Techno-economic analysis for solar thermal integration point in an industrial boiler network: case study from dairy sector

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Abstract

This paper presents techno-economic analysis of a parabolic trough collector (PTC) for various integration points in a boiler network. The complete system is simulated with solar collectors utilized in 3 different integration schemes: a) feed water heating, b) direct steam generation, and c) process integration. The effect of integration point on the solar fraction, levelized cost of heating (LCoH), and carbon mitigation potential is presented for a real case dairy unit in Dubai. The simulations are performed using TRNSYS and MATLAB. Results show that the least global LCoH for highest solar fraction is achieved for process level integration. A relatively higher carbon mitigation can be achieved in steam integration, at expense of higher LCoH. The excess energy from the solar field can be stored in thermal storage tanks and can be utilized when there is intermittency in solar radiation.

Keywords: Solar thermal, Parabolic trough collector, Levelized cost of heat, integration schemes

1. Introduction

All countries are trying to reduce their emissions to achieve the target of limiting the increase in atmospheric temperature to 1.5ºC. The share of renewable energy sources in the energy mix is increasing to realize the commitment agreed in the Paris Climate summit. To be within the targeted limit in temperature rise, reducing the emission of Green House Gas (GHG) from industries, transportation, and residential sectors is required. The final energy consumption in the world can be divided into; 17% is consumed in the form of electricity, 32% is consumed for transportation, and 51% is consumed in the form of heat. Among the total energy consumption by global population, 32% of the energy is consumed in the industries and in that 74% energy is required for heating application (REN21 Secretariat, 2021).

Most industries are still relying on fossil fuels to meet their thermal demand, which leads to significant GHG emissions. Solar Heat for Industrial Processes (SHIP) is a good alternative. Some reasons for the reluctance of some industries to implement these technologies include: previously installed fossil fuel technologies, lack of financial incentives, low cost of conventional fuel and variability of renewable energy sources.

In the industries, 30% of the process requires temperature below 150ºC and 22% of them require the medium temperature category, which is between 150ºC to 400ºC (Hogrefe, 2021). Concentrated Solar Power (CSP) technologies available in the market and can meet all these heat demands. Food processing, textile, dairy and tea are some of the industries that require temperature in the medium and low-temperature levels.

The dairy industry or a dairy processing plant requires heat energy for almost all the processes, and this heat requirement is met from the heat generated by combusting fossil fuels. The dairy industry has processes to increase the shelf life of milk called pasteurization, processes to create value-added products from milk and Cleaning in Place (CIP) for the equipment. All these processes require heat in the range of 50ºC to 200ºC (Sharma, 2016). As per the journal article (Anna Flysjö, 2013), a leading dairy company in Europe emits between 1.1 kg and 7.4 kg of carbon dioxide while producing value-added products like whey-based products, cheese, butter etc.

These CO2 emissions can be eliminated if the heat is generated from a renewable source such as solar power.

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Parabolic Trough Collector (PTC), which concentrates solar radiation to a receiver tube kept at the focal point, can produce the heat required to meet the thermal demand in the dairy industry. These types of collectors track the sun from east to west, thus capturing the maximum radiation.

For creating awareness among the policymakers and the industrial owner about the potential of solar thermal (ST) in reducing GHG emission, providing energy security and minimizing the dependence on fossil fuel, this study was done for finding the effect of integration points on solar fraction, Levelized Cost of Heat (LCoH) and carbon mitigation potential of a solar thermal system.

A step-by-step approach is used to conduct this study. Initially, a detailed literature review as well as interviews with several engineers at the operation from dairy industries were done. We obtained the operation profile of the dairy processes, heat demand, and techno-economic details of the existing boilers in the dairy sector. The results are further used to find the best commercially available solar thermal technology suitable for a given temperature range. This is followed by an energy audit of an existing system to analyse the existing cost of heating, load profile, and boiler information. Later, the system simulations with solar thermal collectors are performed for various integration points in the industrial steam network. The simulations are performed using TRNSYS and MATLAB. The output from the model is used to calculate the LCoH, solar fraction and carbon mitigation. For simulations, three integration schemes are considered namely; direct steam integration, process integration and feed water heating.

2. Renewable energy for industrial process heating and fossil fuel price trend

Industries demand a significant amount of energy for process heating. Solar thermal technologies available in the market such as flat plate, Parabolic Trough Collector (PTC) and Linear Fresnel collectors can meet the heat demand according to the temperature level needed for the industries. A report published by IEA (Weiss & Spörk-Dur, 2019) in 2019 shows that 741 solar thermal systems were installed for industrial heating worldwide by 2018. The utilization of heat energy from solar is expected to increase by 2021-2022, major energy-consuming nations like China, the USA, and European Union will be the reason for the growth and will account for 70% of the contribution (Abdelilah, et al., 2020). Low maintenance and simple technology are pushing factors for are acceptance of solar thermal technology among the industries.

Considering the case of the dairy industry, the heat demand is going to increase in the coming years, and the dairy consumption will be 99 kg/person for a year in the near future as per the UN food and agricultural organization's prediction (Shine, et al., 2020). To meet this high demand, the production of dairy commodity must also increase, which can lead to more carbon emission if fossil fuels are used for process heating. A significant number of industries rely on natural gas and coal for generating thermal energy. Reports show that the era of cheap natural gas is going to end. So natural gas will be a transition fuel as natural gas price is going to elevate in the coming years. Figure 1 is a graph (Shiryaevskaya, et al., 2021) showing that the natural gas is increasing.

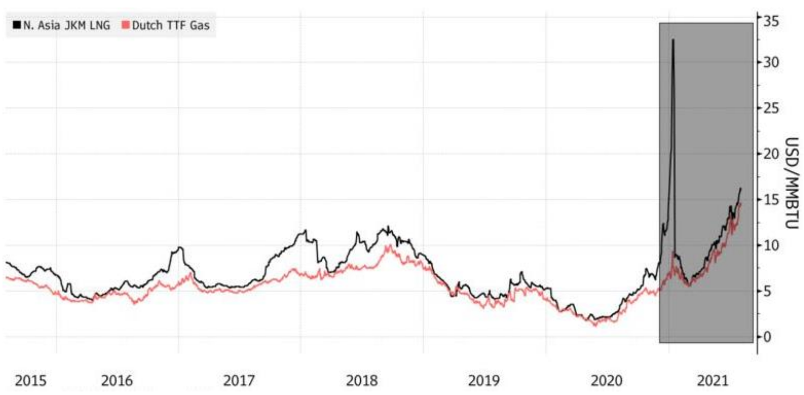

Figure 1: Graph showing a positive trend in the natural gas price

3. Different schemes for integrating solar thermal system in the steam network

In an industrial steam network, the heat carrier medium's temperature, pressure, and flow rate will be different at different points. In this study, the solar thermal system is integrated into three-points: (a) supply level, (b) process level and (c) feed fluid level. According to the integration points, the integration schemes are direct steam integration, process integration, and feed fluid preheating. Different integration schemes are explained below.

3.1. Direct steam integration

In this type of integration, a derivative from the boiler feedwater is fed to the solar collector field. When the water passes through the solar collector field, the feed fluid will be partially evaporated and the mixture of hot water, and steam will be then stored in a steam drum. When the steam attains the required pressure, it will be fed to the main steam line. The schematic diagram below shows the integration of the solar thermal system for direct steam integration (Muster, et al., 2015).

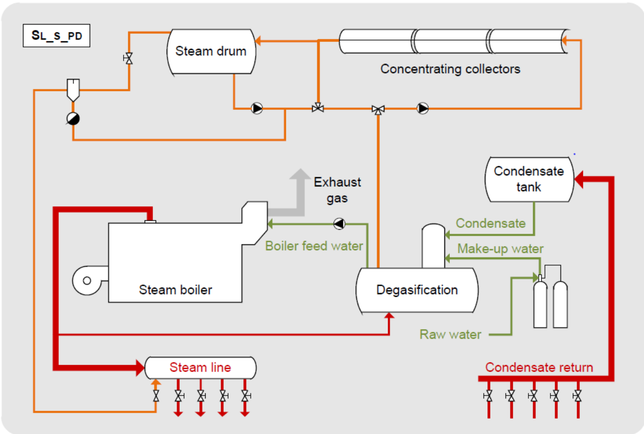

Figure 2: Schematic diagram showing direct steam integration

3.2. Process integration

For a process integration, the heat carrier from the solar collector field is passed through a heat exchanger, connected in series to the conventional heat exchanger in the steam network near the process. The heat exchanger supplied from the solar can either meet the whole thermal demand of the process or a partial demand of the process. Figure 3 shows the schematic diagram showing the serial connection of the two heat exchangers (Muster, et al., 2015).

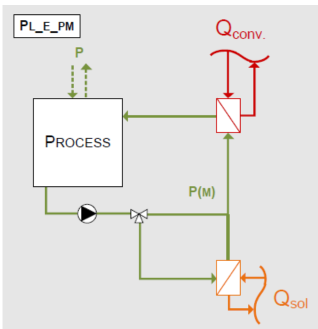

Figure 3: Schematic diagram showing process integration

3.3. Feed fluid preheating

The boiler feed water from the degasification section will be fed to the solar collector, where it will be converted to pressurized hot water. Then the hot water at high pressure will be provided to the conventional boiler for generating steam. Figure 4 is the schematic diagram of integrating solar thermal system for feed fluid preheating (Muster, et al., 2015).

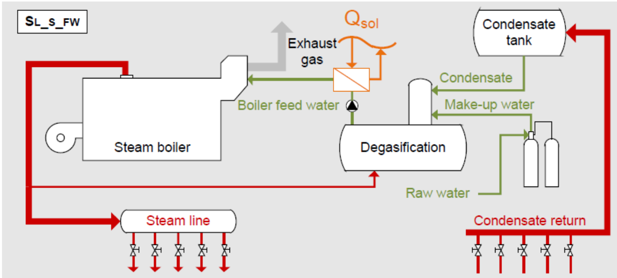

Figure 4: Schematic diagram of feed fluid preheating

4. Key performance indicators

4.1. Levelizes Cost of Heat (LCoH)

Levelized Cost of Heat (LCoH) is a parameter used to compare different systems that generate thermal energy. The LCoH of a system depends upon type of technology, whether condition of the location, and some economic parameters (Kumar, et al., 2020). LCoH is the ratio between the cost expenditure on the system to the energy delivered by the system, expressed in €/MWh. The equation and various parameters needed to calculate LCoH are shown below (Kumar, et al., 2020).

$$LCoH = \frac{I_0 - S_0 + \sum_{t-1}^{T} \frac{C_t(1-TR) - DEP_t * TR}{(1+r)^t} - \frac{RV}{(1+r)^T}}{\sum_{t-1}^{T} \frac{E_t}{(1+r)^t}} \qquad \text{(eq. 1)}$$

Where, I_0 is the cost of the heat generating system, S_0 is any incentives or financial support from any organization, C_t is the cost required for operation and maintenance of the system, TR is the corporate tax rate existing in a particular location where the plant is located, DEP_t shows the asset depreciation, RV is the residual value of the system, E_t is the energy consumed by the system to generate the required heat to meet the demand, r is the discount rate, and T is used to express the life time of the system (Shah, 2021).

The global LCoH is the weighted sum of LCoH of the conventional heat generating technology and LCoH of the solar thermal technology. This parameter is relevant for when the heat generated by a conventional system is assisted by solar thermal technology. The equation used to find the weighted sum is given below (Shah, 2021).

$$Global\ LCoH = \frac{(LCoH\ of\ conventional\ system * Energy\ from\ boiler) + (LCoH\ of\ ST * Energy\ \ from\ ST)}{Energyfrom\ the\ whole\ system} \qquad \text{(eq. 2)}$$

4.2. Solar Fraction

Solar fraction is the ratio of energy supplied from the ST system to the energy supplied to the total thermal energy demand. The value of solar fraction varies between 0 to 1. The heat load at each level of the steam system would be different. In this study, solar fraction at a particular level is considered instead of considering the contribution from the solar thermal system to the whole thermal energy demand of the plant (Shah, 2021).

5. Case description

The study case is located in Dubai. The location has good solar irradiation, but also lower fuel cost compared to other countries. The boiler is oversized so that the plant can expand in the future. The operation is not continuous at the moment, and it occurs mainly during sunshine hours. The plant chosen uses diesel as the fuel for the boiler at a price of 0.45 €/L, and the location has solar irradiation of 1883 kWh/m2. The boiler of the plant produces steam at a temperature of 110ºC with a maximum flow rate of 7 ton/h and operates at an efficiency of 96%. The Figure 5 shown below shows the load profile of the plant.

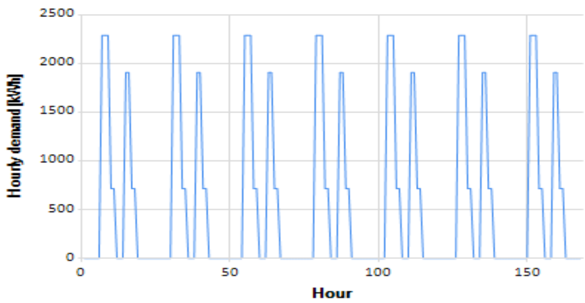

Figure 5: Thermal load profile of the plant over a week

The plant requires heat for cleaning purposes in the milk reception section, pasteurization, and cleaning (CIP). The plant needs heat at 95ºC at a maximum flow rate of 430 kg/h and 750 kg/h for cleaning process in the milk reception section and for CIP. For pasteurization, heat at 78ºC at a maximum flow rate of 3 ton/h is needed. The boiler uses the condensate return from the boiler as feedwater. After the process, a condensate of temperature between 60ºC to 75ºC is available, which is combined fed back to the boiler.

As the heat between the range of 50ºC to 200ºC is needed for dairy processing, the PTC Absolicon T160 is used for analysis. The selected concentrated solar thermal collector can produce hot water up to 160ºC and steam up to 8 bar pressures. The optical efficiency of the selected ST collector is 76.6%.

6. Results

The calculation of the global LCoH with the solar assisted heating system, LCoH with the conventional boiler system and the LCoH with the solar thermal system were found using the equation (1). The initial cost of the boiler is not considered in the calculation of the LCoH of the conventional boiler as the plant already had an existing boiler. By considering the lifetime of the boiler as 25 years, corporate tax rate of 2% and discount rate 4%, the LCoH of the conventional boiler is found out to be 44 €/MWh without considering carbon tax. If there is a carbon tax of 62 €/ton (Whiteley, 2020), then the LCoH of the boiler can go up to 60 €/MWh (Shah, 2021).

The carbon emitted from the diesel boiler is found from the amount of fuel consumed by the boiler and CO2 emitted for a liter of fuel. The combustion of 1 L of diesel emits 2.66 kg of CO2 (AutoSmart, 2014). In the first year, the conventional diesel boiler demands 2386 MWh of energy, and it emits 629 tons of CO2.

Simulation results showed variations in the LCoH, solar fraction and carbon mitigated for different integration schemes. All the simulations are done by considering that a pressurized hot water storage will be included, limiting the energy wastage from the solar thermal system to 20% of the total energy supply of the solar thermal system.

6.1. Direct steam integration

The solar thermal system needs to generate steam at 3 bar pressure for supply level steam integration. The condensate return of 60ºC is fed back to boiler in the plant considered for study. In that case, the annual load of the boiler would be 2386 MWh. Figure 6 shows the variation in the LCoH of the ST system and the solar fraction for the particular load for various field sizes. Figure 7 shows the carbon mitigated for different solar fraction for direct steam integration. The reduction in carbon emission is calculated from the reduction in the fuel consumed when ST system is integrated with the existing conventional steam boiler.

The highest solar fraction that can achieved for steam integration was 66.9% at a global LCoH of 41 €/MWh. More solar integration shows a major increase in the LCoH with minor increase in solar fraction.

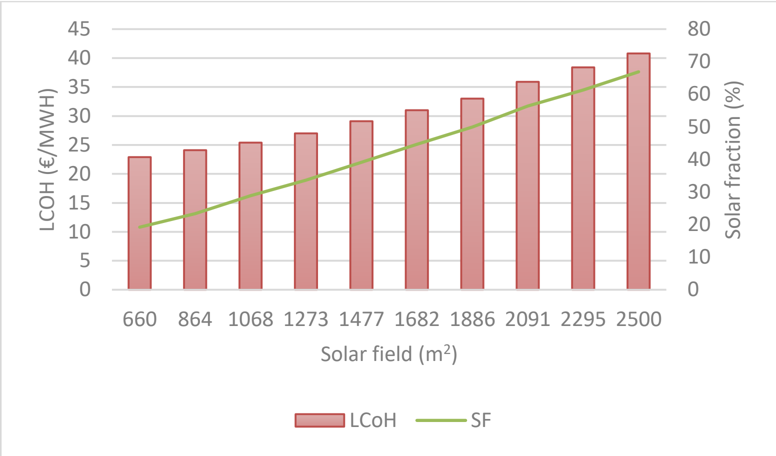

Figure 6: Variation in LCoH and Solar fraction for different solar field integrated for supply level steam integration

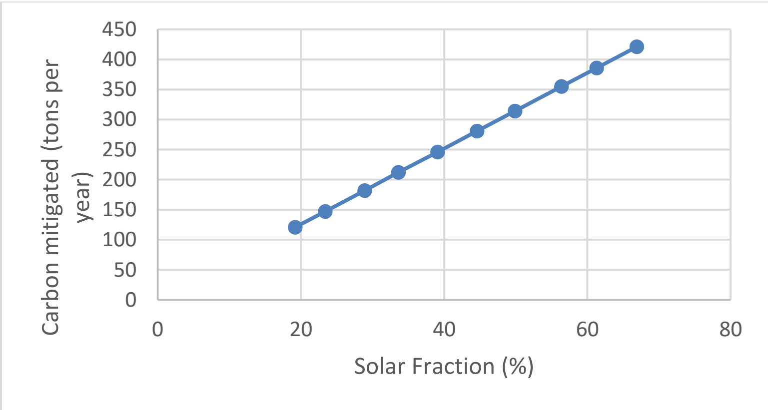

Figure 7: Carbon mitigated at different solar fraction for direct steam integration

6.2. Process integration

For a process integration, it is required to increase the heat carrier temperature to 90ºC. In this level of the steam network as the heat carrier is hot water and Δt is 65ºC, the energy demand is 1201 MWh for a year. Same as the previous case, a storage tank is introduced to limit the wastage of energy from solar thermal system to 20% of the total energy supply from solar thermal system. Figure 8 shows the variation in the LCoH and solar fraction for several solar field sizes integrated to the process level and Figure 9 shows the carbon mitigated at different solar fraction. A global LCoH of 36 €/MWh can be achieved at a solar fraction of 85% for a process level integration.

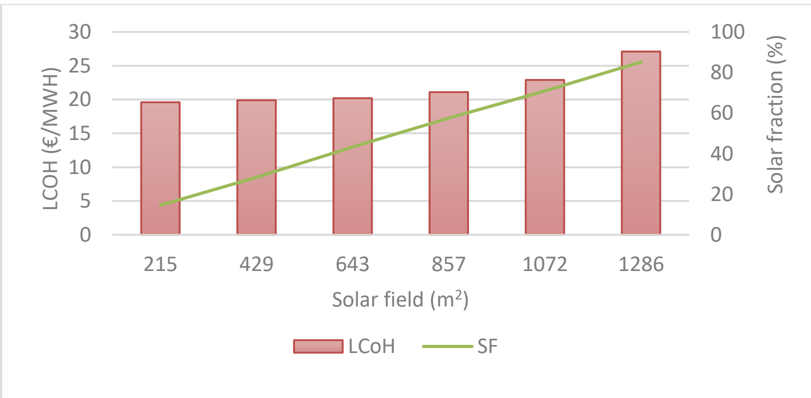

Figure 8: Variation in LCoH and solar fraction against solar field size for process level integration

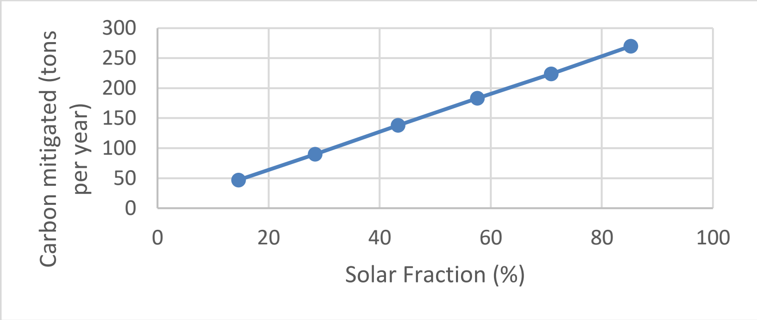

Figure 9: Carbon emission mitigated for at different solar fraction for process level integration

6.3. Feed fluid preheating

Feed fluid preheating is the minimum load in the steam network. The condensate return from the process together with the make up water temperature is increased to 100ºC and fed to the boiler. The energy demand at this point is 118 MWh. Figure 10 shows the variation in LCOH and solar fraction of ST system for feed fluid preheating. Figure 11 shows the carbon emission mitigated at various solar fraction at the preheating level.

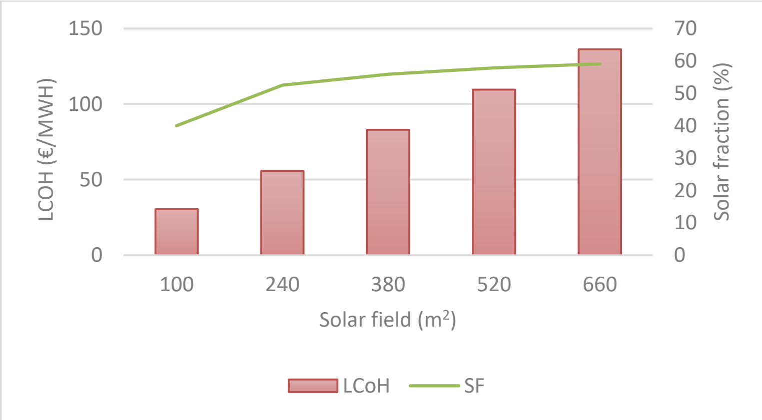

Figure 10: Variation in LCoH and solar fraction for feed fluid preheating integration

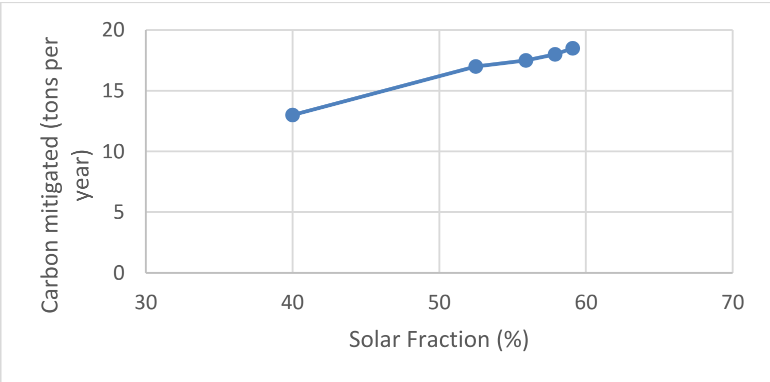

Figure 11: Carbon emission mitigated for different solar fraction for ST integration at feed fluid preheating level

7. Conclusion

This study aims to investigate integration of thermal solar power in different points in an industrial process on various parameters such as LCoH, solar fraction and carbon mitigation of solar thermal system. A PTC developed by the Swedish company Absolicon Solar Collector AB, T160, was selected for analysis. A real case of a dairy industry was selected to present a realistic scenario for the the cost of heating, load profile, and boiler information. Later a system simulation is done to check the variation in LCoH, solar fraction and carbon mitigation potential of the solar thermal system on three different integration points.

It was found that maximum demand occurs in the supply level and maximum carbon mitigation can be achieved if the solar thermal system is integrated in the supply level. Feed water preheating has the least carbon mitigation potential as the heat demand at the feed water level is small compared to process level and supply level.

In this study solar fraction is considered as the energy that the ST system can deliver at a particular load. The optimal solar fraction is calculated at 67% for supply level steam integration and an optimal solar fraction of 85% can be achieved for process level integration for the studied case. The LCoH of the ST system will go high at higher values of solar fraction and the system would become less economical. Almost half of the energy demand of the feed fluid pre hating can be done with ST, but a larger system will require a thermal storage tank with an associated increase in cost.

8. Discussion

There are different motivations to consider Solar Heat for Industrial Processes (SHIP). Industries may have a decarbonizing target; some have the aim of reducing their fuel cost and some industries adopt alternate technology as they may be required by local legislations. Depending upon the intension of adopting ST system, the technology, size and integration points vary. An industry with the aim of decarbonizing the production process may select an integration scheme with least priority to the financials and higher priority to the carbon mitigation potential of the system. Higher degrees of solar fraction require greater energy storage capacity than the optimal economic solution. SHIP is a proven technology with economical incentives that requires a tailor-made solution to determine the optimal solution for each application.

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