types of jobs are reported: *direct jobs* which result from the manufacturing of the specific commodity, and *indirect jobs*, which are created in the economy as a result of the primary manufacturing activity. The estimated job creation associated with the two CSP plant types are shown in Table 7 and Table 8. It should be noted that the jobs listed in the tables are associated with production of the commodity materials that make up the plant. Plant construction and operating jobs are not part of this report. Other studies have estimated construction and operating jobs associated with solar power systems, although reliable data are often difficult to obtain [23]. A recent analysis estimated substantial net job creation from a shift away from fossil energy to renewable energy sources [24].

With the exception of the nitrate thermal storage salts – and possibly solar glass – the materials used in the CSP plants are produced in the U.S. in volumes that can easily support the construction of multiple plants per year. The nitrate salts are a worldwide commodity that are primarily supplied from mines in Chile. The nitrates can be manufactured from natural gas in a process that is similar to the manufacturing of ammonia fertilizer, but solar plants have historically purchased the mined product. It may be interesting to explore how the price of natural gas in the U.S. affects this market dynamic, although it has also been shown that manufacturing of synthetic nitrate salts has a much larger carbon footprint than the mined salts [2].

Table 7. Domestic material and associated potential supply-chain jobs for the salt-HTF parabolic trough plant.

Plant Material	Mass in plant (MT)	Percent of US production	Estimated Value ($2013)	Potential Direct Jobs	Potential Indirect Jobs	Refs
Carbon Steel, Iron & Zn	26,367	0.03%	19,000,000	29	117	[22]
Stainless Steel	2,283	0.12%	7,100,000	9	37	[22], [25]
Alloy Steel (as nickel)	261	0.17%	4,400,000	6	26	[22], [25]
Copper	334	0.02%	2,500,000	4	14	[22]
Silver	1	<0.01%	850,000	1	5	[22]
Ferronickel	10	0.70%	170,000	0	1	[22]
Aluminum	333	<0.01%	700,000	1	4	[22]
Insulation	2,169	0.02%	620,000	1	2	[26]
Glass (low-iron)	11,261	6.5 %	25,400,000	106	114	[27]
Plastics	400	<0.01%	640,000	2	3	[28]
Oils and lubricants	95	<0.01%	240,000	0	0	
Sodium nitrate	16,301	n/a	13,900,000	0	0	[29]
Potassium nitrate	10,867	n/a	12,000,000	0	0	[29]
Concrete and brick	59.088	0.01%	2,500,000	10	11	[30]
Asphalt	7,347	0.04%	4,000,000	1	8	[31]
Crushed Stone & Gravel	49,087	<0.01%	430,000	2	2	[22]
Totals	**186,400**		**90,800,000**	**172**	**344**	

Table 8. Domestic material and associated potential supply-chain jobs for the molten-salt power tower plant.

Plant Material	Mass in plant (MT)	Percent of US production	Estimated Value ($2013)	Potential Direct Jobs	Potential Indirect Jobs	Refs
Carbon Steel, Iron & Zn	28,107	0.03%	20,300,000	30	123	[22]
Stainless Steel	1,010	0.05%	3,100,000	5	19	[22], [25]
Alloy Steel (as nickel)	335	0.22%	5,500,000	8	34	[22], [25]
Copper	427	0.03%	3,200,000	5	19	[22]
Silver	1	<0.01%	770,000	1	5	[22]
Ferronickel	-	n/a	0	0	0	[22]
Aluminum	287	<0.01%	603,000	1	4	[22]
Insulation	1,277	0.01%	360,000	2	2	[26]
Glass (low-iron)	10,055	5.8 %	22,700,000	95	102	[27]
Plastics	617	<0.01%	990,000	3	4	[28]
Oils and lubricants	95	<0.01%	240,000	0	0	
Sodium nitrate	10,451	n/a	8,900,000	0	0	[29]
Potassium nitrate	6,967	n/a	7,700,000	0	0	[29]
Concrete and brick	78,829	0.02%	3,300,000	14	15	[30]
Asphalt	3,879	0.02%	2,100,000	0	4	[31]
Crushed Stone & Gravel	46,889	<0.01%	410,000	2	2	[22]
Totals	**189,200**		**78,400,000**	**166**	**333**	

Figure 6 shows a graphical comparison of the embodied mass and estimated material value for each design. By far the largest impact is due to the decrease in molten salt and oil HTF when one moves to the salt-HTF systems. Lesser effects are seen in the decrease in solar field size, which is also reflected in the lesser amount of sand and gravel for the site. The use of stainless and high-Ni alloy steel increases for the plants with high-temperature salt.

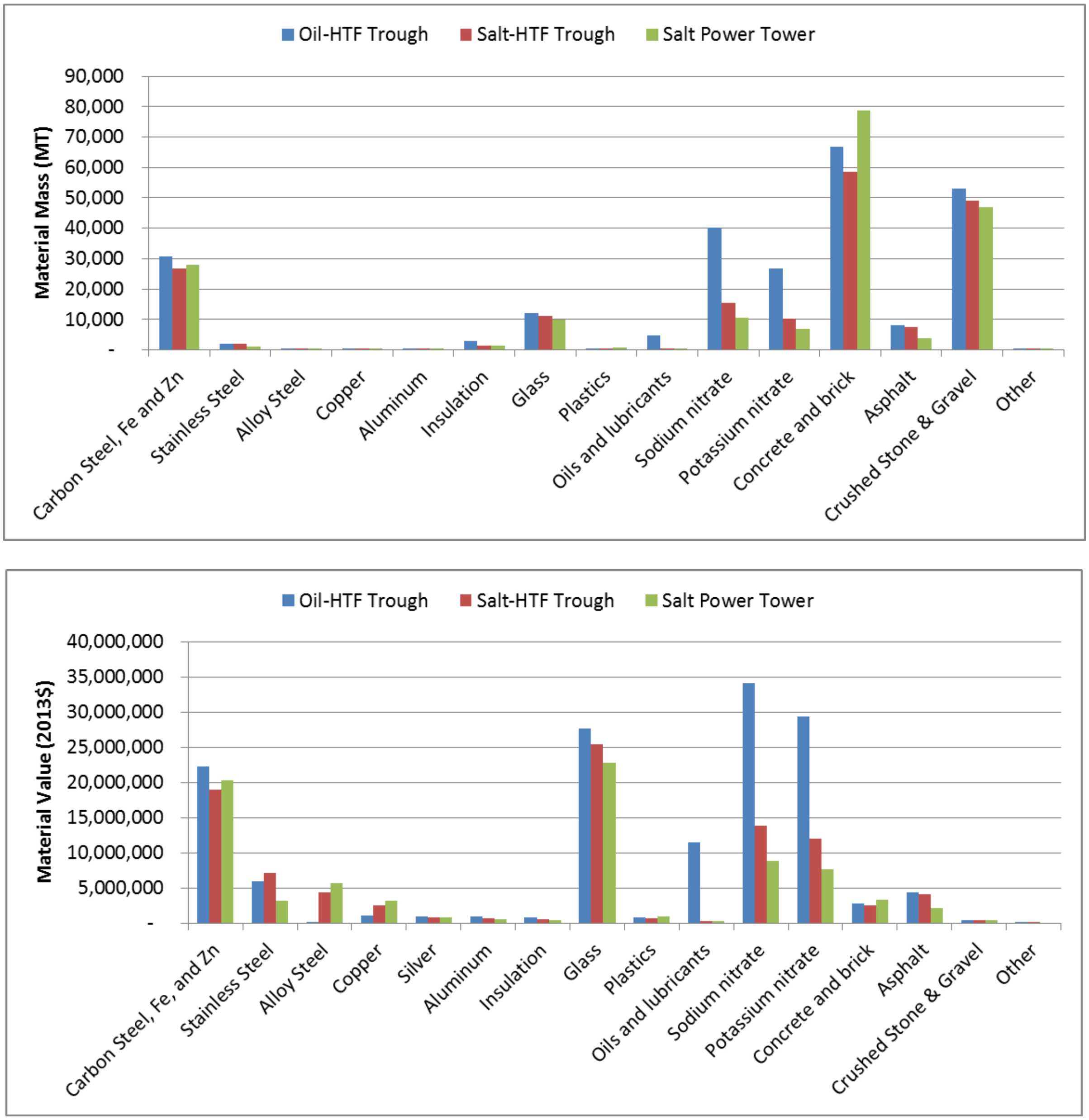

Figure 6. Comparison of material mass and material value for the three different plant designs. Each plant is nominally 103 MWe and has 6 hours of thermal storage.

Material Suppliers and Manufacturers of CSP Components

Table 9 provides an overview of raw material and CSP component providers in the U.S. market. More detailed information can be acquired from industry tracking services such as CSP Today [32], GreenTech Media [33], or Bloomberg New Energy Finance [34].

Table 9. Supply chain of CSP materials and component suppliers in the U.S. market.

Primary Raw Materials	Raw Material Suppliers*	CSP Components	CSP Component Suppliers	CSP Integrator / Developers /EPCs
Steel and Stainless Steel	Nucor US Steel AK Steel Commercial Metals	Piping Pumps Tanks Heat Exchangers	Alstom Power Babcock & Wilcox Bertrams Heatec (Switz.) Foster Wheeler	Abengoa/Abeinsa Acciona ACS Cobra Alstom Power AREVA Bechtel Corp. BrightSource Energy eSolar/GE Florida Power & Light Lauren Engineers & Constructors NextEra Energy SolarReserve WorleyParsons
		Receiver Tubes	Schott (Germany) Huiyin (China) Rioglass (Belgium)†	
		Solar field frames	Abengoa (Spain)† AREVA (France) Gossamer SENER (Spain) eSolar BrightSource SolarReserve	
Alloy steel	Special Metals Haynes Rolled Alloys	Turbine components	Alstom (Switz.)† General Electric SIEMENS (Germany)†	
Aluminum	Alcoa Century Aluminum Ormet Primary Alum. Noranda Aluminum	Solar field frames Cladding	SkyFuel	
Concrete	Suppliers nationwide	Foundations Tower		
Glass	Guardian RioGlass (Belgium)† Saint-Gobain (France)† Flabeg (Germany)	Mirrors	3M Guardian RioGlass (Belgium)† Saint-Gobain (France)† Flabeg (Germany) SkyFuel	
Silver	Teck Alaska Hecla Mining Kennecott Utah U.S. Silver Newmont Mining	Reflectors		
Copper	Freeport-McMoRan Kennecott Utah ASARCO	Reflectors Power system		
Nitrate Salt	SQM (Belgium) BASF (Germany)†	HTF TES media		

* Top domestic producers listed, unless noted ([22] and internet sources).
† Have manufacturing facilities in the U.S.

Conclusions

This study compiled material composition data for a molten-salt power tower and hypothetical molten-salt-HTF parabolic trough plant. The former design is commercial and the latter has reached pilot-scale stage in the form of the Archimede plant in Italy. The analysis sized both plants for similar power production (103 MW_e) and thermal storage (6 hours) capacity. The material composition of the salt-HTF trough plant was approximately 25% lower than a comparably sized conventional oil-HTF parabolic trough plant. Although cost analysis was not part of this project scope, the significant reduction in oil, salt, metal, and insulation mass by switching to a salt-HTF design is expected to reduce the capital cost and LCOE for the parabolic trough system.

The overall embodied mass of the salt-HTF trough plant was slightly below that of the salt tower design. The similarity in the total mass of the two designs, along with their similar power generation profiles and operating requirements, suggests that salt-HTF trough plants could be competitive with molten-salt power towers if the technical hurdles of deploying salt in the solar field can be overcome. Parabolic tough systems have other advantages, such as modularity, no concerns related to reflected sunlight or towers affecting birds or aircraft, and a more extensive operating record, that could influence technology selection. However, questions remain regarding the potential cost and complexity of freeze protection and freeze recovery technology for salt-HTF troughs.

CSP plants are composed mainly of steel, glass, concrete and aggregate materials, which are abundantly available from domestic sources. This is true for most locations in the world where CSP plants might be deployed and is an attractive attribute of the technology with regards to its impact on the local economy. In the U.S., we estimate that 90% by mass and 79% by value of the commodity materials utilized in a CSP plant can be supplied by domestic sources.

The most unique of the materials with respect to potential sources is the nitrate solar salt. The largest supply of nitrate salt is from the Atacama Desert in Chile. Alternative salts based on chlorides or carbonates would be more universally accessible, but the selection of salt is dominated by the thermo-physical properties of the salt, and thus far no material has been able to supplant the nitrates. Nitrate salts can be produced synthetically from natural gas, which may be a viable domestic option with sufficiently low gas prices.

Nomenclature

BEA	Bureau of Economic Analysis
CSP	Concentrating Solar Power
DOE	Department of Energy
EPC	Engineering, Procurement, Construction (type of contract or contractor)
HTF	Heat Transfer Fluid
ITC	Investment Tax Credit
LCOE	Levelized Cost of Energy
MT	Metric Tonne
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
SAM	System Advisor Model
SCA	Solar Collector Assembly
TES	Thermal Energy Storage

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Appendix A – Financial assumptions used to estimate LCOE in Figure 1

The analysis results depicted below were generated using SAM 2013-09-20.

Case	2010 Trough	2010 Trough + TES	2013 Molten Salt Tower
Financial Assumptions			
Plant life	30 years		
Inflation rate	3.0%		
Real discount rate	5.5%		
Federal / State Tax	35% / 5%		
Sales Tax (included in the indirect costs listed below)	5% on 80% of DC		
Project loan period and interest rate	15 yrs at 4.0%		
Construction loan period and interest rate	24 mo at 5%		
Debt fraction	60%		
Required IRR and DSCR	15% and 1.4		
MACRS	yes		
Investment tax credit	0%		
Location (weatherfile)	CA (Daggett)	CA (Daggett)	CA (Daggett)
Design Assumptions			
Technology	Oil-HTF Trough	Oil-HTF Trough	Salt Tower
Solar Multiple	1.3	2.0	2.3
TES (hours)	-	6	10
Plant Capacity (MW, net)	100	100	100
Power Cycle Gross Efficiency	0.377	0.377	0.412
Cooling Method	wet	wet	dry
Cost Assumptions			
Site Preparation Cost ($/m2)	20	20	16
Solar Field Cost ($/m2)	295	295	163
Power Plant & BOS Cost ($/kW)	940	940	1,540
HTF System or Tower/Rcvr Cost ($/m2 or $/kW-t)	90	90	168
Thermal Storage Cost ($/kWh-t)	-	80	23
Contingency	7%	7%	7%
Indirect, including EPC and Owner's costs, land, sales tax (as %	17.0%	17.0%	18.1%
Interest During Construction (as % overnight installed cost)	6.0%	6.0%	6.0%
Fixed O&M ($/kW-yr)	70	70	73
Variable O&M ($/MWh)	3	3	4
SAM Results			
Capacity Factor	24.3%	39.1%	56.1%
Overnight Installed Cost ($/kW)	4,020	7,210	6,496
Total Project Installed Cost ($/kW)	4,280	7,680	6,885
LCOE (c/kWh, real) [2010 dollars, zero ITC]	20.1	20.8	12.9