Levelised Cost of Thermal Energy Storage and Battery Storage to Store Solar PV Energy for Cooling Purpose

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Abstract

In this paper, we define scenarios for cooling applications that are coupled with photovoltaic (PV) systems and highlight the role of energy storage. Subsequently, we advance the method of Levelised Cost of Storage (LCOS), which has been developed for electricity storage in the literature, to compare thermal energy storage and battery storage for cooling application coupled with PV systems. Lastly, we apply the method to a real scenario and determine the LCOS of chilled water storage and battery storage configurations. The existing 11,000 m² office-cum-retail in the tropics of Singapore utilizes a 1055 kW_{th} chiller to supply its air-conditioning needs. Moreover, the rooftop is capable to accommodate a 247.5 kW_p PV system. A parametric simulation study was considered by varying the usable energy storage capacity from 100 kWh to 5000 kWh. It was found that for battery storage 300 kWh capacity offers the lowest LCOS of 0.10 USD/kWh for this particular application. However, the LCOS of the chilled water storage is at 0.06 to 0.08 USD/kWh for various storage sizes. Nevertheless, the battery storage is able to increase the self-consumption of PV energy more than the thermal energy storage option, as the chiller plant control proved to be crucial for the integration of thermal energy storage.

Keywords: Battery, demand side management, energy storage, LCOS, levelised cost of storage, PV powered cooling, solar air-conditioning, thermal energy storage

1. Introduction

Solar photovoltaic (PV) systems added to buildings can contribute a certain portion of the building electricity demand. In sunny areas, the electricity demand is often dominated by the cooling power consumption. Cooling applications such as air-conditioning and food conservation can be coupled with solar PV systems. However, the solar irradiance profile, shown as a graph in Figure 1 (top), does not always match the cooling demand of different applications. Figure 1 (bottom) shows the cooling load requirements of different building types over the course of one typical day. Hence, energy storage is essential for many situations in which cooling applications are coupled with solar PV systems. Energy storage is a necessity in off-grid systems and has been gaining importance in on-grid systems to increase the self-consumption of solar PV energy and provide services to the electricity grid (Luthander et al., 2015). Utilising electrical energy generated by a PV system to run a chiller for a cooling application enables both battery storage (Teleke et al., 2010) and thermal energy storage (Arteconi et al., 2017). The implementation of energy storages in combination with PV systems and cooling systems depends not only on the performance of the energy storage solution, but especially on its economic viability.

The literature discusses such configurations mostly in the form of case studies. For example, Arteconi et al. (2017) analysed a case for an industrial building that has a PV system and uses a chilled water tank. They applied the existing chilled water tank in combination with the PV system for demand side management for an industrial building in Italy, which only requires cooling during daytime on weekdays. Hence, the authors used the chilled water tank to shift the electrical load to the weekend, running the chillers to utilise electrical energy generated by the PV system. Based on a calibrated dynamic simulation model, energy performance and economics were investigated. As expected, the cooling system's energy demand rises when the thermal energy storage is used.

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However, the energy costs decrease, as the cheaper PV energy is utilised, which makes the use of the thermal energy storage profitable. Nevertheless, the study assumed that the systems were already in place and did not take into account the cost of initial investment. Adding the thermal energy storage to the existing PV and cooling system might have resulted in a long payback period.

Meanwhile, utilising batteries for cooling applications has not been sufficiently explored in the literature. Many sources focused on the general electricity demand profile and the PV power generation profile to increase the self-consumption of PV energy. For example, Merei et al. (2016) conducted a sensitivity analysis for a supermarket with PV and battery system in Germany. Energy intensive commercial buildings with large rooftop space can be a compelling case for PV systems coupled with energy storage. According to the economic situation in Germany and the supermarket power consumption profile, the PV system is viable; however, the battery storage becomes only viable when its cost falls below 200 €/kWh. The authors mentioned that for different commercial load profiles, battery storage might be feasible.

Previous studies have analysed the economics of case study systems with PV and energy storage for cooling applications, but there is little research comparing the economics of thermal energy storage with that of battery storage. Thus, the objective of this study is to assess energy storage costs for chilled water storage and battery storage to store energy for cooling purpose. A specific office-cum-retail building in Singapore is analysed, as a major portion of building energy consumption accounts for cooling in cities in the tropics. Therefore, energy simulation models are developed and run with varying storage sizes in order to determine the suitable storage size for the specific application. Moreover, a financial method for the assessment of the costs of energy storage is proposed in this work, as there is no suitable method for comparison of thermal energy storage and battery storage yet.

The subsequent sections of this paper are structured as follows: Section 2 explains the variety of PV powered cooling applications, followed by the scenario description in Section 3. The methodology Sections 4 and 5 describe the energy simulation and financial method, respectively. Subsequently, Section 6 presents the results. Finally, the work is concluded in Section 7.

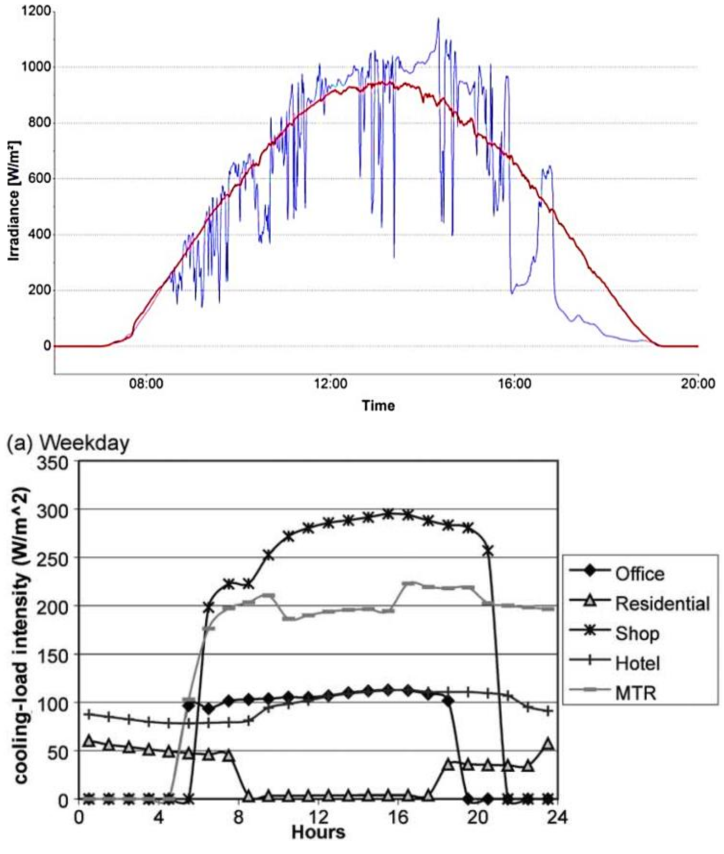

Fig. 1: Measured solar irradiance of a typical clear-sky day (red) and a typical cloudy day (blue) in Singapore (SERIS, 2011) at the top and simulated cooling load for different building types in the subtropical Hong Kong (Chow et al., 2004) at the bottom.

2. Energy storage for cooling applications coupled with PV systems

PV systems to supply energy for cooling applications may be located in areas with access to the public electricity grid (on-grid), or in areas that are not connected to the public electricity grid (off-grid). When PV systems are coupled with cooling system, different configurations can be realised. As shown in Figure 2, the system configuration depends on the availability of a grid connection, which means on-grid (a) or off-grid (b), and the integration of energy storage solutions (1 – 5).

In an on-grid scenario (e.g. air-conditioned building with a rooftop PV system in a city) energy storage is not a necessity (1a). The total electrical load does not only consist of the chiller plant, but also of other appliances in the building. The PV system offsets a certain portion of the building power consumption that varies with the solar irradiance. If a low-rise building is assumed, the PV power might exceed the building power consumption at times. Then, the surplus power is fed into the public grid. When the building power consumption is higher than the PV power, the remaining power is supplied by the public grid.

However, in an off-grid system there is no public grid to buffer the volatility of power demand and supply. In a scenario without energy storage (1b), that would mean the cooling system can only be powered when the solar irradiance is sufficient. This kind of system would not be able to supply continuous cooling; hence it is not applicable in practice. In order to supply a cooling load sufficiently in an off-grid situation, an energy storage technology such as a battery has to be used (2b).

A well-sized battery absorbs the surplus PV energy and releases electrical power when the solar irradiance is not sufficient to power the cooling system. Battery storages are common in PV off-grid systems such as solar home systems and rural microgrids (Aghamohammadi and Abdolahinia, 2014; Chaurey and Kandpal, 2010; Mohamed and Koivo, 2007). While energy storage is a necessity in off-grid systems, the effective utilization of an energy storage in grid-connected systems depends on the economic viability, which may be achieved by increasing the self-consumption of solar energy instead of selling it to the grid for a lower price (Arteconi et al., 2017).

Due to high shares of renewable energy and their volatile nature, research on features for grid stabilisation via energy storage is prompted (Philipps and Warmuth, 2017). Typically, on-grid battery storage (2a) is considered to provide such services to the grid (Teleke et al., 2010). However, cooling is a thermal load that allows for thermal energy storage (3) to shift the cooling demand. There are different thermal energy storage solutions for cooling applications.

Sensible energy storage is most commonly realised in the form of chilled water (Arteconi et al., 2017). On district cooling scale or in large-scale office buildings, latent heat storage in the form of ice is also common (Chan et al., 2006; Sehar et al., 2012). Other phase change materials have been commercialised and are investigated for application in thermal energy storage systems (Souayfane et al., 2016). Using thermal energy storage implies operating the chillers according to the availability of solar irradiance. Surplus cold is stored in the thermal energy storage to be used when solar energy is not available. This is applicable for on-grid (3a) and off-grid (3b) situations.

A combination of battery storage and thermal energy storage is also possible in on-grid (4a) and off-grid (4b) environments. In urban environments, district cooling (Gang et al., 2016) and urban microgrids (Jones et al., 2013) have become popular topics. Thermal energy storage and battery storage can be realised on a district level to serve the urban microgrid (5a).

Rural microgrids (5b) that are not connected to a public grid have also gained attention. They serve basic electricity needs such as lighting for rural communities. If agriculture or fishing is a source of income for a community, a cold storage could have the potential to improve the economic situation of the community. The food conservation requires continuous cooling, which would result into an enormous battery storage. A thermal energy storage could serve to account for a major part of the required energy storage capacity.

All the cases presented in Figure 2 show the need for energy storage on the one hand, and the diversity of ways of coupling cooling systems with PV systems on the other hand.

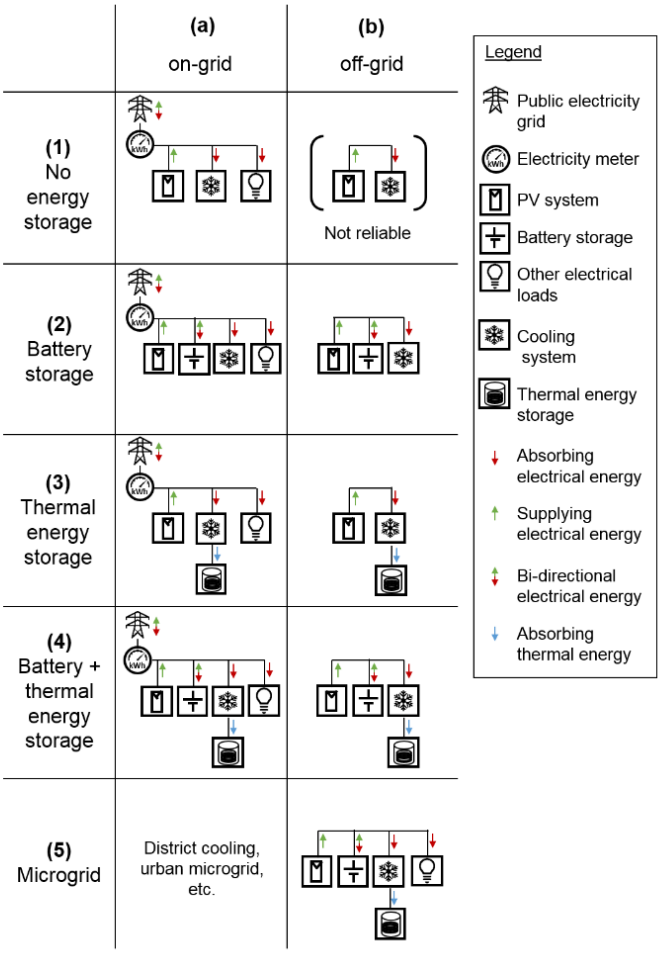

Fig. 2: On-grid and off-grid configurations of PV systems coupled with cooling systems.

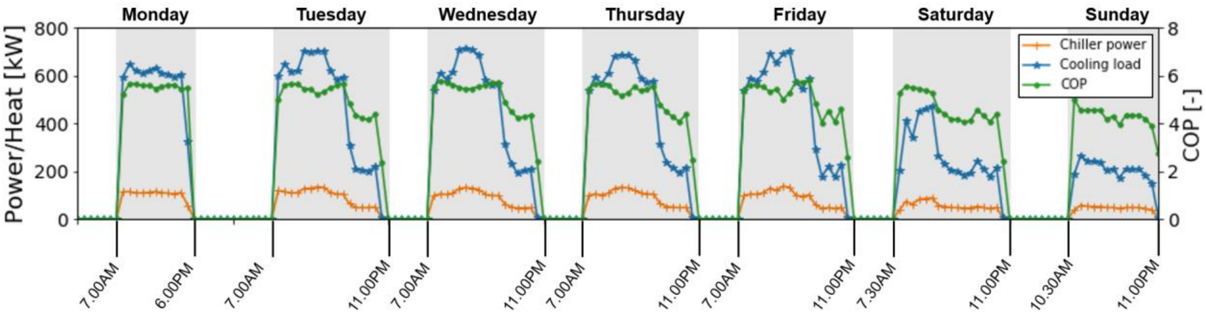

Fig. 3: One week of minutely measured cooling load, chiller plant power and COP profile of an office-cum-retail building in Singapore, which was resampled to hourly data. The weekdays and operating hour are indicated.

3. Scenario description

In this study, an on-grid scenario in the urban setting (case (1a), (2a), and (3a) of Figure 2) of Singapore is analysed with regards to the integration of energy storage. The anonymised office-cum-retail building with a restaurant as well as food and beverage outlets on the ground floor was constructed in the mid-1990s. It has eight stories above ground and a basement carpark. The gross floor area is roughly 11,000 m^2 of which around 10,000 m^2 are air-conditioned. Therefore, it belongs to the category of small office buildings under 15,000 m² according to the local Building and Construction Authority (BCA) Green Mark scheme (BCA_GM, 2018). The air-conditioning needs are supplied by a 1055 kW$_{th}$ (300 RT) water-cooled variable speed drive centrifugal chiller for 96 hours per week. The operating hours, cooling load, chiller power consumption and chiller performance are visualised in Figure 3, which shows one week of measured data for the described building. The data were obtained during an energy audit using calibrated equipment and one-minute data logging by a certified Energy Service Company (ESCO).

During office hours on weekdays, the cooling load is usually within the range of 560 kW_{th} (159 RT) and 740 kW_{th} (210 RT). The peak load occurs from 10.00am to 3.00pm on weekdays, when most of the occupants are in the offices. Some tenants operate for half day on Saturdays, which results into a cooling load of 350 kW_{th} (100 RT) to 420 kW_{th} (119 RT) in the morning. However, the cooling load drops to 265 kW_{th} (75 RT) – 280 kW_{th} (80 RT) on Saturday afternoon, Sunday and on weekdays at night time. During these times, only the restaurant is supplied by the chiller.

The overall chiller plant system COP is approximately 6.0 - 5.5 (0.59 - 0.64 kW/RT) during office hours on weekdays. Whereas at low cooling demand, when only the restaurant operates, the system operates at an inefficient condition where the COP is only 4.7 – 4.4 (0.75 – 0.8 kW/RT). Under BCA Green Mark for existing non-residential buildings (version 3.0) (BCA_GM, 2012), the building was awarded under the highest category (“platinum”) because the chiller plant efficiency is better than a COP of 5.0 (0.7 kW/RT) with less than 1758 kW_{th} (500 RT) cooling load. The COP of the chiller plant found in the audit was 5.5 (0.64 kW/RT) during office hours; however, the chiller itself operates at a COP of 7.0 (0.50 kW/RT) at office hours when power consumption of the cooling towers, chilled water pumps and condenser water pumps are not considered.

As the building is located in the tropics of Singapore, which are characterized by year-round high temperature and humidity, the exemplary week (Figure 3) can be assumed to be representative for the whole year. Hence, it was duplicated to assemble an annual cooling load and chiller power consumption profile. For this study, it is assumed that a major part of the roof is covered by 300 W_p 60-cell PV modules, which sum up to a total capacity of 247.5 kW_p. The 825 PV modules cover approximately 1400 m² of roof area. The annual cooling load profile, the chiller power consumption profile, and the annual solar irradiance from the Typical Meteorological Year (TMY) for the location of Singapore, as well as the PV system size, serve as inputs for simulation models that integrate thermal energy storage and battery storage into the described scenario.

4. Simulation models

Simulation models for the PV powered cooling system of the office-cum-retail building were developed using TRNSYS 17.1 (TRNSYS, 2018), which is a transient energy simulation tool. Figure 4 shows schematics of the different simulation models. Model (a) contains the PV array and a grid connected inverter that can not only supply the chiller plant, but also feed energy into the grid. In case of insufficient solar power availability, the remaining power consumption is supplied by the electricity grid. In model (b), a Li-Ion battery storage is added. It stores excess solar power until it is fully charged at 90% State of Charge (SoC) instead of feeding all excess power into the grid and supplies the load until it is fully discharged at 10% SoC. The grid kicks in only when the battery is fully discharged. This increases the self-consumption of PV power.

As a chilled water storage is integrated into model (c), the chiller plant, including chilled water circuit to supply the cooling load, have to be simulated. Therefore, the chiller was calibrated using the measured cooling load profile and comparing the simulated power consumption profile to the measured chiller plant power consumption profile. The external performance files of the TRNSYS component were adjusted to reflect the real performance at all part load ratios. The full load chiller plant COP was decreased from 5.2 to 4.2, because the chilled water supply temperature is only 4°C as compared to the usual 7°C to operate the chilled water tank (PG&E, 1997).

In order to operate the chiller in synergy with the availability of PV power, a control strategy was implemented. In this study, the chiller turns on as soon as the solar power is larger than 1 kW, and turns off when the solar power is smaller than 1 kW. Additionally, it turns on when the average tank temperature rises above 10°C. And even if solar power is available, the chiller turns off when the average tank temperature decreases to 4.5°C, which means that the tank is fully charged. As a high switching frequency harms the chiller, a minimum runtime and minimum rest time of one hour were implemented as well.

In order to determine the impact of the energy storage capacity on the self-consumption of PV power and the energy storage costs, the simulation models (b) and (c) are run as a parametric study with different usable energy storage capacities of 100 kWh to 5000 kWh (in 100 kWh steps). A time step of 1 minute was chosen to enable minutely control decisions. The discharged energy over the energy storage lifetime serves as input for financial method development in Section 5.

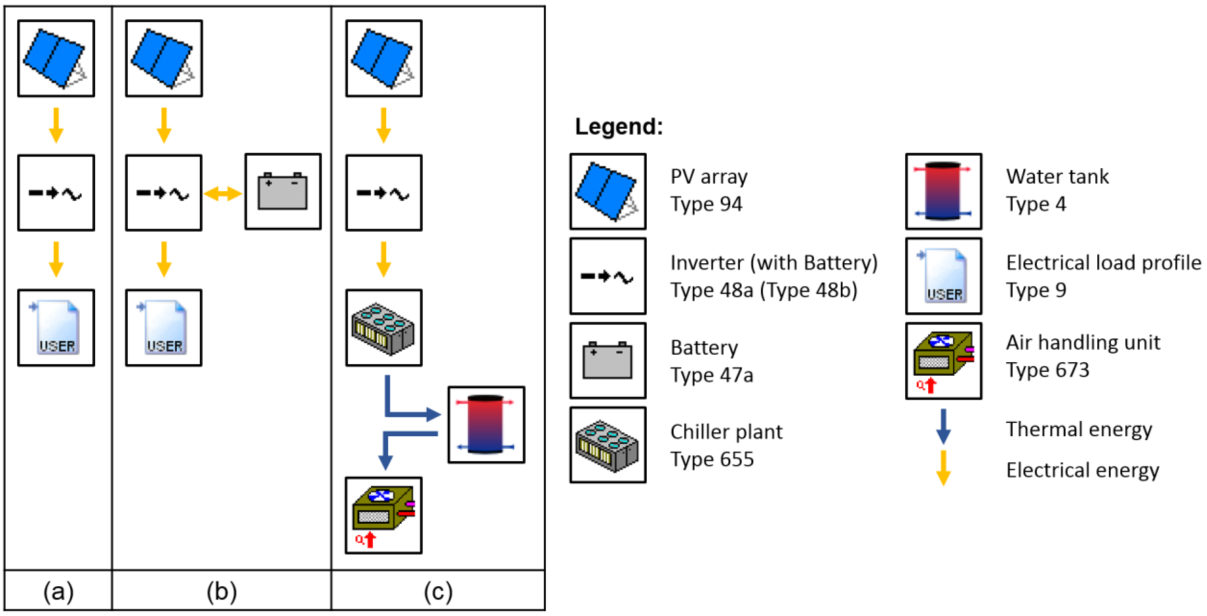

Fig. 4: Schematic of TRNSYS simulation of the PV powered cooling systems without energy storage (a), with battery storage (b), and with chilled water storage (c).

5. Levelised cost of storage

In order to compare the different energy storage solutions for a given scenario, a metric that considers the initial investment ($CAPEX$), the operational costs including the charging costs ($\sum_1^t OPEX$), and the usable energy over the system lifetime ($\sum_1^t E$) is required. Moreover, the residual value ($V_{residual}$) may be considered. Independent researchers (Belderbos et al., 2016; Pawel, 2014) and consultancy firms (Apricum, 2016; Lazard, 2017) established the metric of LCOS in slightly different ways. Essentially, all apply the following principle in different levels of detail:

$$LCOS = \frac{CAPEX + \sum_1^t OPEX + V_{residual}}{\sum_1^t E} \qquad \text{(eq. 1)}$$

Usually the LCOS method is applied to energy storages that have electrical energy as input and output. In the context of thermal energy storage and battery storage that are coupled with a PV system and a cooling application, this formulation does not allow a meaningful comparison, because usable energy is not electrical energy, but thermal energy for cooling applications. That means a conversion of the battery discharge power to thermal equivalent power using the COP is required.

In the case of the battery storage, the charging energy only comes from the PV system, because of the inverter operation strategy explained in Section 4. The configuration with thermal energy storage requires the chiller to charge the storage. In order to identify the charging costs, the thermal charging power needs to be converted to electrical power using the chiller plant COP. However, this charging power is only partly supplied by the PV system, while the rest is supplied by the electricity grid, as the control strategy explained in Section 4 cannot fully avoid the use of electricity from the grid to charge the thermal energy storage.

The specific Operation and Maintenance (O&M) costs, specific investment costs, PV LCOE, and electricity price are inputs for the LCOS formula, and are listed in Table 1. Moreover, the $V_{residual}$ is assumed to be zero for both energy storage systems and the system lifetime is 10 years, which implies that no battery replacement is required.

Tab. 1: Specific costs of NCM Li-Ion battery, water tank and electricity. A 100 kW battery inverter is assumed for all battery storage capacities.

	Specific costs	Reference
Battery CAPEX	387.5 USD/kWh and 675 USD/kW	DNV_GL (2017)
Battery O&M	8.5 USD/kW*a	DNV_GL (2017)
Water tank CAPEX	31 USD/kWh	Comodi et al. (2017)
Water tank O&M	5 % of CAPEX	Zhu et al. (2018)
Electricity price	0.173 USD/kWh	SP_Group (2018)
PV LCOE	0.075 USD/kWh	NSR (2018)

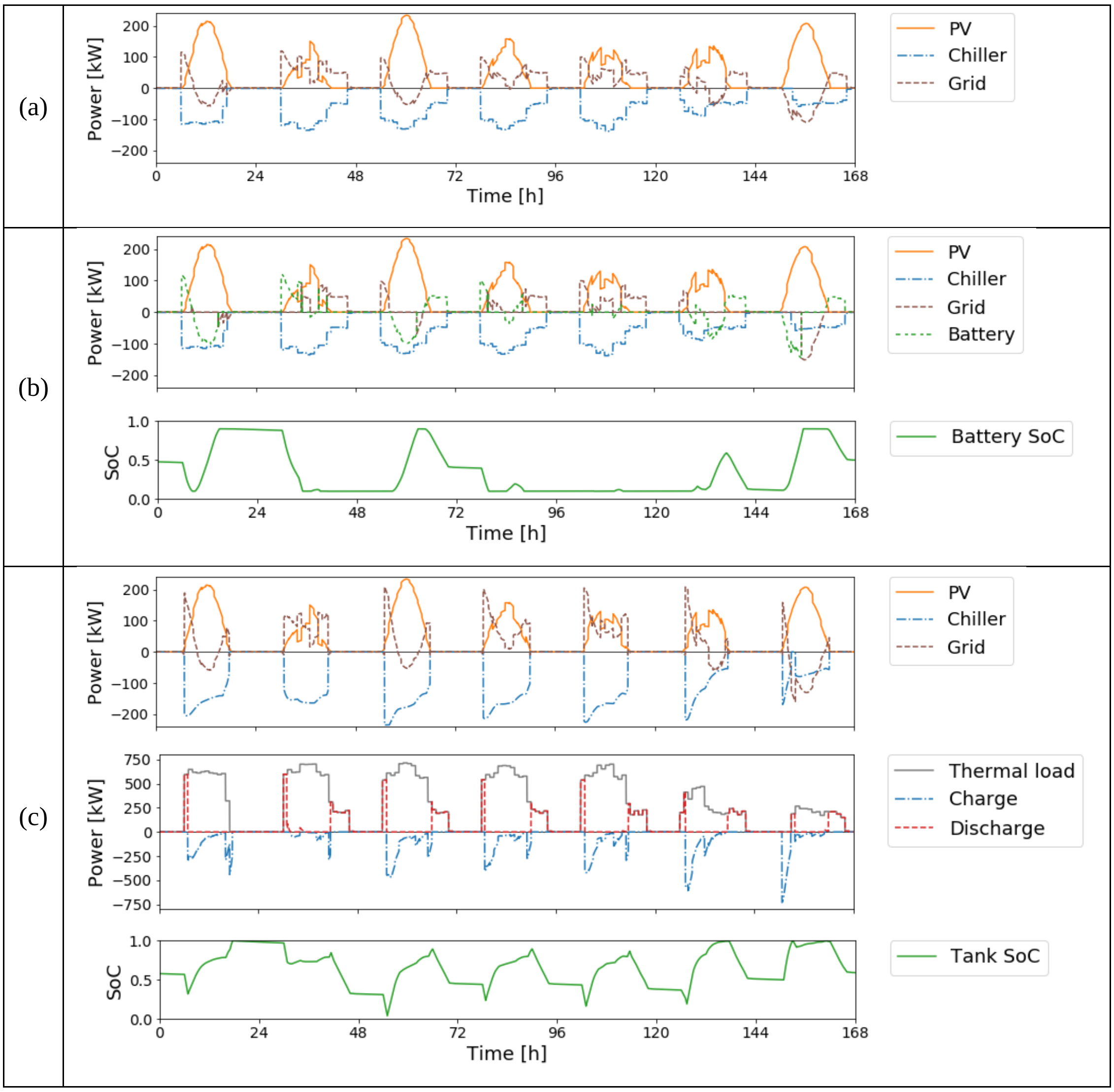

Fig. 6: Dynamic simulation output data of an exemplary week for the simulation model without storage (a), with 500 kWh battery storage (b) and 2000 kWh chilled water storage (c).

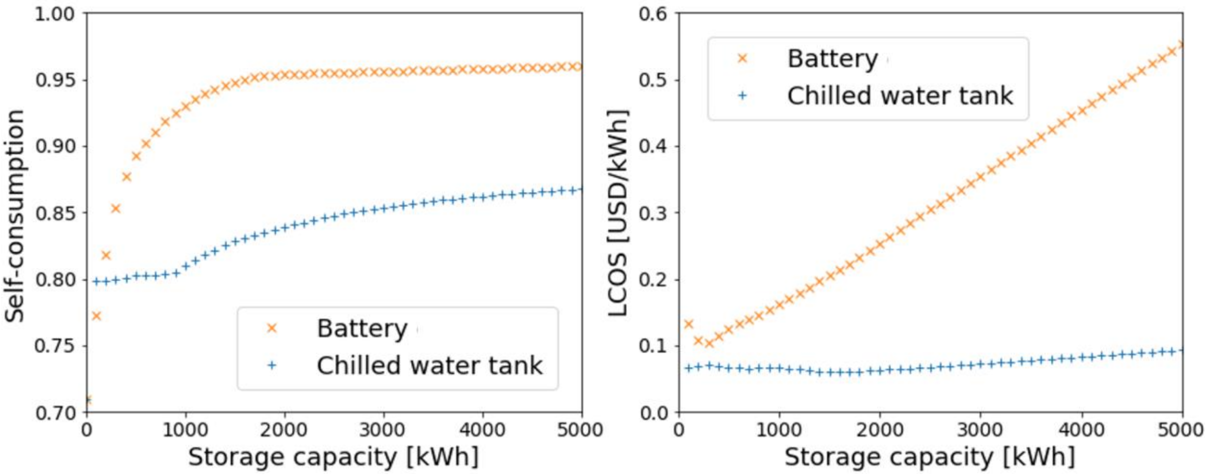

Fig. 7: Energy and economic results for chilled water storage and battery storage: Self-consumption vs. storage capacity (left), LCOS vs. storage capacity (right).

6. Results

The results of this study consist of three parts. Firstly, an exemplary week of dynamic simulation output data is shown to discuss the operation of the three different models – without energy storage, with battery storage, and with chilled water tank. Secondly, different storage capacities are compared in terms of self-consumption of PV energy. Thirdly, the LCOS of the chilled water and battery storage are analysed.

Figure 6 shows the simulated data for relevant parameters of the model without storage (a), with 500 kWh battery storage (b) and with 2000 kWh chilled water storage (c). In the system without energy storage, PV power that cannot be consumed instantly is exported to the grid. And if the PV power is insufficient to fulfill the electrical load, the rest is imported from the grid. The case with battery storage (b) reduces the export and import of power by charging and discharging the battery, respectively. The respective SoC graph shows that close to four equivalent full battery cycles are completed within the that particular week with 500 kWh battery storage. The thermal energy storage that is used in (c) decouples chiller operation from the cooling demand, which theoretically allows the chiller to run only when the solar power is available. As can be seen at the top of Figure 6 (c), the solar power is not sufficient to power the chiller entirely in the mornings and evenings. Large amounts of power still need to be imported from the grid.

The SoC of the thermal energy storage (Figure 6 (c)) is zero when the average tank temperature reaches 10 °C and is one when the tank temperature is 4.5 °C. The tank is mainly discharged before and after office hours when the chiller is not operating. The charging occurs once the chiller turns on and peaks in the morning when the temperature difference between the tank and chilled water supply is largest.

The 247.5 kW_p PV system on the building’s roof generates 383 MWh/a, while the energy consumption of the chiller plant is higher at 460 MWh/a for the cases without energy storage and with battery storage. Due to the lower COP, the annual chiller plant consumption is approximately 100 MWh higher for the case with thermal energy storage, that means approximately 560 MWh/a at a similar cooling load of 2379 MWh/a.

Figure 7 (left) shows the self-consumption of PV energy for various battery and chilled water tank capacities. Without energy storage, 71% of the PV energy are consumed directly by the chiller plant. With the use of battery storage, the amount of exported energy can be reduced to less than 0.18 MWh/a at a battery capacity of 2200 kWh. That results into a self-consumption of PV energy of 96%. However, an import of 94 MWh/a remains as the PV energy cannot fully supply the load. Beyond the usable capacity of 2200 kWh, the self-consumption ratio does not increase significantly.

When a chilled water tank is utilized, the self-consumption ratio remains 80% until a storage size of 1000 kWh. Beyond 1000 kWh storage capacity, the self-consumption increases; however, not as fast as for the battery storage, reaching only 87% at 5000 kWh. An improvement could be achieved by optimising the chiller operation and its power consumption to fit the solar power generation better.

The LCOS for battery and chilled water storage, at various storage capacities is shown in Figure 7 (right). It can be seen that the LCOS for the chilled water storage is lower than that of battery storage for all the storage sizes. It ranges only from 0.06 to 0.08 USD/kWh, most of which is from OPEX. However, the high CAPEX of battery storage causes the LCOS for battery storage to rise linearly for larger storage sizes. Hence, the lowest LCOS is 0.10 USD/kWh at 300 kWh storage capacity.

Eventually, the selection of the energy storage solution might not only depend on the LCOS, but also on the required space. The chilled water tank can only store 6.4 kWh/m³ compared to the Li-Ion battery storage, which can store 142.5 kWh/m³ (DNV_GL, 2017).

7. Conclusion and outlook

In this paper, we proposed an advanced Levelised Cost of Storage (LCOS) method for Photovoltaic (PV) powered cooling application and applied it to an office-cum-retail building in tropical climate to compare chilled water storage and battery storage. The results show that the increase in self-consumption of PV energy is higher using battery storage. This is because the chilled water storage is also partly charged from the grid as the chiller power consumption does not always fit the PV power generation. If more PV energy is used to charge the thermal energy storage, this would not only lead to a higher self-consumption, but also to an even lower LCOS. However, the volume of the chilled water tank is 22 times higher than the volume of the Li-Ion battery, which may not be applicable, especially in urban areas. Therefore, latent heat storage using ice or other phase change materials as media might be an interesting alternative. These solutions could offer a higher energy density at potentially relatively low LCOS.

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