Energy Flexibility Study of a Hotel Using TRNSYS

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Abstract

In this work, a TRNSYS model of a five-story hotel located in Northern Italy is used to evaluate simple energy flexibility strategies for the cooling season to be used in a possible smart grid integration. The strategies are demand-side and include energy efficiency and load shifting. Two models are used, one of the building envelopes, to evaluate the instantaneous heating and cooling demands, and the HVAC system model, used to simulate the heating and cooling production by two multifunctional heat pumps and two heat pump boosters for the domestic hot water production. The flexibility strategies are applied in the building model controlling the room thermostats while the heating and cooling demands are calculated using measured occupation profiles. On the other hand, the hot and cold-water tanks set point temperatures are used to implement the energy flexibility of the HVAC system. In both cases, the target is to shift the loads in the PV panels production hours, reducing the electricity demands from the grid during the other hours.

1. Introduction

With the target of reducing greenhouse gas emissions, energy production is expected to shift from a centralised power grid, based on fossil-fuel generation, to a diversified renewable energy production. This change will also affect the energy availability and cost, which will depend on weather conditions and daylight intermittence. To optimise these conditions, building operations should be able to be managed (demand side management) to concentrate the energy demand during daylight hours, shifting the loads at the PV production hours. This capability, together with the possibility of reducing or shifting the load peaks when needed, is known as energy flexibility. In alignment with the United Nations' Sustainable Development Goals 7 (affordable and clean energy) and 11 (sustainable cities and communities), this paper focuses on the energy flexibility of a hotel in Northern Italy.

Hotels are high energy consumption buildings, not only due to the Heating Ventilation and Air Conditioning (HVAC) operation, but also to other services provided to the guests. The average energy consumption for the Italian hotel sector in 2016 has been estimated by Bianco et al. (2017) to be 203 kWh/m^2. For this reason, it is relevant to study efficiency strategies for the existing hotels to optimize energy consumption. Moreover, when the building is integrated with renewable energy supply such as photovoltaic (PV) panels and thermal solar panels, it is important to match the energy produced in situ with the energy demand through load shifting methods, thanks to electrical or thermal energy storage and the implementation of advanced control. With these methods, it is possible to improve the energy demand flexibility to increase PV self-consumption and the integration of buildings in smart grids.

Examples of regulation strategies to exploit the energy flexibility of a single building to increase the PV self-consumption are presented in Pinamonti et al. (2020), where the utilization of modulating heat pumps and thermal energy storages allows reduce the grid energy demand up to the 22%, depending on the climate and the building characteristics.

The considered hotel is monitored by a supervision system, a common management practice. The system is designed to report the monitoring of the main hotel services, such as HVAC, lighting and charging stations for electric vehicles, together with the

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hourly production of electricity and heat from PV and solar panels on a dashboard. The monitoring systems can also overwrite settings in each room to reduce energy waste by keeping energy saving conditions in empty rooms. The temperature and energy consumption measurements are recorded hourly and stored by the hotel management system. In this research, following Libralato et al. (2023), the utilization of these measurements as calibration and validation variables is explored with the aim of developing an energy model of the hotel, increasing the energy efficiency of the building-HVAC system, also using the heat storage properties of the building envelope to shift and shave the peaks of power demands. Control rules that allow a better match between electrical energy demand and availability, developed, and tested using the building energy model, are used with the final goal to prepare the inclusion of the hotel in a Smart Grid or a Renewable Energy Community, to perform energy sharing strategies as presented, for example, in Franzoi et al. (2021).

2. Methods

The energy flexibility of the hotel is studied comparing the building cooling and heating demand and the plant electricity demand. These are calculated using simulations of the building and the plant with different control strategies using the TRNSYS 18 simulation environment (Klein et al., 2018). The building model is calibrated manually, while the DHW loads are measured by the monitoring system.
The control strategies are implemented at the building level, changing the thermostat settings in the rooms, and at the plant level, changing the thermostat settings of the water tanks. The aim of the study is to maximise the PV consumption shifting the loads of the building/HVAC system using the heat pumps and storing thermal energy in the building envelope and in the water storage tanks.

2.1 Case Study

The building is a 1600 m^2, a five-story hotel in a tourist town on the seaside in Northern Italy. The hotel is a new construction with a high efficiency envelope that should allow the implementation of flexibility strategies (Foteinaki et al., 2018); the thermal transmittance of the wall and windows are 0.20 and 0.13 W/(m^{2}K).
The hotel is heated and cooled with two multifunctional air-to-water two-stage reversible heat pumps (MHP) connected with two tanks (hot water tank and cold-water tank both of 0.9 m^3) that serve 4-pipe fan-coils in every room and common zone and an air handling unit. The fan coils and the ventilation system are turned off in the rooms, when the windows are opened. Domestic hot water (DHW) is heated by two water-to-water two-stage heat pumps (boosters), used as boosters from the hot water tank to heat the water in other two 0.9 m^3 hot water tanks (DHW tanks). The DHW tanks are also supplied with hot water produced with a total of 14 m^2 thermal solar panels. The building is also served by 36 photovoltaic (PV) panels for a total of 16 kWp; for this work the presence of batteries was not considered since they are not currently installed.
The MHPs have a cooling capacity of 80 kW (EER = 2.91, system side water heat exchanger 12 °C / 7 °C with external air at 35 °C) and a heating capacity of 84 kW (COP = 3.28, system side water heat exchanger 40 °C / 45 °C with external air at 7 °C) in standard conditions. When cooling and DHW are required simultaneously, then the cooling capacity is 87 kW and the heating capacity is 111 kW, with a power consumption of 25.9 kW (the water exchanger to the total recovery side is 45 °C while the water to the system side heat exchanger at 7 °C). The Boosters provide 56.7 kW of heating capacity with a COP = 3.48 (70 °C / 78 °C water user side, 35 °C / 30 °C water source side).

2.2 TRNSYS Models

The building-plant system is modelled with two separate decks in the TRNSYS 18 simulation environment. The first deck simulates the building envelope, while the second, uses the heating and cooling demands of the first model to simulate the behaviour of the HVAC system. Both simulations are performed from the 1st of May 2023 to the 31st of August 2023, with a preconditioning period of 1 month (from the 1st of April).

2.2.1 Building envelope

The building envelope is modelled using Type 56 as a multizone building (Fig. 1), with 34 double zone hotel rooms and common zones, for a total of 94 thermal zones.

The used weather file is obtained from the measurements of a nearby weather station (kindly supplied by ARPA FVG (OSMER)), and it is included in the simulation using Type 15, used also to perform the radiation calculations for the Type 56 model. The effective sky temperature is calculated using Type 69b.

The room occupancy recorded by the hotel supervision system is used to define the internal loads and the thermostat settings. The thermostats of the rented rooms (occupied and not occupied) are set to 22 °C by default while the temperature of the DHW is set to 47 °C, which is sufficient to meet the occupants' satisfaction during summer. The DHW tank does not require thermal shock cycles thanks to the chemical-based disinfection for Legionella. The internal loads are estimated considering 115 W (sensible load) per person and the illumination devices loads (from 45 W to 280 W, depending on the room size) activated only when the occupancy is detected, and a constant load to consider other electric devices (7 W).

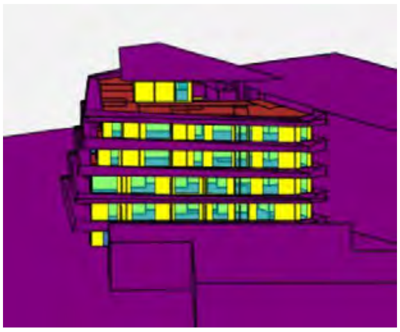

Fig. 1 – Hotel building geometry used in TRNSYS 18 Type 56

The temperature recordings of the month of November 2023 of the hotel supervision system are used to manually calibrate the building energy model. In this period the temperature of the hallways of every floor were recorded and the HVAC system was not active. The free-floating behaviour is measured for few zones, allowing to perform a partial manual calibration of the building envelope model. This preliminary and partial calibration allowed us to estimate the air infiltrations of the hallways and the thermal capacity of the rooms. The thermal capacitance of every room has been increased of 8 kJ/(K·m^2) to model the presence of furniture. The simulated temperatures resulted in an average RMSE of 1 K, which has been considered acceptable, given the low accuracy of the sensors (1 K, with a resolution of 0.5 K) and the preliminary state of the study. The building simulation is performed with a 15 minutes timestep. The building energy model is then used to test control strategies to reduce energy consumption (energy saving strategies) end to match the HVAC system power demands with the PV panels production (flexibility strategies).

2.2.2 HVAC and DHW system

The HVAC and DHW systems scheme are shown in Figure 2. The Fan coils and AHU are modelled as ideal systems, providing sensible heating and cooling loads to the thermal zones without losses. The heating and cooling production of the MHPs are modelled with performance mappings (Type 581c) provided by the producers, depending on the inlet water temperature and on the external air dry-bulb temperature.

The MHPs can provide both heating and cooling using the "recovery mode"; in this mode the performance does not depend on external air, but on the inlet water temperatures of the heating and cooling circuits. The heat pumps are controlled with PID controllers (Type 23) controlling the water tank thermostats, the water tanks are modelled with Type 158, the PV panels with Type 103b. The MHPs and the boosters are programmed to keep their working condition for at least 5 minutes to avoid rapid oscillations between ON and OFF states. To approximate this behaviour, the simulation is performed with a 5-minute time step. For this work, the DHW demand and the Solar thermal panel production have been considered calculating the thermal load on the boosters from the electricity consumption monitoring, using the Boosters model to calculate the heating demand on the DHW tanks.

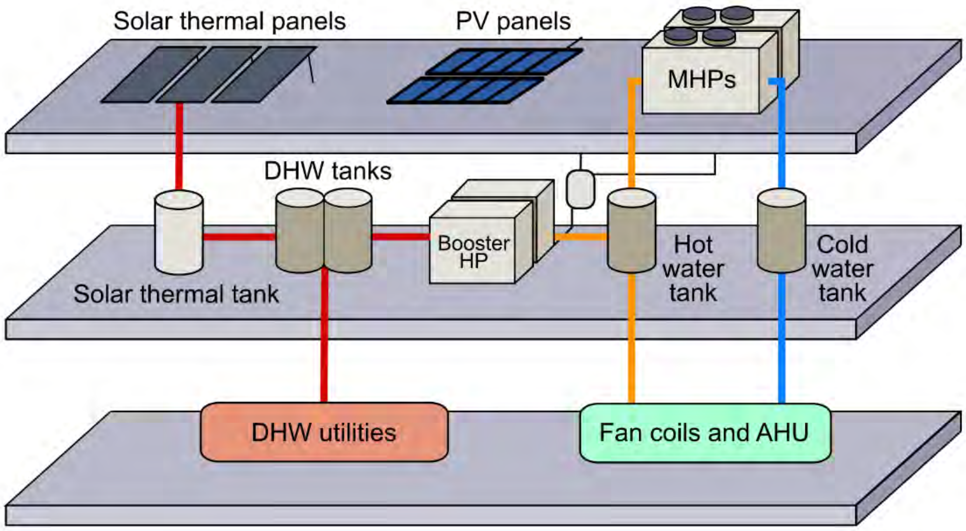

Fig. 2 – HVAC and DHW system scheme

2.3 Energy Flexibility Analysis

This paper presents a preliminary analysis of the utilization of the building and plant energy flexibility performed comparing three building thermostat scenarios and three plant control strategies in summertime. Concerning the building, the flexibility is implemented changing the thermostat settings.

The "Standard" thermostat setting is 24 °C for the rooms that are not booked, while, when a room is booked, the temperature is set to 22 °C.

The "Flexible" thermostat setting proposed in this paper is 24 °C for the unoccupied room, 22 °C when the room is occupied, 20 °C when the room is unoccupied, and the PV panels' energy production is larger than 2.8 kW (25% of the maximum simulated PV power). This setting is intended to reduce the power demand in the evening taking advantage of the room heat capacity. In both conditions, the comfort of the occupants is not significantly affected.

With these two settings, an energy saving one is also considered, the "Energy Saving" combination, with 26 °C in free rooms and 24 °C for occupied rooms.

The settings of the plant used to implement the energy flexibility are the hot, cold and DHW water tanks' thermostats. The standard setting for the tank temperatures is 42 °C for the hot water tank, 12 °C for the cold-water tank and 47 °C for the DHW tank. This setting is used in the cases "Flexibility", "Standard" and "Energy Saving". To increase the utilization of the PV produced electricity, an alternative tank setting is tested using the building demands calculated with the "Flexibility" configuration. The setting is the "Temperatures" tank setting, obtained increasing the temperature set point proportionally with the PV production of 2 K for the hot water tank, decreasing by 2 K the cold-water tank, and increasing by 4 K the DHW tank. Another case is also considered, the "Tank Size" case, based on the "Temperatures" case, with larger tanks, increased by a factor of 1.5.

3. Results

The effects of the load shifting are presented in Figure 3. It is possible to see that reducing the temperature settings of the thermostats during the PV production, the loads are slightly reduced for the first hours of the evening at the expense of a significant energy consumption. The obtained value is also slightly lower than the energy saving setting, with all the thermostats reduced of 2 K.

As reported in the literature (Hedegaard et al., 2019), it is expected that a load shifting strategy could cause the generation of new peaks, also larger than the former.

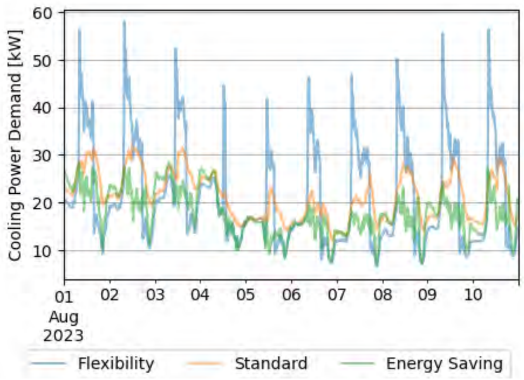

Fig. 3 – Cooling demand calculated with the building simulation with the three studied thermostat strategies (15 minutes timestep). The Flexibility setting allows to reduce the demand in the evenings

The overall effects of the thermostat strategies are presented in Fig. 4. The monthly cooling demands are reduced respect to the "Standard" strategy, except for the month of May. The cooling demand reduction from the "Standard" strategy of all the four months is reduced by t 3% with the "Flexibility" strategy and by 15% with the "Energy Saving" strategy.

Figure 5 presents the monthly electricity demands for the HVAC and DHW systems of the room thermostat strategies. The "Energy Saving" always has lower electricity demands to the grid but presents the lower utilization of the PV panels production ("PV not used" negative values).

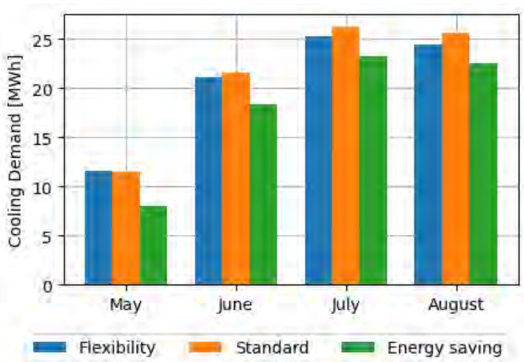

Fig. 4 – Monthly cooling demand calculated with the building simulation with the three studied room thermostat strategies. The "Standard" and "Flexibility" strategies have similar performances

The "Flexibility" configuration is an implementation of flexibility using only the building thermal mass as energy storage and the fixed thermostats for the tanks. In the following, the flexibility will be quantified with the percentage of PV usage, also reported in Table 1.

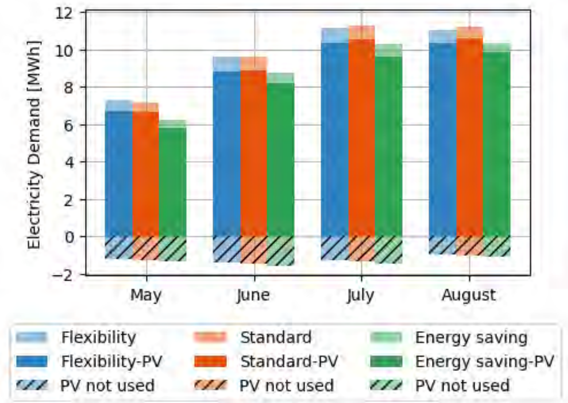

Fig. 5 – Monthly electricity demands of the hotel's HVAC and DHW systems, with the three-room thermostat strategies. The "-PV" columns represent the net energy demand (considering the PV production instantly used), while the "PV not used" columns represent the energy produced by the PV not instantly used by the system

The "Flexibility" case registered 36.1% of PV usage (calculated as the ratio between the PV energy used by the HVAC system and the total PV energy produced), just 3.9% more than the "Standard" case. The net energy demand, calculated adding the energy demands of the MHPs and the boosters and subtracting the PV energy production, is comparable in both the "Flexibility" and the "Standard" cases, while the "Energy Saving" allowed to save about 3 MWh.

In Figure 6, the HVAC system control strategies are compared. Changing the temperature settings of the water tanks allows for the storage of more energy, but requires a higher electricity consumption, due to the lower efficiency of the heat pumps with higher temperature differences. As expected, the "Temperature" case obtained higher electricity consumptions, but had a higher PV energy consumption (42.2%) 10% more than the "Standard" mode. The PV covers 7.7% of the energy demand, but the total net energy is increased by 2.4 MWh.

The last study case "Tank size" involves the addition of 50% of the tank volumes and it is not actually feasible in the real hotel, due to the lack of space in the technical rooms. Nevertheless, it has been included to quantify the relevance of hot and cool water storage systems. With the additional storage, not only is the PV usage high, but also the net energy consumption is lower than the "Energy Saving" setting, while keeping the "Flexibility" room thermostat settings.

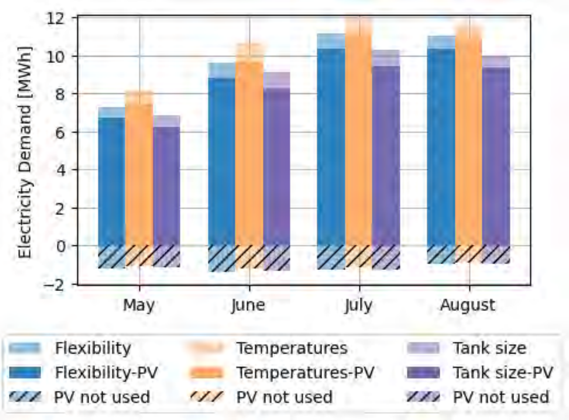

Fig. 6 – Monthly electricity demands of the hotel's HVAC and DHW systems, with the three tank thermostat strategies based on the "Flexibility" cooling demands. The "-PV" columns represent the net energy demand (considering the PV production instantly used), while the "PV not used" columns represent the energy produced by the PV not instantly used by the system

Table 1 presents a summary of the five cases studied in this work. The "Net Demand" is calculated as the sum of the HVAC and DHW electricity demands minus the PV electricity production. The PV demand coverage shows the fraction of the demands covered by the PV panels, while the "PV usage" is selected as the flexibility indicator, since the load shifting strategies aim at maximizing the consumption during the PV production hours. The "Standard" strategy is used as the reference case. Despite the building demand shifting, the energy demands of the heat pumps are concentrated only in some timesteps during the day, due to the small size of the tanks (the tanks reach the setpoint temperatures after less than 5 minutes). For this reason, the electricity produced by the PV panels is not used in every time step and its usage is limited to 32.2% in the "Standard" strategy. The "Flexibility" strategy allows an increase of the PV usage of only 3.9% while the "Temperatures" strategy that considers a flexibility strategy in both building envelope and tanks, reaches the higher PV usage, with an increase of 10.6%. The "Tank size" strategy allowed us to reduce net electricity demand, saving 3.4 MWh during the four months, and to increase the PV usage of 6.2%. Finally, the "Energy Saving" strategy, provided a low net electricity demand, similarly to the "Tank size" strategy, but at the cost of changing the thermostat settings in the building at higher temperatures during summertime and slightly reducing the comfort of the occupants. The PV usage of this strategy is also lower, 1.9% less than the "Standard" strategy, with a 6.1% PV cover of the total electricity demand. In all the cases, the strategies did not allow to significantly increase the PV total demand coverage (the increase from the "Standard" strategy is always less than 2%).

Table 1 – Net demand of electricity for all the studied flexibility strategies from May to August, with the demand coverage by the PV panels production and the percentage of the usage of the PV energy produced.

Case	Net Demand [MWh]	PV demand coverage	PV usage
Standard	36.7	6.3 %	32.2 %
Flexibility	36.2	7.1 %	36.1 %
Energy Saving	33.5	6.1 %	28.3 %
Temperatures	39.1	7.7 %	42.8 %
Tank Size	33.3	8.1 %	38.4 %

While most of the strategies reduced the electricity demand, the "Temperature" strategy increased it in all the four months and the "Flexibility" strategy increased it in May. This consumption increase is the energy cost of the flexibility that is "paid" to shift the loads to the PV production time. These electricity increase depends on the PV electricity production, which is not sufficient to cover the load during the production time (no increase in load is expected during the other hours). To evaluate when this shift is economically advantageous, the minimal energy discount to reach economical advantage of flexibility is calculated as follows:

$$\Delta C_{\%}=(E_{f}-E_{s})\cdot 100\%/E_{St} \quad (1)$$

and represents the minimum discount that is necessary on the energy during PV production time to meet the same costs of the "Standard" strategy, considering the installed PV panels. If the "Flexibility" strategy has a low energy cost and implies a slight increase in economic cost, the "Temperatures" strategy, on the other hand, requires a discount of about 13% at most, in May, during solar production hours to become economically advantageous. This scenario could be plausible in the context of a smart grid where energy supply costs are lower during PV production hours.

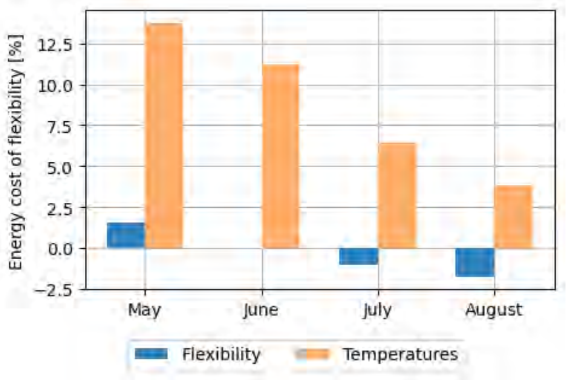

Fig. 7 – Monthly energy cost of flexibility operations of load shifting. The "Temperatures" strategy requires the consumption of more energy during the PV availability to allow the load shifting strategy

4. Conclusion

In this work the energy flexibility of a hotel has been evaluated during the cooling season. Two flexibility strategies are implemented at the building level, changing the thermostat set points of the rooms to shift the loads during the PV electricity production hours, while two other strategies are implemented at the thermal storage components of the HVAC and DHW plants, changing the thermostats and increasing the size of the tanks. The results showed that it is possible to increase the PV energy usage by 10% just changing the thermostats of the rooms and the tanks during the PV production hours with a relatively small increase of the energy demand ("Temperatures" strategy). Moreover, increasing the tanks' sizes would reduce energy demand and would increase the PV energy usage, more than increasing all the thermostats in the hotel rooms of 2K. The proposed strategies did not allow us to significantly increase the PV total demand coverage suggesting that other storage systems should be included in the plant.
Future work will focus on extending the monitoring system in the studied building to obtain a fully calibrated model of the building envelope and of the HVAC and DHW systems, including the possibility to apply the flexibility strategies on the real building, measuring the real load shifting capabilities. Other energy storage systems and strategies will be considered.

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Nomenclature

Abbreviations

AHU	Air Handling Unit
DHW	Domestic Hot Water
HVAC	Heating Ventilation and Air Conditioning
HP	Heat Pump
MHP	Multifunctional Heat Pump
PV	Photovoltaic

Symbols

$\Delta C_{\%}$	Minimal energy discount to reach economical advantage (%)
E_f	Energy required during the PV production time to shift the loads (kWh)
E_s	Shifted Energy load (kWh)
E_{St}	Energy demand obtained with the "Standard" strategy (kWh)

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