

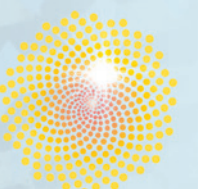
Image: Crescent Dunes created 4,300 direct, indirect and induced jobs with over 11,000 workers on-site during peak construction © Solar Reserve

THE VALUE OF THERMAL STORAGE

*THE CHALLENGE OF INTEGRATING
INTERMITTENT RENEWABLE
GENERATION INTO POWER
SYSTEM OPERATION*



**STELA
WORLD**



ESTELA

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ABOUT ESTELA

ESTELA, the European Solar Thermal Electricity Association, is a non-profit association created in 2007. ESTELA represents members from the industry and research institutions, active along the whole STE value chain. Joining hands with national associations – Protermosolar (Spain), ANEST (Italy), Deutsche CSP (Germany) and the SER-CSP (France), ESTELA is devoted to promoting solar thermal electricity not only in Europe, but also in MENA region and worldwide. To act widely, ESTELA with AUSTELA and SASTELA in 2012 jointly created STELA World. Today, ESTELA is the largest industry association in the world promoting the solar thermal electricity sector.

ABOUT SOLAR THERMAL ELECTRICITY

Solar Thermal Electricity (STE), also known as concentrating solar power (CSP), is a renewable energy technology that uses mirrors to concentrate the sun's energy and convert it into high-temperature heat to create steam to drive a turbine that generates electricity. STE is a carbon-free source of electricity that is best suited to areas in the world with strong irradiation: Southern Europe, Northern Africa and the Middle East, South Africa, parts of India, China, Southern USA and Australia.



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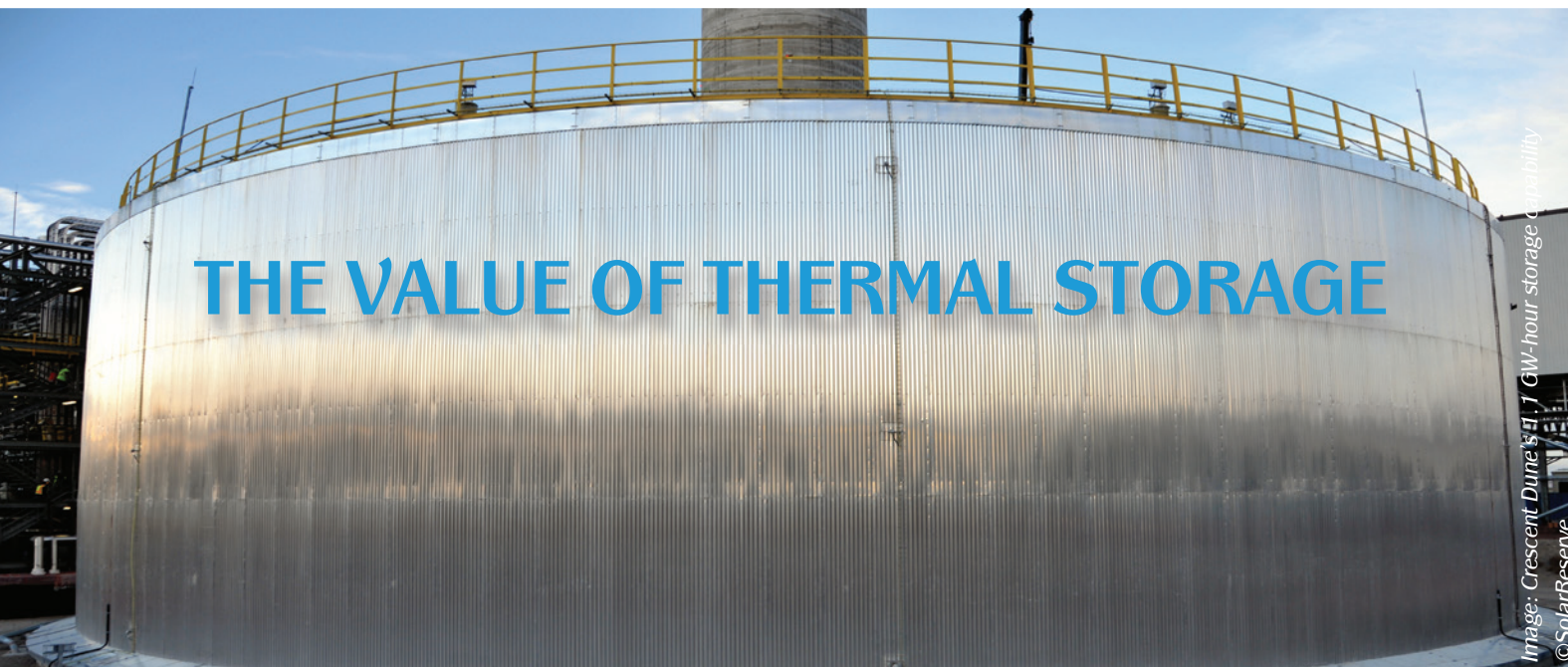


STELA World

**World Solar Thermal
Electricity Association**

www.stelaworld.org

Image: Crescent Dune's 1.1 GW-hour storage capability is almost 40 times the size of the largest battery storage project in construction or built to date ©SolarReserve



Power System Basic Features

Unlike water or gas, electricity cannot be stored in large quantities. It must be generated at the instant it is used, which requires supply to be kept in constant balance with demand. Furthermore, electricity flows simultaneously over all transmission lines in an interconnected power system. This means that generation and transmission operations must be controlled in real time, 24 hours a day, to ensure a reliable and continuous supply of electricity to homes and businesses.

This diagram below depicts the basic elements of the electricity system: how it is created at power generating stations and transported across high-voltage transmission and lower-voltage distribution lines to reach homes and businesses. Transformers at generating stations step the electric voltage up for efficient transport and then step the voltage down at substations to efficiently deliver power to customers.

The generation and transmission components (without the distribution elements) and their associated control systems comprise the “bulk power system”.

The reliability of the interconnected bulk power system in terms derives from two basic functional aspects:

- ▶ **Adequacy:** the ability of the electricity system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking scheduled and reasonably expected unscheduled outages of system elements into account.
- ▶ **Reliability:** the ability of the power system to withstand sudden disturbances, such as electricity short circuits or unanticipated loss of system elements from credible contingencies, while avoiding uncontrolled cascading blackouts or damage to equipment.

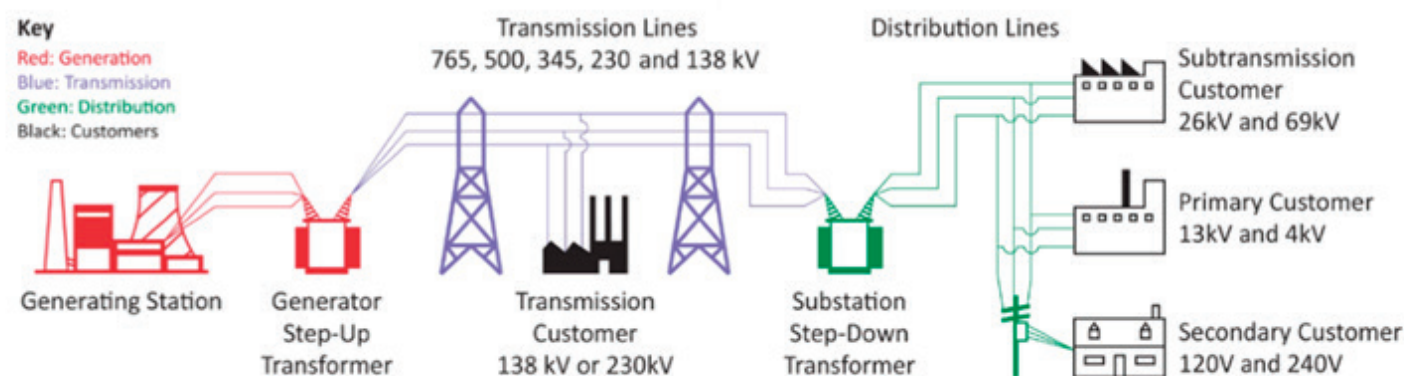


Figure 1: Basic elements of the electricity system

The Effects of the Rapid Deployment of Intermittent Generation

Keeping these principles of system operation in mind, system operators are facing a new challenge: with the increase of installed capacity of intermittent renewable technologies for power generation, industrialized countries are today frequently needed to master situations that the power generated by these technologies, together with the base load generation from conventional power plants – with reduced or inexistent regulation possibility, is close to or even goes beyond the demand in specific places at many moments along the year.

This leads often to a restriction or even curtailment of the operation of renewable plants and to an increase of the costs of ancillary services for balancing the system, in order to have sufficient spinning and short term power reserve available in case of a rapid drop in the supply from intermittent renewable sources.

In other words, the more installed capacity in intermittent generation, the higher the probability to face such an imbalance between supply and demand.

In emerging economies, there is often a need to increase generation capacities in all timeframes at a high rate – doubling in a decade – and especially for covering the afternoon-evening peak; therefore, the penetration of intermittent generation in such systems needs to be backed by fossil-fuel plants – with a large share of combined cycles.

This has three concomitant effects:

- ▶ a two-fold investment for adding additional capacity (RES sources plus back-up capacity);
- ▶ a considerable restriction of operation time of the added fossil-fuelled capacities that substantially increases their operating costs;
- ▶ a barrier to achieving a carbon-free generation system.

The increase of the share of intermittent electricity generation is due to the fact that in most of the power systems, additional generation is auctioned so as to secure a long-term power purchase agreement (PPA). But in countries without auction practice in such cases, generation turns to be remunerated based on the marginal cost of the last offer matching the actual demand. In turn, this results from the fact that:

- ▶ there is no repercussion on the generation units of the costs triggered by the necessary adjustments of system services to the needs (for balancing);
- ▶ for the purposes of the “energy transition”, a reasonable priority of dispatch was given to renewable energies.

This is a serious issue today around the world and especially in the European Union, where adjustments of the power market design are being evaluated in order to counteract the negative effects of the current “marginal cost approach”.

What Kind of Solutions Can Be Envisaged?

This is also why electricity storage is starting to be considered as a global solution to:

- ▶ the problems of ‘oversupply’ and;
- ▶ cutting down the high costs induced by non-flexible renewable generation in place in most power systems.

What has been envisaged in Europe so far in order to better control those issues?

- ▶ New interconnection capacity targets of 10%, later 15% of the installed generation capacity between national systems. However, it is not likely for the medium term that interconnection capacity may be easily increased and definitely not at the same pace

of further penetration by intermittent RES sources. The most important reason is that implementing a new high-voltage interconnection infrastructure needs often more than 10 years in Europe.

- ▶ Demand-side management especially by citizens (“prosumers”), especially the potential effects resulting from the development of e-mobility, since recharging batteries might appear to be able to absorb a substantial part of intermittent power surpluses. However, it is questionable whether a stronger increase in demand, even alongside a more flexible consumption of final users, would require increases in firm capacity, that intermittent renewables alone would not be able to deliver.

The Only Sustainable Solution: Preventing the Causes of the Problem Instead of Having to Cure Its Effects

The problem originates from the current imbalance between dispatchable and non-dispatchable technologies in the power systems triggered by the low up-front investment costs for wind and PV units.

In a moment where deep and irreversible changes of the global energy model for Europe are envisaged and politically targeted (such as Energy Union, Climate and Energy Package 2030, Market Design and Renewable Energy Directive), impacting especially the future power system, there is a need to set up new legislation based on the value – but not just on the costs – of the new elements of the power system. This will lead to specific requirements in terms of a significant share of dispatchable renewables in the overall renewable goals. This issue applies not only to Europe but also to most of the countries in the world.

A study by NREL (National Renewable Energy Laboratory), referring to California in 2014 with a 33% share of renewable energy in the power generation mix in the short term, demonstrates that it was economically equivalent to remunerate 5 US cents/kWh to a new PV plant and 10 US cents/kWh to a STE plant with storage.

Moreover, the study assesses also with a 7% increase of the share of renewables in the system, this difference in remuneration worth gets higher.

This result is based on two components of the value of a new generation unit:

- ▶ Operational value: represents the avoided costs of conventional generation at their respective dispatching times along with related ancillary services costs, such as operating reserve requirements. Savings on emission costs are also taken in to account.
- ▶ Capacity value: reflects the ability to avoid the costs of building new conventional generation in response to growing energy demands or conventional power plants decommissioning/dismantlement.

This study points clearly out the need for a more rational approach to cope with the demand for new capacity in the electrical systems. Auctions for selecting the lower prices would lead to further system costs, which would not be fair to charge to the system as a whole.

The study shows the following results:

Value Component	33% Renewables		40% Renewables	
	STE with Storage Value (USD/MWh)	PV Value (USD/MWh)	STE with Storage Value (USD/MWh)	PV Value (USD/MWh)
Operational	46.6	31.9	46.2	29.8
Capacity	47.9-60.8	15.2-26.3	49.8-63.1	2.4-17.6
Total	94.6-107	47.1-58.2	96.0-109	32.2-47.4

Figure 2: Estimating the Value of Utility-Scale Solar Technologies in California under a 40% Renewable Portfolio Standard, NREL/TP-6A20-61695, Jorgenson, J., P. Denholm and M. Mehos, 2014 May.

Exploring More Potential Solutions

The challenge of integrating larger quantities of intermittent energy sources into grid operation is not only a System Operator's technical issue. The current situation in several countries shows that a power system can withstand shares of wind electricity generation beyond 50% while still having a lot of spinning and short-term capacity reserves. The question is more about the kind of business model the society at large is willing to accept for the global electricity system in

this critical phase of the energy transition – once well aware of the consequences on economy and citizens. This is becoming more urgent as the penetration of wind and PV are reaching significant shares in the electricity production and most importantly, more and more frequent surpluses are being produced along with a considerable reduction in the operation hours of conventional power plants that claims for higher compensation in capacity payments.

The diagram below shows the different approaches to produce dispatchable electricity from renewable energy technologies.

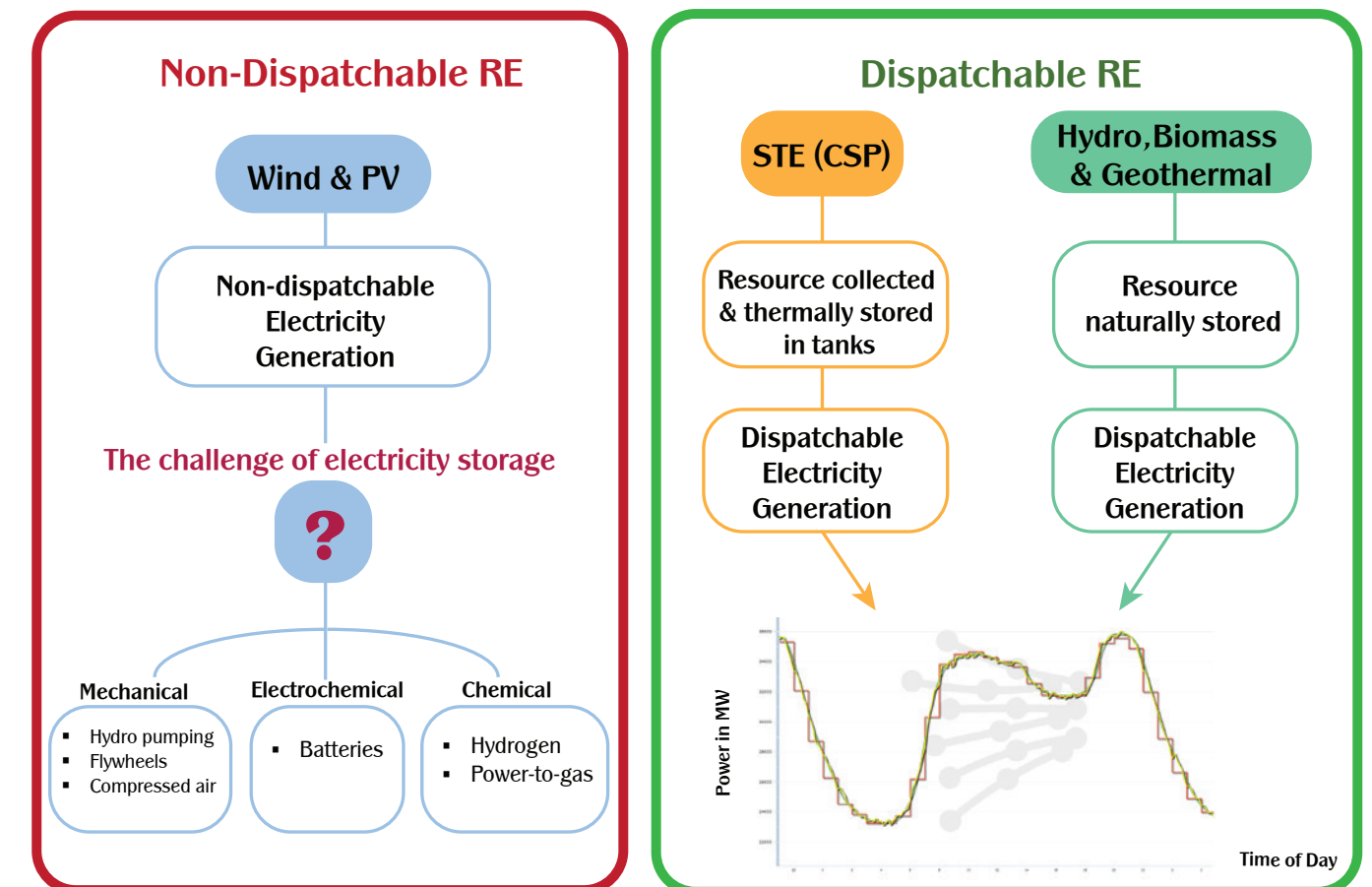


Figure 3: Different approaches to produce dispatchable electricity from renewable energy technologies.

All approaches try to deal with the problem – how to store the electricity and pursue the same objective: large-scale storage of surplus power using available technologies in order to avoid the waste of available primary renewable energy sources or to reduce payments for generation surplus at specific times. After all, the only rational and sustainable solution is to prevent the causes of the problem instead of having to cure its effects.

Currently, hydro storage appears as the first suitable technology, even if the number of available sites and the costs and/or social acceptance for such new large infrastructures are limitations to this solution.

Moreover, the electrochemical storage close to sub-stations could also be a solution to increase reliability of the system, but so far such storage systems with a capacity range of GWhs are unlikely to be developed in this decade with the necessary operational durability and at competitive prices. Besides that, there are also potential bottlenecks and undesirable footprints.

Also, the use of renewable generation surpluses to generate gas (be it hydrogen by electrolysis or hydrocarbons to be injected in the gas pipelines), known as “power-to-gas”, is being promoted as another option. This technology, although sufficiently demonstrated at

laboratory level, has not been implemented at industrial and large commercial scale. Furthermore, the life cycle assessment of this solution shows poor results; eventually, this solution is not competitive, except in cases of huge electricity surpluses at very low or even negative prices, which is unlikely to be a driver for further investments in intermittent renewable technologies.

Built-in storage in plants is finally also being investigated. This refers to:

- ▶ Mechanical systems for flywheels or compressed air for wind farms, or electrochemical batteries for PV plants.
- ▶ PV plants with battery storage.
- ▶ Solar thermal plants, including thermal storage.

With respect to wind energy, mechanical systems for storage on wind farms sites do not appear yet as a viable solution.

Even if storage systems based on kinetic energy (such as flywheels) show a good response, their power range is not very high (up to only 20 MW), and they have a high level of auto discharge with a complete cycle efficiency of approximately 85%. Not to mention, their costs

are not competitive. Storage systems based on air compression and discharge can be implemented in the range of some hundreds MW and have a good response, but their efficiency yield is around 40%, since they lose a lot of energy. Their costs are not competitive either.

With regard to PV, commercial solutions are not yet available to provide storage for utility scale plants. There are some technological research lines covering different technologies including promising ones. Nevertheless, most experts in the sector do not believe that these solutions can offer systems with more than 5000 cycles in the GWh-range with competitive prices and efficiency higher than 75% within 10 years.

The performance in real operation of solar thermal plants has been demonstrated since 2008 with 300 cycles of charge/discharge yearly, without any detrimental incidence on the storage system based on two tanks – hot and cold – with molten salts in the range of 1 GWh capacity. Operating this system is very simple with a

reduced auto discharge and a cycle efficiency close to 100%.

Among all the systems mentioned below, the only technologies available at utility scale are hydro pumping for intermittent technologies and thermal storage for STE plants. Other technologies like biomass and geothermal have the resources already stored and can provide dispatchable electricity as well.

Hydro storage features an efficiency for the complete cycle of 75%, in which 25% of losses can be discounted upon analysis of business plans based on this technology. Its main limitations are the need for a favourable hydrography and the social acceptance difficulties faced today for such infrastructures. Thus, a future storage capacity in this technology will remain limited and cannot be considered as a solution to accommodate important quantities of intermittent renewable generation.

Storage Technology	Hydraulic Pump	Copressed Air	Batteries	Flywheels	SMES	Super Codensers	Molten salt tanks (STE plant)
Storage Capacity	500-8000 GWh	580-2860 MWh	0.001-250 MWh	0.0052-5 MWh	0.01-0.001 MWh	0.01 MWh	1 – 10 GWh
Duration of Discharge at Max. Power	1-24h	1-24h	1-8h	15s to 15 min	10s	10s	1 – 24h
Nominal Power	10-1000 MW	50-300 MW	0.015-50 MW	0.1-20 MW	1-10 MW	0.05-0.1 MW	10 – 300 MW
Response Time	minutes	3-15 min (big scale)	30 ms	5 ms	5 ms	5 ms	minutes
Auto Discharge	Very small	Small	0.1-20%	100%	10-15%	20-40%	Very small
Effective Life-time (years)	50-100	30	02-10	20+	20	20+	40
Energy Density (Wh/kg)	0.5-1.5	3.2-5.5	20-200	5-00	10-75	0.1/30	30 - 100

Figure 4: Source: CIEMAT. Own elaboration from: Characteristics and technologies for Long-vs Short Term Energy Storage. A study by the DOE Energy Storage Systems program. Susan M. Schoenung. 2001, y F. Diaz-Gonzalez et al. / Renewable and Sustainable Energy Revi and ESTELA figures on STE.

The Most Efficient Solution for Solar Energy: Dispatchable Solar Thermal Plants

To date the only flexible renewable energy plants at utility scale are solar thermal plants with storage systems using molten salts.

In parabolic trough plants, the solar energy is collected in the heat transfer fluid (synthetic oil), which circulates through the solar field. To charge the storage system, this oil is sent to a heat exchanger where the molten salt coming from the cold tank is heated and then stored in the hot tank. Whenever energy delivery is requested, the salt flows through the same heat exchanger in the opposite direction and heats the oil which then produces the steam required by the turbine at the steam generator.

In central receiver plants, the function mode is even simpler. The molten salt from the cold tank is pumped up to the receiver where it is heated and stored directly in the hot tank. When power is needed, the hot salt is sent to the steam generator and returns to the cold tank.

The following picture shows the two-tank storage system in one of the 50 MW power plants in Spain. This system has a nominal capacity of 7.5 hours at nominal power of the turbine.



Image: Andasol I, II, III CSP Plants ©ACS Cobra



Image: Andasol I, II, III CSP Plants ©ACS Cobra



Image: PS 20 ©Abengoa Solar

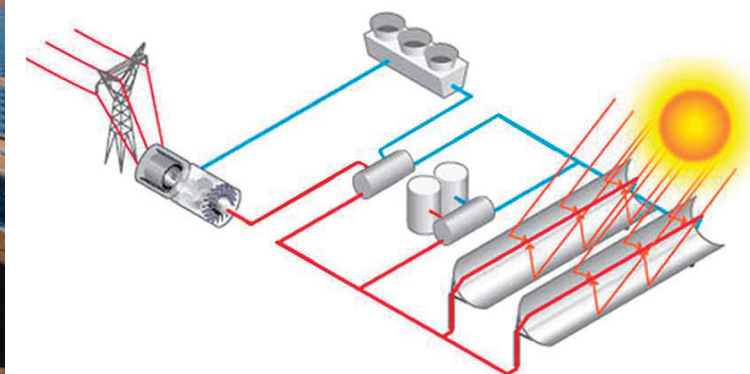


Figure 5: Parabolic trough plant with thermal storage

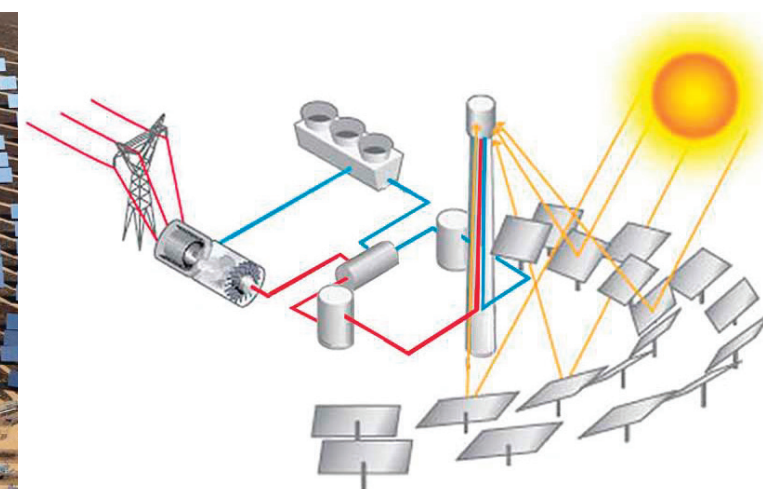


Figure 6: Central receiver plant with thermal storage

The energy stored in the two-tank system depends on the temperature difference between the hot and the cold tank. This difference is in the range of 100°C in parabolic trough plants, while in tower plants the difference is around 300 °C. This means that central receiver plants can store three times more energy per ton of salt than parabolic trough plants.

This is also why the costs of systems with two tanks for the storage of thermal energy with molten salts are very different in terms of €/kWh between parabolic through and central receiver technologies.

For a parabolic through plant, for example in 2010, the system costs for the full storage system (tanks, salts, heat exchangers, etc.) were approximately 35 M€ for a storage capacity of about 1 GWth that could be converted into 375 MWhe. The relative costs of the system per unit of stored energy would then be 35 €/kWh or around 100 €/kWh.

For a central receiver plant, in accordance with the above said and taking into account the fact that no heat exchanger is needed, the corresponding investment costs can be currently estimated to date at 50 €/kWh.

The two-tank systems with molten salts are running since 2008 in Spain without any relevant disturbance in operation nor any performance degradation.

Conversely, PV plants are to date lacking battery-based storage systems offering an operational reliability more than ten years at competitive costs. Lead acid batteries are the most common ones. They are used in the automotive industry, especially for uninterrupted security

systems, as well as in domestic PV systems. Their cost per kWh of installed capacity is in the range of 150€ but the number of cycles is in the range of 3000 and the performance degradation is significant. The new generation of batteries (e.g., Ni MH, NaS, Li and VFR) feature a higher number of cycles but still higher costs compared with lead acid batteries and some open issues regarding the charge and discharge process control. Most of the experts in this field do not expect competitive batteries in the GWh range in much less than ten years.

When both the durability and the real storage capacity at utility scale of battery systems will be sufficiently developed, the generation costs of PV plants to be compared to the costs of solar thermal plants (that will have at that time undergone a substantial cost reduction) should be based on the following terms:

- ▶ Both systems designed to cover the same demand curve;
- ▶ Efficiency of the process of charge and discharge of the storage system;
- ▶ Degradation of the PV panels as well as of the batteries compared to the components of the solar thermal plants;
- ▶ Operational lifetime without repowering;
- ▶ Contribution to grid stability (comparing to the mechanical inertia, which is provided by STE plants);
- ▶ Life Cycle Assessment (including CO₂ emissions).

CONCLUSION

As long as the power market design in Europe remains unchanged, the already visible surplus of intermittent renewable generation will further increase in most industrialized countries. Even taking into account the currently available overcapacity in the European power market, this will soon lead to a corresponding increased need for back-up capacities. This development turns hence to become a vicious circle that will definitely not serve the ultimate goal of decarbonisation.

Having this in mind, it appears that the only sustainable solution is to prevent the causes of the problem instead of having soon to cure its effects.

It is foreseeable that markets will at this point send investors signal about an expected low investment yield for a product offered by most market actors at the same time into a surplus market. Even in case of no surplus, non-flexible supplies offered at the same time will certainly reduce the resulting marginal prices and will challenge the business cases of such investments. As further consequence, this will most probably limit intermittent renewable generation to distributed generation, especially for self-consumption purposes.

However, the further penetration of renewable generation in the centralized bulk power system – that might in Europe increasingly co-exist with decentralized system parts – can only be achieved using flexible technologies allowing for storage and delivery on demand.

This stands true for both industrialized countries that will soon need to decommission their conventional

generation units and in emerging economies that will sooner or later be facing the need for managing the new capacities that they will have to add to their respective systems.

Solar thermal plants with storage appear to be to date the nearly unique viable option. In addition to their added value to the power system in terms of operation and capacity, they add inertial stability to the grid and have a highly positive macroeconomic impact. Hybrid PV-CSP plants would also make up an attractive solution that low generation costs are combined to increase flexibility of dispatching power generation.

The non-differentiated allegation of higher “costs” of STE without consideration of its “value” roots essentially in the current small market volume for this technology. The large cost reduction potential for STE technology (“maturity factor”) when comparing the currently 5 GW installed worldwide in STE with approximately 200 GW of PV and 400 GW for wind is simply a matter of evidence.

However, in order to make this happen, all policy-makers driving the ongoing energy transition should provide an efficient framework to industry and markets to achieve a more balanced ratio between dispatchable and non-dispatchable technologies in order to reach the penetration objectives for renewables.