Molten salt energy storage

MAN Energy Solutions
Future in the making

Ensuring the reliability of renewable power generation with superior time flexibility

List of standard abbreviations

cf.	confer (compare)
e.g.	for example
et al.	et alii (and others)
et seq.	et sequens (and the following)
ff.	following pages
fig.	figure
p.	page

List of technical abbreviations

BESS	Battery energy storage system
°C	Degree Celsius
CO_2	Carbon dioxide
CSP	Concentrated solar plant
ELCC	Effective load carrying capacity
°F	Degree Fahrenheit
f	Feet
h	Hour
kg	Kilogramm
Lb	Libra pondo (Pound weight)
LDES	Long-duration energy storage
min	Minute
MOSAS	Molten salt energy storage
MW	Megawatt
MWh	Megawatt hour
PRM	Planning reserve margin
psia	Pound-force per square inch
VRE	Variable renewable energy source
yd	Yard

Synopsis

Long-duration energy storage (LDES) is needed to ensure the reliability of electric utilities as they move toward 100 % clean energy targets. MAN Energy Solutions has developed the Molten Salt Energy Storage System, or MOSAS, to meet and exceed utility customers' expectations. MOSAS uses renewable electricity to raise molten salt to very high temperatures and this salt can be stored for any length of time.

When power is needed, the hot salt is used to produce electricity with a steam turbine. The duration, or the length of time during which the system provides full rated output, can range between eight and 24 or more hours. Optional fuel heaters allow renewable fuels, such as hydrogen or carbon-neutral synthetic methane, to provide supplemental heat. This enables MOSAS to raise the temperature of the salt and provide continuous power when renewable electricity is not available for electrical heating. This, in turn, means that MOSAS can be treated as firm capacity. Conditions under which a fuel heater would be beneficial include extended peak-load conditions, when power is needed beyond the duration of the stored renewable energy, and during weather-related events that prevent storage systems from recharging, such as extended lulls in wind over multiple days, or during storm or cloud cover events that last multiple days and compromise solar output. This paper provides an overview of the MOSAS system, its component parts and their technological maturity, as well as the benefits of MOSAS technology relative to reliability criteria required by electric utility systems.

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The future is zero CO_2

The drive towards a net-zero carbon future is a global phenomenon, with entire countries committing to deep decarbonization. In addition, where national measures are lacking, states, provinces, cities and counties, as well as corporations whose reach extends beyond political boundaries, are all committing to the same goal. Electric utility providers in particular are making zero or net-zero CO_2 commitments even when their local or national governments do not require them to do so or have less ambitious goals.

Technology and climate are driving change

While most of the movement towards clean energy commitments is driven by climate change concerns, these choices are also driven by the ever-improving cost-effectiveness of the two technologies at the forefront of zero-carbon energy – wind and solar. Wind and solar power are considered variable renewable energy sources (VREs) as they produce electricity when the wind is blowing and the sun is shining respectively. Their output can change dramatically hour by hour and minute by minute, and they both have seasonal patterns of energy production. As electric power systems gain higher and higher penetrations of VREs in their systems, the volatility of VREs introduces reliability and planning challenges that are unique to the nature of VREs themselves.

Seasons, weather and the role of energy storage

Solar output is maximized in summer months when daylight hours are longest and minimized in winter months when they are at their shortest. Wind output varies across the globe but a given region also typically follows seasonal patterns, with some months producing more power than average and others being lower than average. This means, in general, that if a utility system has a constant load, VREs cannot be relied upon to produce the same amount of energy to meet this load each month. The output would vary and other mechanisms would be needed to fill the gap.

The seasonality concern is most pronounced as an electric utility system approaches very high VREs penetrations – much higher than most power systems are dealing with today. However, this concern can easily be understood when looking at another type of renewable energy – hydroelectric reservoir power plants. Such power plants generate a reduced amount of annual energy during years of drought. Similarly, wind and solar produce a reduced monthly amount of energy during the winter months and months with little wind. Planning for reliability requires sufficient generation capacity across all seasons and weather patterns.

In addition to seasonal variations, VREs energy production is typically out of phase with peak-load conditions. For example, a solar-dominated system would see maximum solar output at midday, while peak load often occurs later in the afternoon or in the evening. The midday solar output could actually exceed the utility load at midday, in which case there is excess generation, also called overgeneration.

Overgeneration leads to grid operators curtailing VREs, meaning the systems are made to reduce their output or stop power generation altogether. This is a non-ideal situation as the value of wind and solar is diminished whenever their entire daily and annual output is not utilized.

Energy storage systems are a solution to this dilemma because they can utilize that excess, or overgeneration, by storing renewable energy and then releasing it at a later time. In the solar-dominated example above, this would lead to excess midday solar energy being stored for release during peak load hours in the evening. This time-shifting of renewable energy allows stored energy to offset fossil-based generators, which do not need to operate to meet the load, ultimately reducing CO_2 footprint of the utilities sector.

There are challenges to this approach from a reliability perspective. If a utility relies on short-duration storage (<= 4 h) to shift renewable energy, what happens when the renewable energy is not available? For example, in a solar-dominated system, multiple days of low solar output (due to rain, heavy clouds, storms, snow, etc.) will hinder the ability of short-duration storage systems to recharge (cf. Collanton et al. 2020, cf. ISO New England 2021). It is not unheard of for wind-dominated systems to experience multiple days of little to no wind generation (e.g. cf. Morison 2018), which brings about the same challenge. In other words, the volatility inherent in wind and solar energy as generation and capacity resources also extends to renewable energy storage systems. Electric utilities have mechanisms to assess reliability (and how to maintain it), and these are related to the concepts of effective load carrying capacity (ELCC) and their interplay with planning reserve margins (PRMs).

Planning for system reliability

While there are no universally accepted mechanisms by which electric utility systems assess or quantify reliability and resource adequacy, a common method used is related to a "one-day-in-ten years" standard.

This approach requires sufficient generation capacity (hereafter referred to as capacity) so that any form of system failure, from brownouts to blackouts, can be minimized to no more often than a few hours on one day every ten years. The calculations required to measure or assess the capacity needed for this standard are system-specific, data intensive, complex and computationally expensive. These calculations all tend to be used in the concept of a PRM.

The planning reserve margin

A PRM is a simple metric that indicates how much capacity is needed above and beyond the peak electric load conditions expected for a given year. Peak conditions may be assessed across multiple peak events occurring throughout the year (e.g. winter peaks, summer peaks, etc.). A common metric many utilities adopt is a 15 % PRM. This means that the amount of available capacity (measured in MW) must be 115 % of the peak load, or 15 % larger than the expected peak loads. PRMs can be higher than 15 %, depending on the system (cf. Collanton et al. 2021).

An obvious question is how much is a MW of capacity "worth" towards PRM accounting? This question gives rise to the concept of ELCC (cf. Schlag et al. 2020-1). Historically, traditional capacity types, from fossil-based power plants to nuclear power have been assigned ELCC values of ~1. In other words, if the peak load is 1,000 MW, the system could meet a 15 % PRM by installing 1,150 MW of thermal generation[1].

Performance challenges for renewables

The ELCC of VREs is difficult to characterize, but tends to fall as more capacity is added (cf. Schlag et al. 2020-1). This is, in part, due to the fact that renewable assets for large power systems are spread out over broad and diverse geographic areas, making it unlikely that all of the assets can maximize their output simultaneously at a given hour of the day.

[1] In reality, thermal assets are rarely assigned an ELCC of exactly 1.0. The ELCC is often adjusted to account for data-driven assessments of forced outage rates and maintenance outages so that ELCC for these assets is less then, but typically close to 1.0.

Figure 1 indicates the decline in ELCC as VREs make up larger and larger proportions of the installed capacity in an electric utility system. The consequences of a reduced ELCC are illustrated in Figure 1 (Based on data from North American power systems. See also Mills/Wiser 2012 for solar energy and Söder et al. 2019 for wind energy). When a system has 40 % renewable penetration, the next 100 MW of renewables can only count 20 % of the capacity towards the PRM. This means that to obtain 100 MW of capacity for PRM purposes, 500 MW of renewable capacity is needed.

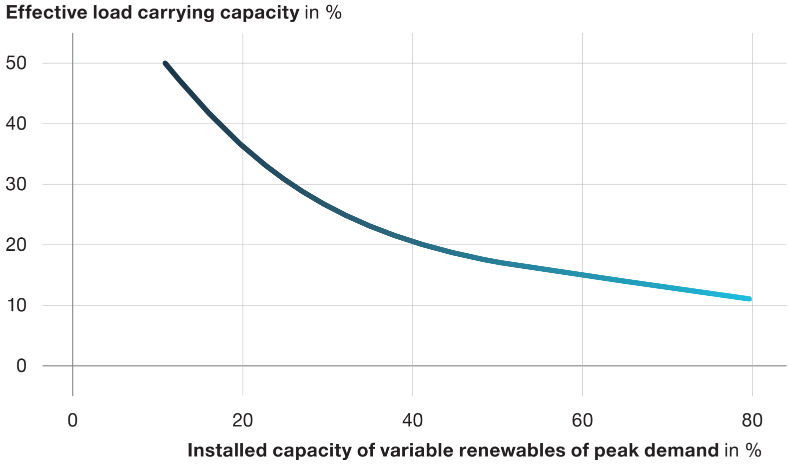


Fig. 1: Representation of the decline in ELCC for variable renewable energy sources as more of these resources are added

The limitations of short-duration energy storage

In many power systems with increasing renewable penetration, there are also increasing numbers of short-duration (< = 4 h) energy storage systems, typically battery-based. Short-duration energy storage is also considered to be capacity, but its marginal ELCC is not constant and also diminishes as more of this type of capacity is added (Fig. 2). This is because as storage penetration increases, the discharge durations must also increase. This limits the ability of 4 hour duration storage to meet the load when the durations required exceed their ability to discharge for more than 4 hours at full rated capacity (cf. Schlag et al. 2020-2).

Diminishing Value of four hour Storage ELCC

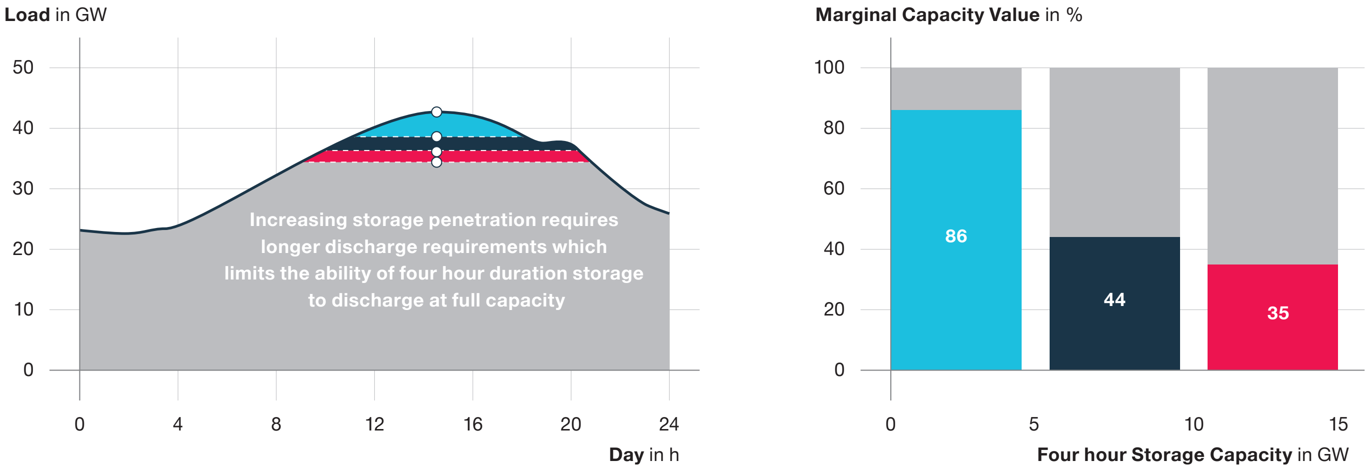


Fig. 2: ELCC for four hour storage systems as more of this type of capacity is added to a power system

The need for long-duration energy storage

Renewable power cannot deliver its full environmental benefits, generate economic profit or guarantee grid stability without the deployment of LDES.

Defining long-duration energy storage

Experience of VREs and short-duration energy storage (< = 4 h) in power systems has demonstrated that power systems need LDES in order to maintain their reliability. There are many definitions as to what LDES means in terms of duration, but many people consider this term to signify durations of between eight and 12 hours or more.

The reason LDES are needed when renewable penetrations increase is that some firm capacity is required to fill the gaps when VREs are not generating enough power to meet the load and shorter duration storage technologies have exhausted their charge (cf. Ciampoli 2021).

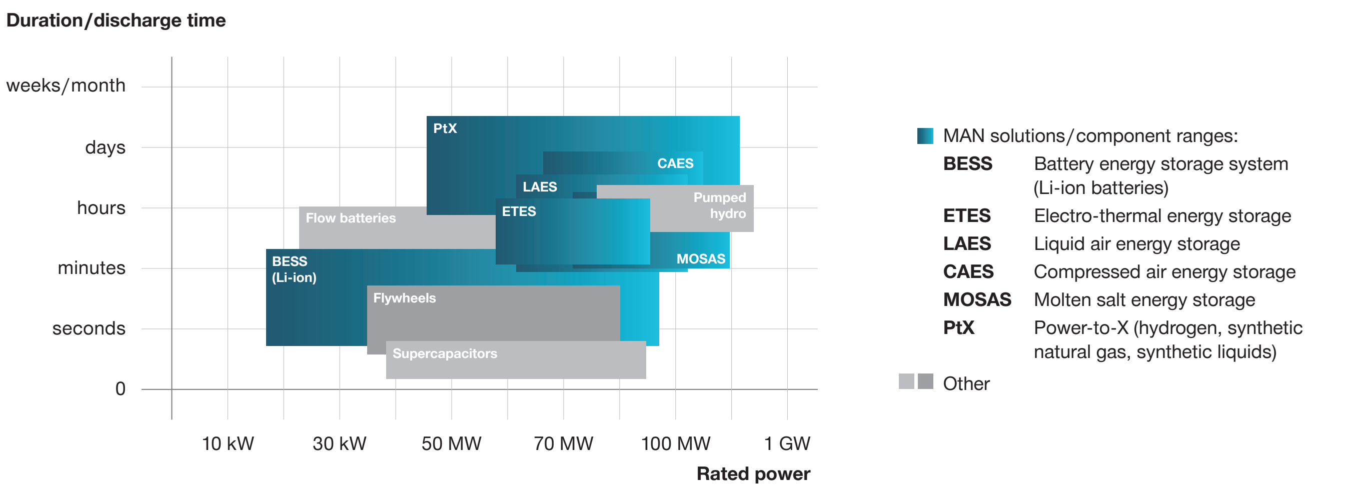
LDES type	Source of energy for charging the system
Mechanical	Renewable electricity
BESS	Renewable electricity
MOSAS	Renewable electricity, renewable fuels or heat (concentrated solar)

Tab. 1: Source of renewable energy for charging LDES systems

Types of long-duration energy storage

LDES comes in multiple forms – advanced batteries (e.g. flow batteries), mechanical (e.g. pumped hydro, compressed or liquefied gases) and thermal (e.g. molten salt). In all cases, the ideal scenario is to use excess, cheap renewable energy for charging a medium (battery cells, pumping water to a higher elevation, compressing/ liquefying a gas, heating molten salt) to create a large store of potential energy. This potential energy is then released, when needed, and converted back into electricity to provide MWh to the grid.

There is a major difference between grid-scale thermal energy storage systems for power generation and the other types of storage systems (Tab. 1). Since thermal systems store renewable energy as heat, they do not necessarily need to use electricity to charge the medium. For example, the best-known applications of molten salt energy storage are concentrated solar plants (CSPs). CSPs store solar energy directly as heat in media such as molten salt. The heat can be supplied by other means as well, from heat pump systems to electrical heaters and the direct combustion of renewable fuel.



Tab. 2: Classification of energy storage solutions by size and duration

How to store energy with salt

MAN Energy Solutions has developed MOSAS for stationary LDES applications. MAN MOSAS can be configured to generate power for electric utility applications, or for power-to-heat for industrial applications (Fig. 3).

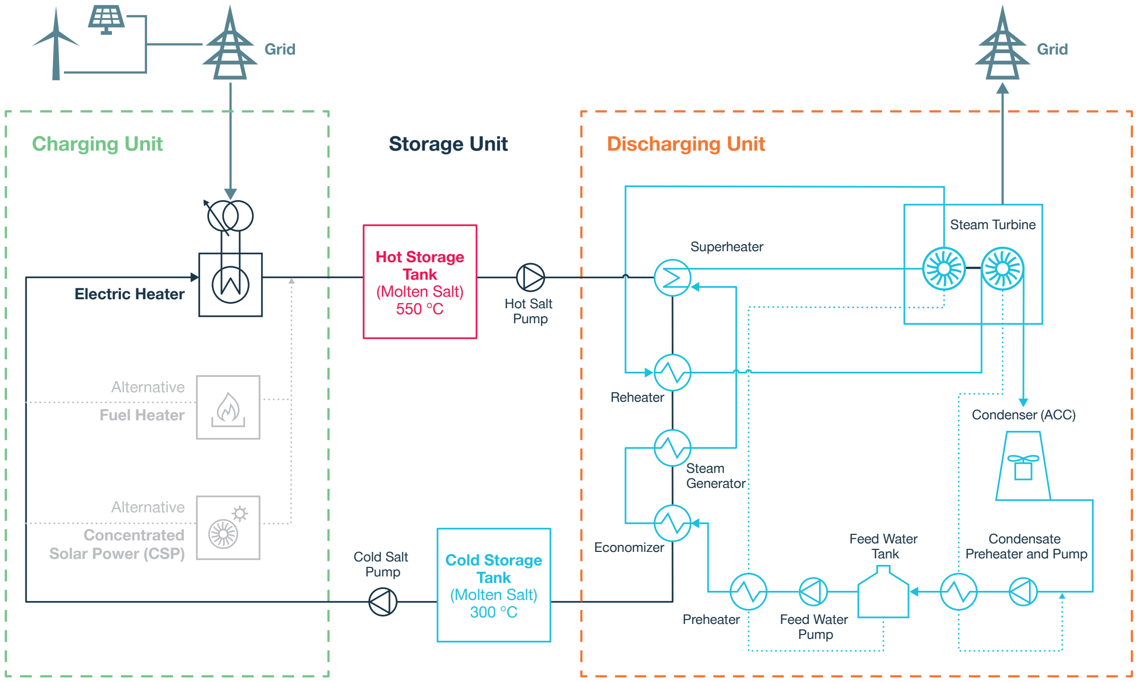


Fig. 3: MAN MOSAS system

Charging

The charging part of MOSAS consists of electrical heaters connected to the grid (Fig. 4) to heat salt. In an energy arbitrage context, the electrical heaters would purchase grid power when it is at its lowest cost on a given day, and discharge it when the prices are highest. Electrical heaters are an established and well-known technology and mean that a MOSAS plant can be located anywhere.

Electrical heaters heat salt in the storage part of the MOSAS system to temperatures as high as 600 °C. When configured with electrical heaters, the MOSAS system shifts the time when the renewable energy is delivered.

Fig. 4: MAN Energy Solutions electric salt heaters used in MOSAS long-duration energy storage

Storage

Molten salt, typically a mix of potassium and sodium nitrate, is pumped to a hot storage tank. Salt is used as the energy storage medium for two major reasons. Firstly, other materials can be used for thermal storage, including thermal oils. Thermal oils can be heated to the range of approximately 400 °C, which brings a high vapor pressure and leads to thick-walled equipment being used. Salt, in comparison, can be heated to approximately 600 °C and is not pressurized, so vapor pressure does not need to be considered. A system's thermo-mechanical efficiency is maximized at higher temperatures, so molten salt is a natural choice over alternatives. Secondly, salt has a better environmental profile. Oil leaks can be problematic and require substantial remediation if oil escapes from containment berms. In the event of a salt leakage at ambient temperatures, the salt hardens and can be picked up like lumps of stone. The salt itself is non-toxic. Furthermore, salts used for MAN MOSAS applications are lower cost than comparable volumes of thermal oil, and salt has an incredibly long lifetime. It can be heated, cooled, reheated on daily cycles for decades before needing to be replaced.

The heated molten salt is pumped to a "hot storage" system, a high-temperature molten salt tank, at temperatures of ~570 °C. When heat is extracted during the discharge process to produce steam, cooled salt is pumped to the cold tank at temperatures of ~270 °C. Hot and cold tanks (Fig. 5) are insulated. Temperature losses are in the region of 1 °C per day, which equates to approximately 0.3 % of the stored energy.

The duration of MAN MOSAS systems is application-specific, tailored to customers needs and depends on the size of the hot/cold tanks. Typical durations are between eight and 16 hours or more.

Fig. 5: MAN MOSAS Andasol

Discharging

Power-to-power applications: High-temperature steam is fed directly to a steam turbine for power generation (Fig. 6).

Power-to-heat applications: While this text describes MAN MOSAS with respect to power applications, molten salt energy storage also has the ability to decarbonize steam generation and process heating in industrial processes. This is done by omitting the steam turbine/power generation to ensure the direct delivery of steam, offsetting the need to combust fossil fuels. Thanks to the high salt temperatures of ~570 °C, high-quality steam can be produced for industrial/manufacturing/oil and gas applications.

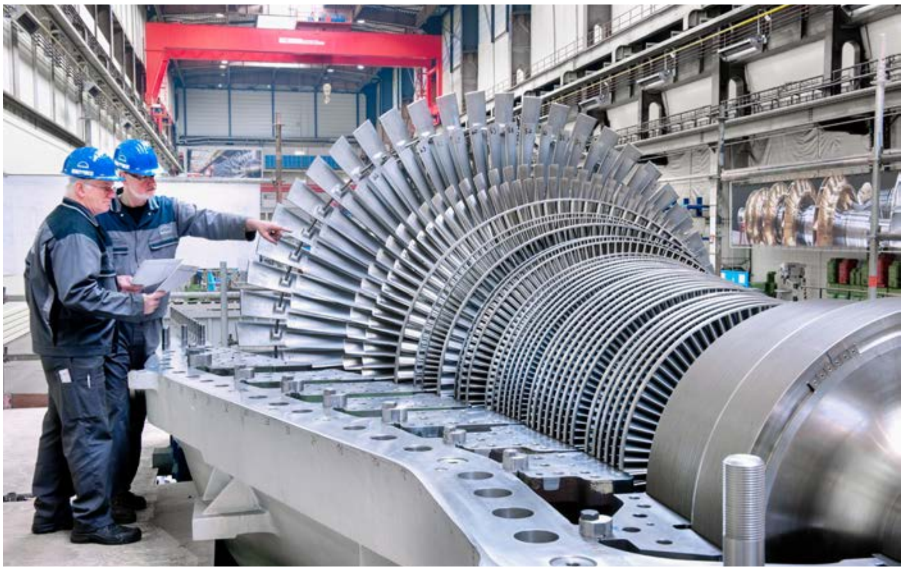


Fig. 6: MAN Energy Solutions steam turbine

Charging with electric heaters or renewable fuels

In order to make the system more reliable, fuel heaters can be installed parallel to the electric heaters. They are essentially additional fuel burners that can be configured to use carbon-free fuels (such as hydrogen or ammonia) or carbon-neutral fuels such as synthetic methane or methanol, biofuels, etc.

The addition of the fuel burner coupled with renewable fuels makes MAN MOSAS a hybrid LDES system. For day-to-day long-duration discharge of between eight and 12 or more hours, MAN MOSAS uses renewable energy stored in molten salts. If conditions arise under which MWh are needed from MAN MOSAS for longer durations, or during extended periods of compromised solar or wind output, the fuel heater can be used. This ensures that there is a continuous and reliable capacity under any weather conditions and even allows for seasonal energy storage.

One feature of the charging system for MAN MOSAS is that it can charge the system and discharge it at the same time with the fuel heater, if needed.

When to use fuel burners

There are two conditions under which the fuel heater may be needed. The first is if the power system needs capacity and energy on the system for a longer time period than the duration of the stored energy in the molten salt. If a MAN MOSAS system is designed for a duration of 12 hours and the system needs those MW for an additional one or more hours, the fuel heater can be used to ensure a continuous output independently of the availability of low-cost renewable energy (Fig. 7). This is made possible because the fuel heaters can charge the system at the same time as power is being produced. This fuel option allows MAN MOSAS to be treated as firm capacity and avoids the problem of diminishing marginal ELCC as greater volumes of LDES are added to a power system.

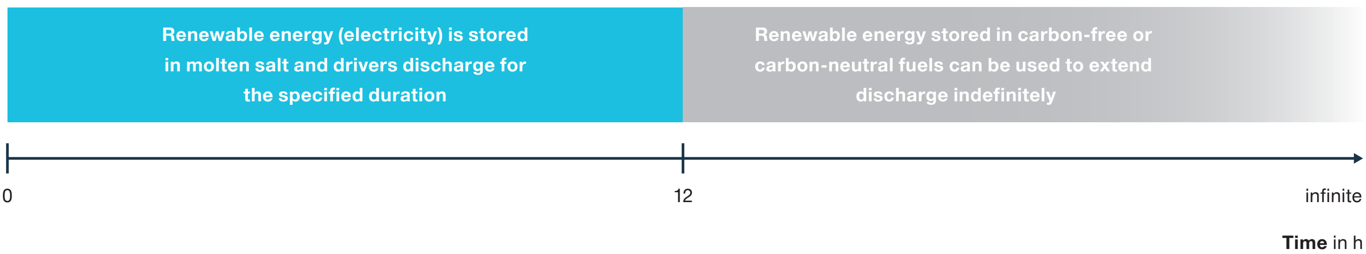
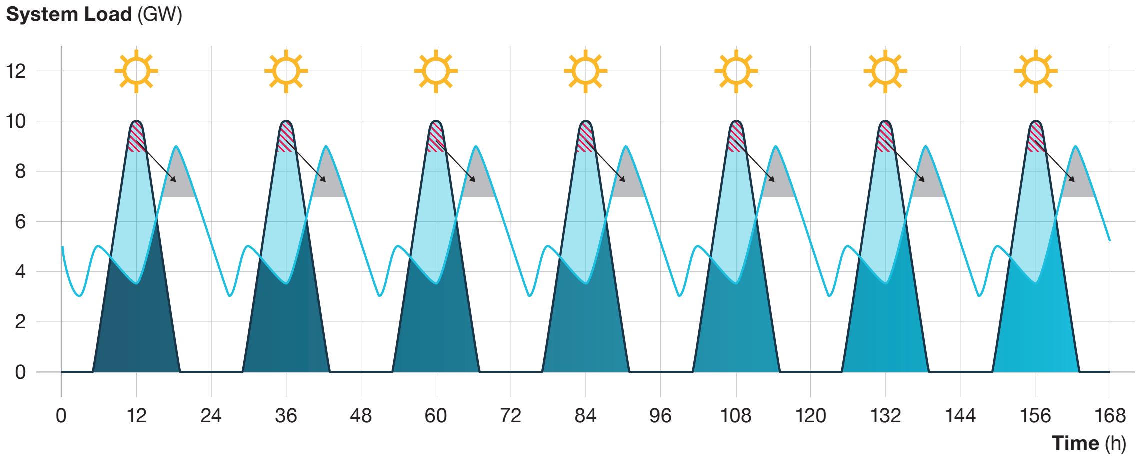


Fig. 7: An MAN MOSAS system designed for 12 h discharge can use the fuel heater to extend the discharge duration indefinitely

Daily Time-Shifting with MOSAS, Ideal Solar Conditions



MOSAS Reliable Capacity In Non-Ideal Solar Conditions

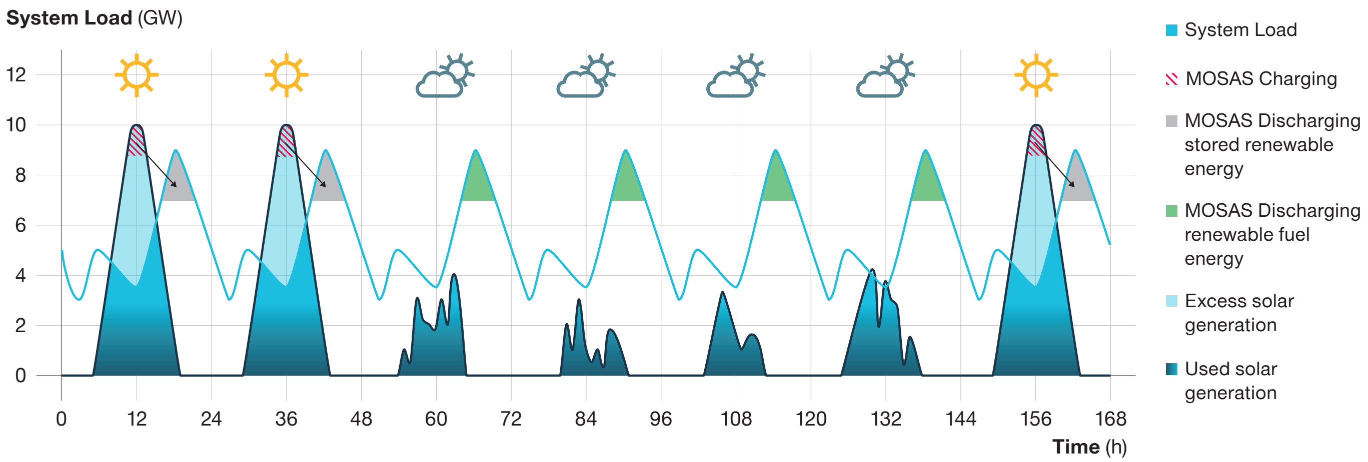


Fig. 8: The first figure shows MAN MOSAS dispatch under ideal solar conditions when the energy storage system absorbs excess solar energy midday to meet the load in the evening. The second figure illustrates when stored renewable energy is used in the form of fuel to meet the load if a diminished renewable output is insufficient for charging the storage for daytime shifting

The second condition that could warrant the need for fuel heaters involves emergency scenarios where long-duration energy storage systems (of any type) have exhausted their energy and are unable to recharge using renewable or other forms of low-cost energy. These conditions could occur during extended weather events that compromise solar and wind output.

For example, in an ideal week in a solar-dominated system, a MAN MOSAS would absorb excess renewable energy at midday and use that stored energy in the evening to meet the load after the sun has set (Fig 8, top panel).

However, if solar conditions are compromised due to cloud cover, rain, snow, etc., there may not be sufficient renewable energy on a given day to recharge the energy storage systems.

This compromises the system reliability, especially if low renewable output continues over several days. In these circumstances, the MAN MOSAS system with fuel heaters can draw from stored renewable fuels to continue to provide output, independent of solar or wind conditions (Fig. 8, bottom panel). A benefit of using renewable fuels as a secondary energy source is that the duration of MAN MOSAS can be extended to days, weeks or months, depending only on the volume of on-site fuel storage.

Reliable seasonal storage

The benefit of the MAN MOSAS system with fuel heaters is that it overcomes the dilemma of typical energy wind, solar and storage systems – namely that their ELCC falls as you add more of them. Electric utility power systems need long-duration and seasonal energy storage systems with ELCCs of ~ 1 (similar to traditional thermal systems). Moreover, these systems must maintain a high ELCC independently of the location, duration or the amount of capacity added to the system. MAN MOSAS with renewable on-site fuel storage and fuel heaters satisfies these requirements and acts as a form of reliable, long-term and seasonal energy storage.

Technical characteristics of MAN MOSAS

LDES type	Unit	Value
Rated capacity	MW	100
Charging	h	8
Discharge	h	8
Steam production[2]	kg/h/Lb/h	292,000/644,000
Steam temperature[2]	°C/°F	540/1,004
Steam pressure[2]	bara/psia	130/1,885
Round trip efficiency, electric	%	40
Round trip efficiency, fuel heater	%	35

Dispatch	Unit	Value
Start time	min	15–30
Minimum runtime	min	30
Minimum downtime	min	30
Minimum stable load	% of rated capacity	10
Ramp rate	% per min	10

Project site	Unit	Value
Interconnection	MW	260
Hot/cold salt tank size	m^3/yd^3	11,300/14,800
Plant footprint	m x m/ft x ft	136 x 150/466 x 492

Tab. 3: Characteristics of a 100 MW MAN MOSAS long-duration energy storage system with eight hour charging and discharge cycles

100 MW MAN MOSAS as a sample project

MAN Energy Solutions can custom-design molten salt energy storage systems for any application, adjusting the system size (MW) and rated duration (between eight and 16 or more hours). For industrial applications, a MAN MOSAS system can be designed for specific steam production (kg/h) and pressure requirements.

Reference details are provided here for a 100 MW MAN MOSAS system with an eight hour rated duration at full rated capacity.

[2] Steam flow rate, temperature and pressure can be custom-configured depending on customer needs.

Conclusion

MAN Energy Solutions is happy to work with our customers to explore how MAN MOSAS long-duration energy storage systems can help maintain reliability while striving towards a clean, net-zero carbon energy future. The MAN MOSAS system can be located anywhere, uses non-toxic media and relies on established technologies such as molten salt equipment (heaters, pumps), steam turbines and other equipment made by MAN Energy Solutions.

Figures

Tables

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