Replacing Fossil-Fueled Combined Heat and Power Plants with Malta's Pumped Heat Energy Storage Technology to Provide Clean Power and District Heat

February 2024

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Abstract

This study analyzes the potential integration of a 100-MW_{el}, 36-hour Malta Pumped Heat Energy Storage (PHES) system into the district heating network of the city of Hamburg, Germany, using energy from a nearby offshore wind farm that would otherwise be curtailed to charge the system. Publicly available data showing the times when curtailment instructions were given by the transmission grid operator were used to determine the hours during which the storage system should be charged. Malta's proprietary hourly performance model was used to simulate the behavior and performance of different plant configurations. It was shown that this configuration could avoid the curtailment of 227 GWh_{el} of wind energy per year. The study showed that the system could provide 117 GWh_{el} of electricity to the grid, as well as 72 GWh_{th} of thermal energy for Hamburg's district heating network, during periods where less renewable energy was available. This system could reduce the annual CO_2 emissions by 101,400 tonnes compared to the coal-fired combined heat and power (CHP) plant that it would replace.

Introduction

In addition to the EU climate and energy targets for 2030 and the objective of climate-neutrality by 2050, as set in the European Climate Law (EU, 2021), some member states such as Germany have set even more ambitious targets to be climate neutral by 2045 (BMUV, 2021). To reach these objectives, further targets on the build-out of renewables together with a phase-out of coal have been established.

The transition from fossil fueled to renewable electricity generation impacts not only the power sector but also the heat sector. The retirement of coal power plants, among them many that are operated in a CHP mode to supply heat for district heating, and the electrification and increased build-out of district heating systems using renewable heat will require the implementation of new, innovative technologies. One of the technical solutions that provides flexible power and heat is Malta's Pumped Heat Energy Storage (PHES).

There are many locations in Germany with high installed onshore and offshore wind capacity, e.g. in the states of Schleswig-Holstein and Lower Saxony, where not all the available renewable electricity can be transmitted to consumers on windy days due to the lack of grid capacity. In these cases, wind turbines must be curtailed. In 2020, 6,146 TWh of renewable energy was curtailed across Germany. In 2022, curtailment grew to 8,071 TWh (Bundesnetzagentur, 2023). This figure will continue to rise in the future with the increasing expansion of renewables. In the medium- and long-term, long duration energy storage (LDES) systems will be needed to provide green power and heat in times of low solar radiation and low wind.

Detailed meteorological studies of the site analyzed in this white paper were carried out, showing that such periods frequently occur for up to five days or more. The curtailed energy could be used to charge a Malta M100 PHES system in the city of Hamburg, which comprises a large district heating network. For the example analyzed in this study, a large CHP plant near Hamburg is considered, which is still using hard coal for the time being but will phase-out coal by 2025 and switch to sustainable energy sources. This white paper studies the integration of a 36-hour 100 MW_{el} Malta PHES system ("M100"), storing only otherwise curtailed wind energy, into Hamburg's district heating system, providing 24/7 green heat as well as green power in times of low wind energy availability to the city of Hamburg.

Technical Concept for the M100 to Provide Electricity and Green Heat

Malta's PHES technology, also called M100, is a 100 MW_{el} net AC, synchronous-discharge-power LDES system designed to meet grid-scale energy storage needs for various market applications. This technology brings stability and resiliency to the grid by alleviating load mismatch between demand and generation and providing grid services, such as frequency control, rotating inertia, and short circuit current. It uses molten salt and a coolant to store variable renewable energy that has been converted to thermal energy (heat and cold) through a Charge Heat Pump and reconverts it into dispatchable synchronous power and process heat through a Discharge Heat Engine, as illustrated in Figure 1. The M100 can operate at any power between minimum rated power (25% of nominal charge power and 35% of nominal discharge power) and full rated power for both charge and discharge as application demands.

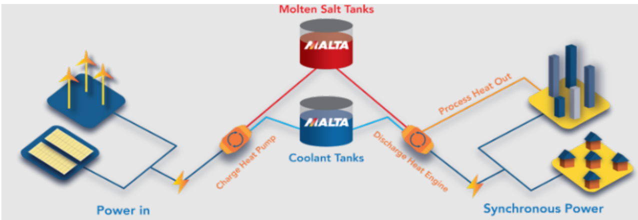

Figure 1: Conceptual diagram of the Malta charge and discharge sequence

The added value of pumped heat electricity storage over battery storage systems is that its synchronous charge and discharge turbomachinery trains offer all the flexible power generation abilities of gas turbine cycles. Malta PHES can provide the following storage services:

- Electricity storage (i.e., energy shifting, arbitrage, reserve power, ramping, etc.);
- Auxiliary services (i.e., synchronous inertia, frequency control, voltage control, reactive power, short circuit current, etc.); and
- Supply of process heat for the decarbonization of industrial processes.

Malta PHES fully replaces conventional gas-fired power plants and CHP plants by providing dispatchable power and heat. A 3D view of the M100 plant is shown in Figure 2Figure 2. The storage duration is easily scalable and customizable to specific applications by just increasing the size and number of the salt and coolant tanks.

Figure 2: 3D view of Malta M100 plant with 12-hour storage duration

While in discharge mode, 121°C heat is extracted from the system and can be used as industrial process heat or for district heating systems. As indicated in the red oval in Figure 3, the discharge heat is extracted from the main system in the Heat-Rejection Heat Exchanger downstream of the recuperator. A Discharge-Heat Heat Exchanger (DHHX) is used to extract heat from the hydronic fluid from the discharge heating subsystem. The secondary side of this DHHX is expected to be water, so the DHHX is a liquid-to-liquid type. The heat can be distributed directly to the end-use facilities and/or stored in a hot water storage tank.

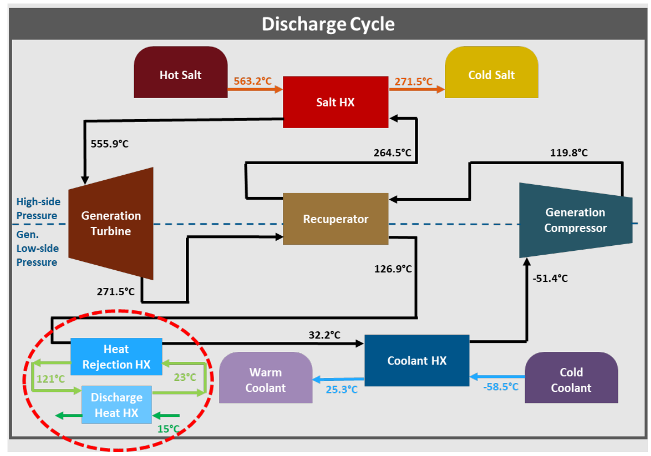

Figure 3: Extraction of discharge heat from the discharge cycle

If the whole temperature range is used, up to 81 MW_{th} of heat can be extracted at full rated condition. Additional storage and backup heating are options to ensure 24/7 heat delivery. To optimize the use of the discharge heat, the combination of high and low temperature heating networks would ensure that the heat is used in the highest possible temperature range.

Modelling Methodology

For this study, the curtailment instructions ("Redispatch") for the offshore wind farm "Borkum West 2" in 2020 were considered as a reference for a typical hourly dispatch profile. The data is made available publicly in one minute resolution by the Transmission System Operator (TSO) who operates this part of the German transmission grid (TenneT). It was assumed that the storage system would be charged at full rated power whenever Redispatch occurs at the reference location and discharged at full rated power when no Redispatch takes place.

The system was simulated in Malta's proprietary, detailed thermodynamical performance model on an hourly basis. The model calculates the charge and discharge cycle efficiencies and the working fluids' mass flows and temperatures based on the ambient conditions and the conditions of the storage media (e.g. hot salt temperature, cold coolant temperature, etc.) in every hour individually. It also considers startup times and ramp rates. The thermodynamics of the charge and discharge cycles are simulated in Ebsilon, considering actual performance parameters, such as heat transfer coefficients and isentropic efficiencies provided by original equipment manufacturers.

To optimize the system configuration from a techno-economic perspective, the storage duration was varied in two-hour steps between 10 and 72 hours. The Levelized Cost of Electricity (LCOE) was calculated for each configuration. Sensitivity analyses were carried out, varying the total installed cost of the system and the cost of charge energy. Apart from the LCOE, attention was given to the annual operation hours of the storage system and the total amount of electrical and thermal energy that can be made available by the system.

Results and Discussion

The wind farm was curtailed for 1,440 hours in the year 2020. The variation of the storage duration shows that the LCOE reaches its minimum with a storage duration of 26 hours, as shown in Figure 4.

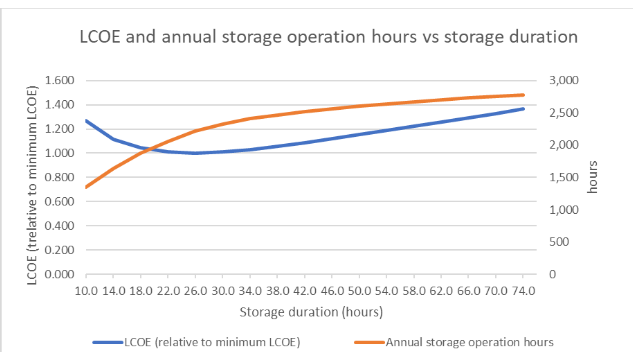

Figure 4: LCOE (relative) & annual operation hours of Malta M100 vs. storage duration

From this point on, with increasing storage duration, there are less and less annual operation hours during which this additional storage capacity can be used. The LCOE is not shown in absolute numbers (EUR/MWh), but relatively to the lowest LCOE. This is because the values strongly depend on the assumptions for the installation and operation cost of the storage system. A cost estimate for this specific site and configuration was not carried out at this stage and will be done in a second step after a detailed techno-economic pre-feasibility study.

The LCOE also depends on the price of the energy used for charging. Under current German regulations, wind farm operators get paid for the curtailed energy, and it may not be used to charge storage systems. This regulation is currently under discussion, though, and it is expected that it will change in the near future in a way that otherwise curtailed energy will be made available to storage systems at a very low price or even for free.

Nevertheless, as mentioned above, the LCOE is not the only parameter to be taken into consideration. The number of operation hours and thereby the amount of electrical and thermal energy delivered by the storage shall be as high as reasonably possible. The total operation hours increase with increasing storage duration, but the curve flattens out notably beyond 36 hours. Therefore, a 36-hour storage system has been chosen as recommended for this study.

With this configuration, out of the 1,440 hours of Redispatch, 1,195 hours, or 83.0% of the available hours, could be used to charge the storage system. A total of 227 GWh_{el} of otherwise curtailed wind energy could be stored. 117 GWh_{el} would be returned to the electricity grid, while 72 GWh_{th} of thermal energy could be used in the district heating network (see Figure 5). This corresponds to a roundtrip efficiency (power-to-heat-to-power-and-heat) of 83.3%. As this energy storage plant would replace a hard coal-fired power plant, assuming an average specific CO_2 emission of hard coal of 867 g/kWh_{el}, the CO_2 reduction results in 101,400 t per year.

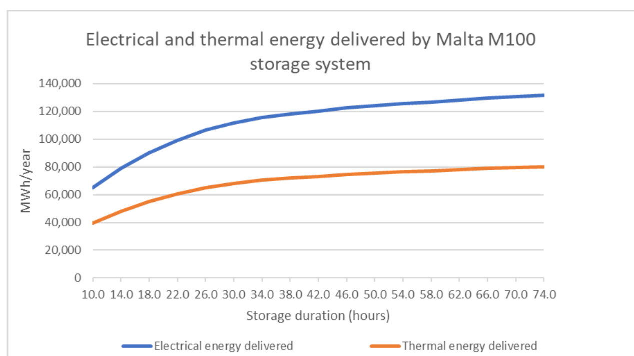

Figure 5: Electrical and thermal energy provided by Malta M100 vs storage duration

As can be seen in Figure 6, most curtailment occurs in winter between November and March. The typical heating period of Hamburg is from October to March, so the availability of heat from the PHES system matches very well the district heating demand.

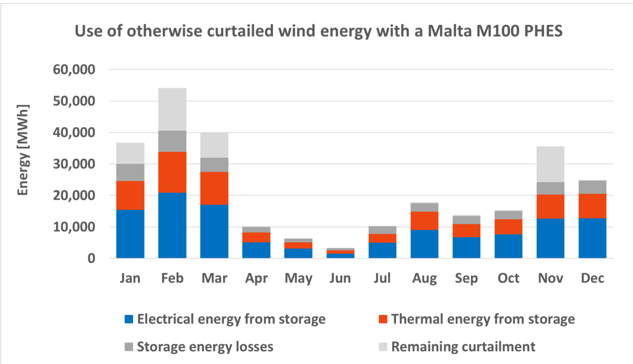

Figure 6: Monthly distribution of otherwise curtailed wind energy stored in the Malta M100 PHES system

It should be noted that, in addition to only using otherwise curtailed energy, the storage system discussed here can be used in further situations. It could be charged when electricity market prices are low and discharged when prices are high (arbitrage), independently of the occurrence of curtailment. This will increase the annual operation hours and hence decrease the LCOE. Further analyses with future market prices, taking into account the increasing penetration of renewable generators and the decommissioning of existing fossil-fueled power plants, will be conducted in a next step.

Conclusions

The study that was carried out shows that a large part of wind energy from an offshore wind farm in Northern Germany that would otherwise be curtailed can be stored in a long duration energy storage system and be made available in the forms of electricity and heat at a later stage, when renewable resources are low and energy demand is high. It is shown that the occurrence of excess wind energy is much higher in winter, thereby matching very well the heat demand in a district heating network.

As more and more renewable power plants are installed, energy storage systems are necessary to avoid further curtailment. As shown in this example, there are energy storage technologies that can balance electricity supply and demand while also providing grid services and heat, thus being able to fully replace fossil-fueled CHP plants.

A precise cost estimate for this specific site and configuration was not carried out at this stage and will be done in a second step after a detailed techno-economic pre-feasibility study. The business case depends on the development of future market prices and on potential additional revenue streams, such as arbitrage, frequency services, and payments for capacity or rotating inertia. In most scenarios analyzed, a green premium in the form of a feed-in tariff or a Contract for Difference (CfD) is necessary to make a project like the one described in this study economically feasible under the current market conditions. Nevertheless, LDES systems are absolutely essential to reach the EU climate and energy targets and to make the transition to climate neutrality possible.

References

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