MODULATING THE HVAC DEMAND OF A WAREHOUSE TO PROVIDE LOAD FLEXIBILITY FOR CHARGING ELECTRIC TRUCKS

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KEYWORDS

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ABSTRACT

The charging load of electric vehicles, the magnitude of which is expected to increase, creates complex balancing challenges for the power grid. Elevated thermal inertia of warehouses offers a promising flexibility potential that can be leveraged as a buffer in case of high power demands to avoid blackouts or notable increments in the user's cost of energy owing to the rise in the peak load. The present work investigates the feasibility of utilizing a conditioned warehouse's flexibility by modulating the indoor air temperature's setpoint to reduce the demand while electric trucks are being charged. Within this framework, energy simulation of a cooled fine storage warehouse has been used while considering the scenario of 2 electric trucks being charged (for a night shift delivery) immediately after the offices' are closed. The possibility of providing sufficient power to partially charge the trucks without exceeding the building's peak demand by increasing the warehouse's setpoint temperatures by 2.5 °C (for a maximum of 4 hours each day) has been investigated. It was found that the proposed approach enables the charging of the two electric trucks on 60% of the days of the cooling season (for an average duration of 170 minutes).

INTRODUCTION

The rising concerns about global warming and climate change has made taking measures to reduce the greenhouse gas (GHG) and air pollutants emissions a critical task (IPCC Climate change, 2013). The building sector has been reported as a consumer of 36% of global energy, accounting for nearly 39% of energy-related carbon emissions, which is expected to rise at a concerning rate (Gassar et al. 2020) taking into account specifically the increase in the demand of heating, ventilation and air-conditioning systems owing to the notable rise in population, the living and economic standards, and industrial and urban development (Mohammadi and McGowan 2019). Given the growing efforts that are being made to mitigate climate change (Jakučionytė-Skodienė et al. 2021), performing interventions on the operation management of building systems has received increasing attention. Warehouses that are facilities where goods are received, stored, and dispatched are one of the common commercial buildings that are also a crucial part of the supply chain network (Sarkis 2003). Around 11% of the total global greenhouse gas emissions generated in the logistics sector are caused by the warehousing activities (Doherty and Hoyle 2009). HVAC systems, lighting, and material handling equipment are influential energy consumers and contributors to warehouses' high carbon dioxide emissions (Ries et al. 2017). The abundance of spaces in warehouses and high ceilings would often lead to higher opportunities for air leaks and open points, which in turn increases the energy required for temperature control.

Freight transport encompassing both light and heavy-duty vehicles accounts for up to half of local emissions and CO2 emissions. By significantly reducing the emissions in the utilization phase, EVs have reduced life-cycle carbon emissions by 47% compared to gasoline vehicles (Guo et al. 2023). Battery-electric trucks are reducing CO2 emissions by up to 28%, NOx emissions by up to 19%, and particulate matter emissions by up to 7%, and are viable alternatives to solve urban areas' emission and pollution problems (Breuer et al. 2021). Therefore, Electric Vehicles are considered the future of

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transportation as they are a feasible solution for reducing carbon emissions in the transportation sector (Sheng et al. 2021), and growing penetration of EVs is expected in transporting merchants from warehouses which comes with some drawbacks regarding the stability of the electrical grids. For instance, Volvo FE Electric with a 200-265 kWh battery would charge at 22kW when charging with AC (Liimatainen et al. 2019). With a higher number of EVs, problems of thermal or voltage will arise, and grid stability will be jeopardized (Qiao and Yang 2016).

Buildings can support the stability of the electrical power grid due to their considerable energy demand, which can be leveraged to provide flexibility to the grid, allowing it to maintain a stable balance between energy supply and demand (Aduda et al. 2016). More specifically, due to their inherent high thermal inertia, warehouses have outstanding flexibility, rendering them highly suitable for demand-side flexibility (Akerma et al. 2018). Demand-side flexibility would allow a cost-effective and sustainable power system, therefore avoiding the need to expand generation capacity (Pinson and Madsen 2014).

Warehouses would need to charge electric trucks at certain fixed times owing to the delivery schedules, leading to a significant surge in power demand that may exceed the facility's typical power load. However, conditioned warehouses' thermal mass has a considerable capacity to absorb and retain heat, allowing for changes in cooling load and the corresponding energy consumption at certain times. Therefore, the flexibility offered by the warehouses through modifying energy usage can be harnessed to provide flexibility during the charging of the electric trucks. This approach would allow warehouses to use their existing infrastructure to charge trucks while avoiding peaks in demand and helping stabilize the power grid.

In addition to the grid stability improvement, peak demand shedding utilizing the offered flexibility can benefit buildings economically. Demand response programs engage customers to change their energy use behavior, whether voluntary (price-based or incentive-based) or involuntary (periods when demand is near maximum power generation to avoid grid failure). A voluntary demand response program aims to temporarily mitigate power demand, particularly during peak demand hours or emergencies (Li et al. 2021), by offering incentives that buildings can exploit, avoiding the consumption peaks of charging electric trucks. Alternatively, in power-specific billing scenarios, where the highest power peak during the billing period decides the base for the price per kW (Martins et al. 2018), the peak power demand occurring during the simultaneous charging of electric trucks would tremendously undermine the buildings economy.

Consequently, the high flexibility offered by the buildings can be utilized for peak shedding either in a demand response program or when the load in the building is excessively high such as charging EVs.

Ioakimidis et al. (2018) elaborated on the so-called vehicle-to-building concept for peak shaving and valley filling of the power consumption profile in non-residential buildings for an electric vehicle parking lot. EVs' charging or discharging (delivering electricity) rate was controlled based on building’s power consumption. It was concluded that this approach can flatten the power consumption profile during daytime. Similarly, Bhundar et al. (2023) investigated the possibility of providing flexibility in building load using electric charging as storage. In an attempt to reduce the peak load in residential distribution networks, Mahmud et al. (2018) proposed a decision tree-based control of electric vehicles, photovoltaic (PV) units, and battery energy storage systems (BESSs). It was shown that peak load occurs most often in the evening when electric vehicles are absent or fail to provide charge (arriving from long trips with drained batteries). Therefore, it was concluded that integrating fixed batteries with EVs is required to achieve more promising results. Similarly, due to delivery schedule constraints in warehouses, the charging time window for the trucks is limited and constrained, meaning the trucks might need to be charged upon their arrival and simultaneously with other trucks. Commonly, warehouses are not provided with PV panels and BESSs on a scale large enough to charge electric trucks. Accordingly, a solution is required to incorporate trucks' charging with the warehouses' existing infrastructure. Therefore, warehouses should provide flexibility in their consumption to avoid grid balancing issues. To the best of the author’s knowledge, no previous work has investigated the possibility of incorporating the charging of electric trucks by shedding the peak load in conditioned warehouses using the HVAC load flexibility. Motivated by this research gap, the present work investigates the possibility of using the flexibility offered by the thermal inertia of conditioned warehouse by modulating the indoor air temperature to mitigate the cooling demand during the charging of electric trucks using the existing infrastructure to provide charging services to trucks. An extreme scenario is considered where electric trucks need charging before their night delivery. Hence, charging load from the trucks would be added to the HVAC load and cause various problems, from overloading of the grid (in case there are multiple warehouses in the vicinity) or peaks in consumption leading to the increased price of electricity.

METHODOLOGY

This section outlines the methodology employed to simulate the charging of electric trucks in the considered conditioned warehouse, both with and without utilizing the HVAC system's flexibility, for all days of the cooling season. Thus, the specifications and geometric configuration of the considered warehouse are first presented, and the corresponding physics-based energy simulation details are then described. The regular operation schedule and the flexibility scenario, which involves shedding the demand peaks while incorporating electric truck charging, are then explained. Finally, a brief description of the electric trucks considered in the present work and their features is provided.

Case Study and Details of the Simulations

In the present work, a physics-based energy simulation based on EnergyPlus V9.4 (Crawley et al. 2001) and its Python API (U.S. Department of Energy 2021) has been deployed to initially simulate the regular operation of the conditioned warehouse for all weekdays in the period of June to September (see Figure 1) with the established indoor temperature setpoints. This initial simulation creates a comparative baseline demand profile in the investigated period. Subsequently, a simulation is conducted, in which the setpoint in the conditioned storage zones is relaxed for 2.5°C allowing a limited rise in temperature and evading the use of cooling systems to reduce electrical consumption and provide energy flexibility. The thermal inertia of the warehouse is thus used as a buffer for peak shedding to counterbalance the truck charging's load.

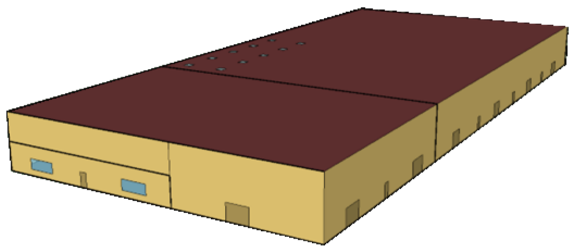

Figure 1: Sample of the Warehouse Building Used on Physical-Based Simulations.

The standard operating interval of the offices within the building ends at 5 p.m., resulting in decreased personnel within the corresponding specified zone. As the HVAC system in the offices no longer operates after this hour and the staff-related energy consumption is also reduced, the baselined load of the entire building notably declines. Concurrently, the HVAC load dispatching process of the conditioned warehouse is performed to further reduce the load. Accordingly, the increase in the cooling setpoints in the storage zones results in an immediate drop in electrical demand of the entire facility for a rather long interval (several minutes that is extended to a few hours on certain days). As a result of this shedding in demand, trucks can be plugged in for charging ahead of their nighttime deliveries, while the building's electrical demand remains within the established baseline during the standard operating hours of the warehouse.

The utilized model corresponds to a modified version of the warehouse proposed and developed by Deru et al. 2011 under the ASHRAE 90.1 standard (ASHRAE 2010). It consists of three zones, one office building of 238 [m2] and two storage zones, with surface areas of 1393 [m2] and 3205 [m2], respectively. More details about the system and regular imposed setpoints in the zones are presented in Table 1.

Table 1: Description of the Warehouse Used and the Simulation Parameters.

Location	Bologna, Italy
Simulation Period	June- September
Frequency	10 [min]
Status	New Building
Total Floor Area	4836 [m^2]
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
Thermostat - Offices	23.9°C Cooling/21.9°C Heating
Thermostat – Storage zones	25°C Cooling/18°C Heating

Electric Trucks' Charging Scenario

EVs are being increasingly employed in various applications, from public transport to last-mile logistics and distribution in multiple industries. Despite their negligible near-zero emission, electric vehicles come with several limitations, particularly those corresponding to charging time, driving range, and the number of charging stations (Touati-Moungla and Jost 2012). The recharging of EVs is known to be more time-consuming compared to the rapid refueling of liquid fuels. However, EV charging can occur at any battery level, with recharge time being clearly dependent on the amount of the required charge. In the present paper, a partial recharging scenario, which is more practical within the considered context, is considered. For instance, the need for a full charge is obviated when EV visits a charging station near the hub or undergoes two consecutive partial recharges (Keskin and Çatay 2016). In the scenario considered in the present work, trucks arrive in the afternoon at the warehouse and are charged while unloading/loading and getting ready for the next delivery for the night. Thus, partial charging is required as they can be charged again later at night. Considering the load profile of the modeled warehouse, two Volvo electric trucks with a battery capacity of 200 kWh (Liimatainen et al. 2019), with the specifications provided in Table 2, are accordingly assumed. This case study also considers using the standard 22 kW (AC) chargers, providing 22 km of autonomy per hour of charging (given the 1 kWh/km consumption). It is worth noting that this scenario is a specific case study that has been chosen based on the demand profile of the modeled warehouse, along with the size of the utilized cooling system and the corresponding available flexibility.

Table 2: Description of the Electric Trucks Utilized in the Simulation

Company	Volvo
Number of Trucks	2
Commercial Name	FL Electric
Maximum Weight	16t
Battery Capacity	200 kW h
Energy consumption (kWh/km)	1.00

RESULTS AND DISCUSSION

As was previously pointed out, the simulations with both regular operation (to create the baseline) and while undergoing flexibility scenario are performed for all weekdays during the cooling period. In order to show the resulting consumption and temperature profiles, in a detailed manner the corresponding simulation results for a typical warm day and an excessively warm day are represented. Next, to demonstrate the achieved flexibility to enable the electric trucks being charged without increasing the load of the building (with respect to the average load between 16:00 and 17:00), the resulting permitted hours of charging for all of the days in the investigated interval, is determined and represent.

Typical Warm Day

Figure 2 represents the load and consumption profile of the building on a typical warm summer day. A notable drop in the load at 17:00 is evident due to the previously explained termination of the offices' HVAC system operation (as the offices are closed at this hour). The observed fluctuations in the baseload after 17:00 are thus solely due to the cooling demand of the (conditioned) storage zones. As demonstrated in the baseload with EV charging profile, charging the trucks without applying a flexibility measure results in significant peaks beyond the regular load of the building (with respect to the corresponding average load between 16:00 – 17:00). Instead, after performing the flexibility measure, in which the setpoint of the storage zones are increased resulting in a decrement in the corresponding HVAC consumption, the mentioned observed peaks are avoided. It is also worth mentioning that, due to the reduction in the outside temperature, the storage zones' HVAC system operation already terminates at 19:00 (that can be observed in the baseload with regular operation), and the trucks could thus have been charged without resulting in a notable increment in the load after 19:00 in both scenarios. Therefore, the flexibility provided by applying the flexibility measure that is demonstrated by the area (in blue) between the base load and flexible load with EV charging is shown to permit around two additional hours of stable charging (between 17:00 and 19:00), which allows the trucks to be sufficiently charged before departing for nighttime delivery. It is also noteworthy that, for this typical warm day, due to the reduction in outside temperature, the maximum allowed temperature of 27.5 °C is not reached, and the observed maximum temperature is around 26.5 °C (1.5 °C degrees above the regular setpoint).

It is worth mentioning that once flexibility measures are implemented, there is commonly an uptick in energy demand immediately after completion, which is considered a penalty (Junker et al. 2018). However, such penalized consumptions are avoided thanks to the decline in outside temperature, which drops the storage zones' temperature later in the evening when flexibility measures finish. Therefore, this specific timing choice for flexibility presented in this work would provide both the advantage of the reduced load from the offices and the downward temperature trend in the evening, evading the penalized consumption after the conclusion of flexibility measures.

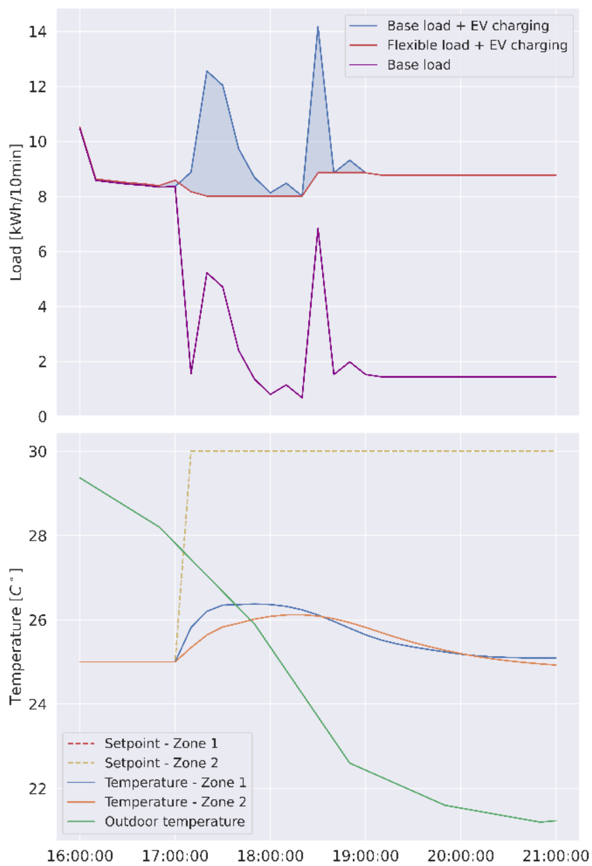

Figure 2: Demand and Temperature Profile for a Typical Warm Day (Daily average of 23°C).

Excessively Warm Day

Figure 3 illustrates the simulation results on an excessively warm day in the summer season, in which the maximum outside temperature (around 32°C) is significantly higher than that of the previous case and decreases at a lower rate (compared to the previous case) in the evening. Furthermore, the solar irradiation is higher than that of the previously discussed typical warm day. A similar approach is deployed in this scenario, where the setpoint of the rooms is relaxed to 30°C at 17:00 while setting a threshold of 2.5°C for indoor temperature increase. The controller is imposed to dynamically and gradually adjust the setpoint of the zones back to 25°C whenever the temperature overreaches this threshold. It can be observed that the temperature of Zone 1 reaches the allowed threshold after almost one hour, while the second zone reaches it after around 90 minutes. The resulting consumption profile thus demonstrates that the flexibility is offered for around 90 minutes between 17:00 and 18:30 (even if the temperature threshold is reached by zone 1 earlier), in which EV charging does not result in an increment in the load (with respect to the average base load between 16:00 and 17:00). Therefore, performing the flexibility measure permitted charging the trucks (without a resulting in an increase in the load) even if for a short period (permitting short-range deliveries only).

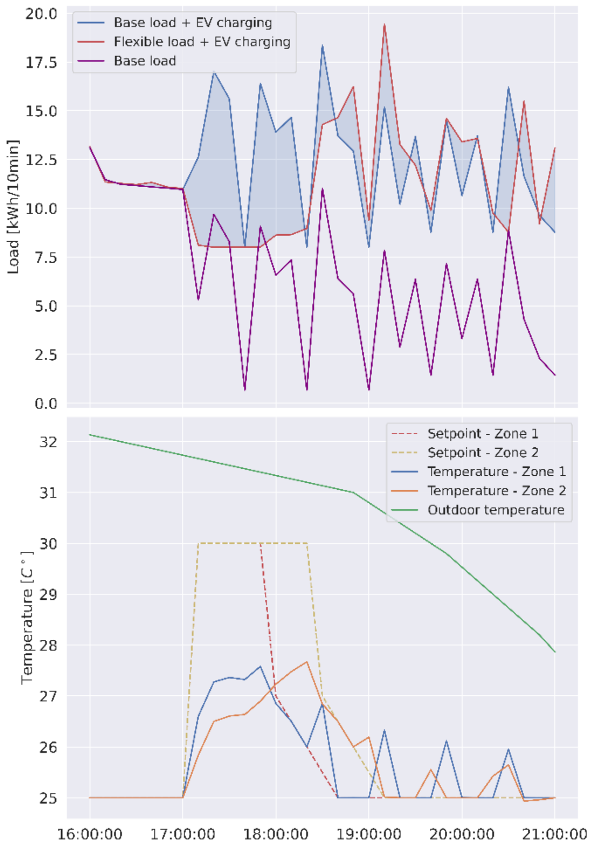

Figure 3: Demand and Temperature Profile for an Excessively Warm Day (Daily average of 28°C).

Determination of Provided Flexibility

Figure 4 displays the sum of the provided flexibility in terms of kWh (represented by the area between blue and red profiles in Figures 2 and 3) for one to four hours after the start of the flexibility measures for different days of the investigated period. The results clearly demonstrate the potential of performing the proposed flexibility measure for permitting (or extending the duration of) electric trucks' charging without incrementing the facility's load. It also includes the trend of the outdoor temperature to illustrate its corresponding impact on the provided flexibility. It can be noted that the days with lower outdoor temperatures are characterized by a low amount of provided flexibility which can be attributed to the fact that (owing to the resulting low temperatures in the storage zones) the corresponding cooling system's load is already low (or HVAC system is not operating), thus performing the flexibility measure would not reduce the load any further. Conversely, during warm/hot days, a substantial increase in the achieved flexibility is observed due to the notable increase in the cooling system consumption, resulting in a more pronounced reduction of demand being achieved by modulating the setpoints. However, as was previously noted, excessively elevated outdoor temperatures result in a rapid rise in the zones' temperature, surpassing the specified threshold and triggering the activation of the cooling systems, consequently leading to a surge in demand.

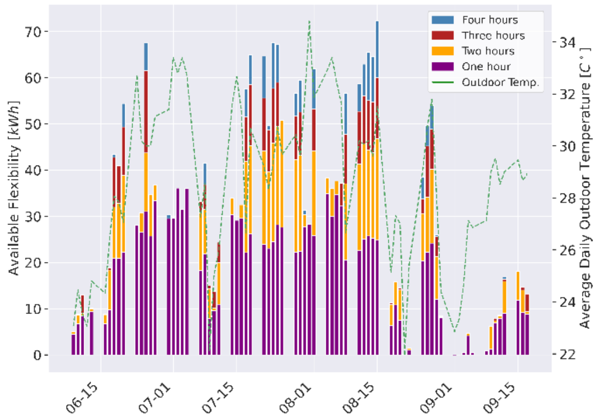

Figure 4: Available Flexibility [kWh] in the Summer Months Considering 1,2, 3, and 4 Hours After the Setpoints Modification.

Generally, it can be concluded that on 60 % of the days during the summer season, charging electric trucks is feasible without causing surges in consumption. The flexibility offered by the cooling system, reduction in consumption due to the closure of the office zones, and finally, the decreasing trend of temperature in the evening hours would allow an average of 170 minutes of charging for two electric trucks, which ultimately allows charging each of them for 62.4 kWh (which provides 62.4 kilometers of additional driving range). It is worth noting that the scenario of two electric trucks being charged was chosen considering the consumption profile of the modeled conditioned warehouse, and the resulting impact of applying the proposed flexibility measure in other scenarios is a subject of further investigation.

CONCLUSION

The present work investigated the potential of modulating the setpoint of the cooling system of a conditioned warehouse to balance the charging load of two electric trucks. The scenario of charging being started at 17:00 (after the offices are closed) to achieve a partial charging for nighttime delivery, was specifically studied. It was shown that in 60% of the days in the investigated interval (cooling season) charging the trucks is feasible without increasing the load beyond the corresponding average value in the last hour in which the offices are open. It was also shown that the decrement in consumption due to the closure of offices, the reduction in outside temperature, and the implemented flexibility measure (using the warehouse's cooling system), allows a daily average of 170 minutes of charging for the two trucks, providing an average range of 62.4 km for nighttime delivery per each truck (for the specific model considered in this study). Therefore, the approach proposed in the presented work allows the facility managers of conditioned warehouses to use their existing infrastructure to provide charging services to trucks while avoiding an excessive increase in the building's load. It is worth noting that the considered electric trucks' loading scenario (their number and schedule) has been chosen based on the modeled warehouse's consumption profile and the impact of implementing the proposed flexibility strategy in other scenarios should be analyzed in future studies.

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