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How IoT and Artificial Intelligence can improve energy efficiency in hospitals - a North Italian case study

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Abstract. Because of the COVID-19 pandemic, healthcare facilities have experienced pressure of increasing occupancy rates and more demanding Indoor Air Quality requirements in recent months. In this context, the efficient management of the HVAC system in these buildings has become a crucial topic to address. The retrofit project was the result of the joint effort of a digital solution provider, Enerbrain, and the Hospital's energy services provider, Edison. By exploiting IoT and ICT technologies and cloud-based machine learning algorithms, the HVAC-related control features of the main heating and ventilation systems of the hospital have been upgraded with no major modifications to the existing setup. The implemented solution allows energy managers to remotely verify the real-time indoor comfort conditions and to control the upgraded systems, which, thanks to the machine learning adaptive algorithms, are now effectively meeting the required set-points through advanced optimization strategies. This paper presents the implementation of a retrofit measure applied to the HVAC Building Management System of a big public hospital in Lombardy and the energy savings achieved in the 2020-2021 heating season.

1 Introduction

The COVID-19 pandemic has brought to light and exacerbated all the challenges that health and care systems have been facing in recent years. In the health sector, efforts to cope with global problems, ranging from the sudden spread of unknown diseases to the constantly increasing demand of an ever-expanding and ageing population, are coupled with rising financial restrictions and issues of sustainability. There is a wide consensus that health systems globally but particularly in Italy need to undergo dramatic operational change if they are to adequately respond to present and future population health needs.

Reducing operational costs is pivotal in this context. Due to its size, specific processes, and operations, the health sector is a sizable consumer of energy and resources and a major producer of emissions and waste, and health facilities such as hospitals are the major contributor to this issue. A hospital consumes, on average, from two to five times more energy than an office building. In Europe, there are about 15.000 hospitals that are responsible for at least 5% of the overall European annual CO2 emission, equivalent to 250 million tons (Economidou, 2011). The projection trend has worsened in the COVID period, when, while the overall global energy use has witnessed evident reductions, the health sector has increased its expenditure (Jiang et al., 2021).

An added complexity to the efficient operation of a hospital is the fine line and balancing of topics like resource efficiency and environmental sustainability with the daily operational management, no trade-offs can be accepted between environmental sustainability and the core health systems functions performance: core functions of a hospital can have very different energy use profiles and environmental conditions to be maintained (Grassi et al., 2009): intensive care units and operating blocks, where case-specific indoor environmental conditions have to be maintained rigidly, are the most energy-intensive areas; labs and diagnostics, where biomedical equipment is used, have high energy demand both in power supply and in thermal dissipation; in-patient facilities and clinics, where typically hosting and office actions are performed, use energy mainly for climatization and lighting purposes, with different requirements according to the specific functions.

New digital technologies, such as IoT and Artificial Intelligence (AI), can play an important role in addressing above – mentioned issues and complexities of healthcare facilities by leveraging advanced logics in control systems and hence allowing for an optimized use of energy and resources. Among the most sought-after solutions for hospitals, are tools to facilitate the administration of real estate assets to increase their efficiency and sustainability, with the effective management of Heating, Ventilation, and Air Conditioning (HVAC) systems being one of the key challenges in the field. Indeed, the climatization of hospital environments requires putting in practice a wide variety of design techniques to meet the three main objectives hospitals HVAC systems are designed for: maintain a safe, healthy and comfortable environment; minimize nosocomial infections; curtail energy expenditure.

To win this challenge Advanced Building Automation and Control Systems (BACS), capable of managing Technical Building Systems (including HVAC) based on the monitored building status and predicted needs for optimizing occupants' comfort, maintenance, and energy use, are needed. The Standard EN 15232-1 (CEN, 2017) defines BACS classes according to their energy efficiency from class D, not efficient, to class A, high performing, and quantifies the energy saving potential of advanced BACS with respect to standard ones. Such estimations confirm the crucial role of advanced control strategies in improving hospitals' energy efficiency, with expected energy savings up to 45%.

In this context, the paper describes the process and results of upgrading the existing HVAC control system of one of the main public hospitals in the North of Italy. The retrofit project, implemented in the 2020-2021 heating season, is a result of the joint effort of the hospital's energy services provider, Edison, and a digital solution provider, Enerbrain, who proposed to optimize the management of the main HVAC components of the hospital by integrating and benefitting from ICT and IoT technologies with a cloud-based AI algorithm.

2 Case study

The hospital complex which constitutes the topic of the retrofit project is one of the main hospital facilities of the North of Italy, first built in the 1930s and nowadays consisting of an array of pavilions with different sizes, heights, and purposes, totalling approximately 44.000 m^2 of heated surface, offering 24/7 hospital care and in-patient service all year.

The thermal power plant was designed with a steam production system consisting of two large steam generators and a hot water boiler. The two steam generators are in operation all year round to provide the technical steam necessary for the sterilizers in the operating block and the domestic hot water, while in the heating season they are integrated with a hot water boiler which produces the additional thermal load for heating the various pavilions. In the heating period, the hot water coming to the steam generators heat-exchanger is mixed with the hot water produced by the boiler and then sent to the different distribution areas of the system through two circulation pumps.

The three generators are supplied with natural gas, accounted for by a single gas meter that records approximately 1.100.000 standard cubic meters (scm) used every year, corresponding to a useful thermal effect of around 8.500 MWh/year.

The retrofit project focused on the main pavilion of the hospital (13 floors, heated surface of approx. 18.000 m^2), which hosts diagnostics, clinics, and in-patient facilities, where the main HVAC components for heating and ventilation were objects for the intervention (see Table I).

Prior to the integration of the Enerbrain system, no capillary indoor environmental monitoring system had been in place, and only dialysis and gynaecology AHUs were managed via a remote-control system, thus leaving to the facility management team the burden of daily, manual adjustments of the operational parameters for the majority of the HVAC components. Moreover, all control actions performed by the facility team were typically driven by occupants' feedback on the perceived indoor thermal conditions. Occupants' feedback, coupled with spot indoor measurements, was indeed considered as the chief indicator for verification of the thermal comfort requirements agreed between the hospital and its energy services provider, set to 22±1°C during the heating season (Consip specifications).

The goal of the project was to improve the energy efficiency of the HVAC system without compromising occupants' comfort and with no major modifications to the existing set-up.

3 Implemented retrofit measure

The solution selected to upgrade the control features of the existing HVAC components is made up of IoT sensors, a cloud-based adaptive and predictive algorithm, and IoT controllers. The proposed configuration avoids major changes to the existing infrastructure by proposing a "man in the middle approach", in which new IoT devices are installed between the existing controllers and the physical component steered by it.

In this set-up, IoT controllers act on selected actuators of the existing HVAC system (e.g. to modulate the opening of the valve of a heating circuit). These actions on existing actuators are dictated by commands elaborated by the cloud-based algorithm, that uses as inputs for its commands the desired settings for the building (e.g. temperature set-points and schedules), a number of external variables gathered in cloud (e.g. weather data) and the real-time conditions (e.g. indoor temperatures, CO_2, fluid temperatures) monitored by newly installed IoT wireless sensors.

The control of the new system is offered through a web-based application, where the facility managers can:
- visualize and download the real-time and historical data about the environmental parameters and the fluid temperatures monitored;
- set the desired set-point and schedule for each controlled area;
- access the controllers status and the algorithm commands;

Table I lists the HVAC components under consideration, the monitored parameters, and the controlled actuators. Figure 1 shows, as an example, the three IoT controllers installed to control the turning on or off of the supply fan and the degree of opening of the pre- and post-heating coil valves of one of the selected AHUs.

Table 1. Detail of the HVAC components and actuators object of the Enerbrain intervention in the hospital.

HVAC component	Actuators under Enerbrain control	Served area	Monitored parameters
Hot water boiler	Diverter valve	Whole hospital	External air temperature Supply water temperature
Radiant Panel North circuit	Mixing valve	Main Pavilion: floors -2 to 9 North façade	Air temperature Relative Humidity CO_2 concentration
Radiant Panel South circuit	Mixing valve	Main Pavilion: floors -2 to 9 South façade	Air temperature Relative Humidity CO_2 concentration
Radiators circuit	Mixing valve	Main Pavilion: floors 0, 2	Air temperature Relative Humidity CO_2 concentration
Fan coils circuit	Mixing valve	Main Pavilion: floors 0, 2, 4	Air temperature Relative Humidity CO_2 concentration
Main AHU	Pre-Heating coil valve	Main Pavilion: floors -2 to 9	Air temperature Relative Humidity CO_2 concentration
	Post-Heating coil valve	Main Pavilion: floors -2 to 9 North façade	Air temperature Relative Humidity CO_2 concentration
	Post-Heating coil valve	Main Pavilion: floors -2 to 9 South façade	Air temperature Relative Humidity CO_2 concentration
Diagnostics AHU	Post-Heating coil valve Supply fan	Main Pavilion: Diagnostics	Air temperature Relative Humidity CO_2 concentration
Nuclear Medicine AHU	Pre-Heating coil valve Post-Heating coil valve Supply fan	Main Pavilion: Nuclear Medicine	Air temperature Relative Humidity CO_2 concentration
Dialysis AHU	Pre-Heating coil valve Post-Heating coil valve Supply fan Return fan	Main Pavilion: Dialysis	Air temperature Relative Humidity CO_2 concentration
Gynecology AHU	Pre-Heating coil valve Post-Heating coil valve Supply fan Return fan	Main Pavilion: Gynecology	Air temperature Relative Humidity CO_2 concentration
Operating Block AHU (monitoring)	No control	Main Pavilion: Operating Block	Air temperature Relative Humidity CO_2 concentration
Hospitalizations AHU (monitoring)	No control	Main Pavilion: Hospitalizations	Air temperature Relative Humidity CO_2 concentration

Figure 1. IoT controllers controlling the fan and the pre/post-heating valve of Nuclear Medicine AHU.

3.1 Operational aspects

The new system was installed in October 2020 - with no interruption of the building operation nor system down time during the installation - commissioned in November and fully operative by the 1st of December.

From the very first weeks of operation, due to the complex configuration of the existing HVAC system, as well as the specific requirements of each area, the need for a strong cooperation between the facility management team and the digital solution provider became evident: incorporating the existing profound understanding of the status quo, of the plants' working conditions, of the daily management of the hospital, the Artificial Intelligence algorithm could swiftly and effectively respond to the hospital climatization needs.

Once the adaptive and predictive control algorithm was set a fine-tuning phase was defined for the overall duration of the heating season - based on the specific site needs and features, defining for instance:

- custom schedules and setpoints for each area;
- minimum operating values (e.g. minimum degree of opening of the valves of a circuit) for all HVAC component, to ensure a minimum thermal flow for the h24 operation;
- a tailored climatic compensation curve for the management of the hot water boiler diverter valve, operating 24/7.

This synergic approach also empowered the onsite facility team to manage extraordinary maintenance activities without jeopardizing the overall system efficiency nor comfort conditions. In the event of a fault occurring on any components (e.g. mixing valve stuck, steam boilers lockout), the new system enabled the project team to spot/verify the anomaly and to define alternative control strategies to efficiently deliver the required indoor temperature while performing the maintenance works.

A crucial aspect of this “human-machine” cooperation was the trust in the technical capabilities of the newly installed solution, gained over the course of the entire heating season. The accuracy of measure of the wireless IoT environmental sensors was verified with a measurement campaign performed by the onsite team; the commands given by the algorithm were always preliminarily tested against the actual effects on the indoor conditions.

In this context, the benefit reaped from the retrofit action implemented at the hospital consists not only in the achieved energy savings but also in the new tools and strategies now at disposal of the facility team to further improve the efficiency of the daily and long-term management of the building.

4 Results and discussion

The new control system was activated on the 1st of December 2020 and running until the end of the 2020 -21 heating season. In this timeframe, periodical assessments of the system performance have been carried on verifying the energy consumption trend and to continuously improve the control settings. The following paragraphs describe the savings assessment method adopted and the energy savings achieved over the whole period, with a focus on the maintained indoor conditions.

4.1 Assessment method

To verify the energy savings achieved thanks to the upgraded control strategy, the energy use of the hospital monitored from the activation of the new system to the end of the heating season (1 December 2020 – 30 April 2021) was compared to the historical data given by the hospital’s energy services provider.

The adopted calculation method, in line with the guidelines by the International Performance Measurement and Verification Protocol (EVO, 2012), involves the identification of a calculation-based energy model that describes the normal behaviour of a building's energy consumption, which can then be used as a baseline for comparison with the consumption measured after the implementation of a retrofit measure. The saving, or rather, the "avoided consumption", is determined by the difference between the post-retrofit measured consumption and the baseline energy model.

In this project, the baseline energy model was built by plotting the monthly energy consumption data recorded from until November 2020 versus corresponding the monthly Heating Degree Days (HDD), calculated as prescribed by (UNI, 2008) using the historical weather data available from the closest ARPA weather station.

4.2 Overall natural gas consumption

Baseline

The first considered energy model describes the baseline natural gas energy use of the whole hospital, thus including all the related end uses (space heating, domestic hot water, sterilizers, kitchen). The calculation model is built by comparing the average gas consumption recorded from January 2017 to November 2020 with the corresponding average HDD. The resulting regression equation is based on a sample of 12 observations, one per month, each of them representing the average monthly value obtained from the considered historical records. Figure 2 depicts the plotted data and the resulting regression line, elicited in Equation (1).

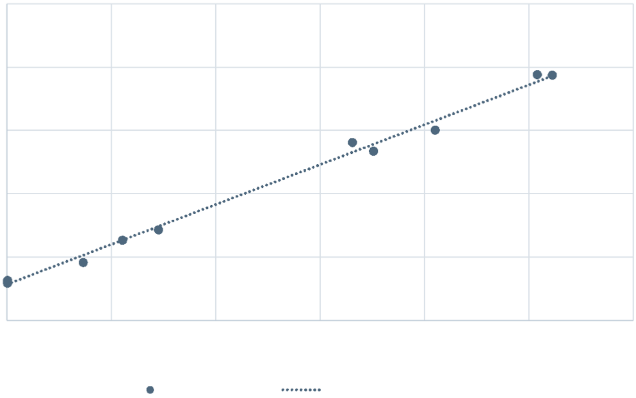

Figure 2. Baseline: Overall natural gas consumption [smc] vs. Heating Degree Days.

$$y = 315{,}18 \cdot x + 28.864 \qquad ()$$

Results

The obtained regression equation (1) is used to calculate the baseline energy use from December 2020 to April 2021, during which the new control system was active.

The comparison between the calculated baseline and the monitored gas energy consumption is displayed in Figure 3 with a monthly granularity. The obtained energy-saving totals to **5,2%** for the five months under consideration.

It is worth noticing that the savings recorded for the whole facility are in fact generated by interventions on selected HVAC components serving a pavilion that covers approximately 40% of the heated area.

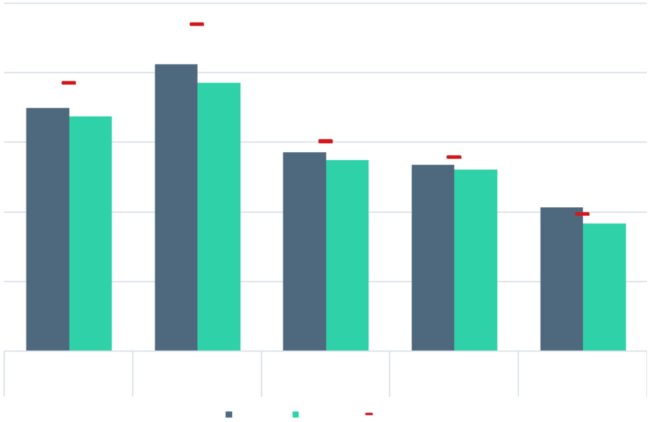

Figure 3. Natural gas consumption from baseline and measured vs. Heating Day Degrees (period 02/12/2020 - 29/04/2021).

Another aspect to consider is that, while the baseline describes the standard energy use of the building, the retrofit measure was implemented in the COVID period, during which the energy demand of the building increased to face the emergency. To understand how COVID has impacted the overall gas energy use, the hospital consumptions monitored between December 2019 and April 2020, i.e. in the first months of the pandemic, were also set against the baseline energy use for the same period. As shown in Figure 4, given similar COVID-related conditions of use of the building, in heating season 2019-'20 (before retrofit) gas consumption recorded a 0,9% increase with respect to baseline.

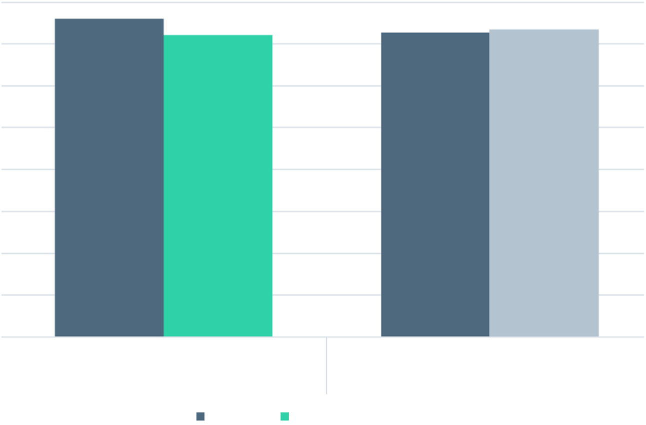

Figure 4. Natural gas consumption from baseline and measured for the period December-April in 2020-’21 heating season (2nd COVID season) and in 2019-’20 heating season (1st COVID season).

4.3 Space-heating-related consumption

Baseline

Since January 2019 energy sub-meters are installed in the hospital, allowing the energy service provider to monitor the energy used for kitchen, sterilization, and domestic hot water purposes. In the context of this project, these data were exploited to derive the energy use for space heating and to assess the actual energy savings achieved thanks to the optimized control of the HVAC systems.

The calculation model is built by comparing the average heating-related consumption recorded from January 2019 to November 2020 with the corresponding average HDD, following the same approach described in section 3.1. Figure 5 depicts the plotted data before and after the implementation of the retrofit measure, and the regression line describing the baseline energy use is expressed in Equation (2).

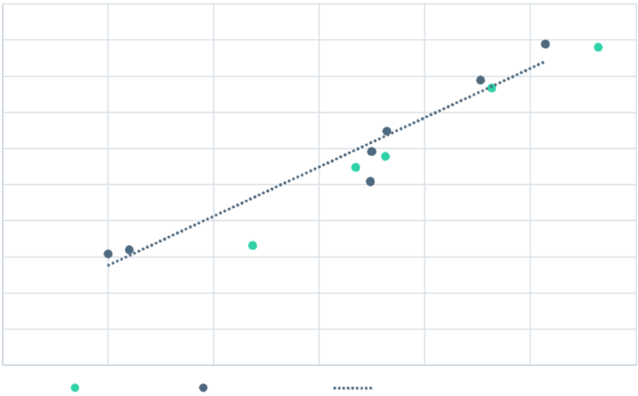

Figure 5. Gas consumption for space heating [smc] vs. Heating Degree Days before retrofit (Baseline) and after retrofit (Measured).

$$y = 272{,}81 \cdot x + 28.319 \qquad ()$$

Results

The baseline energy use from December 2020 to April 2021, calculated with equation (2), was compared to the recorded energy use for space heating, resulting in an overall **8%** energy savings with respect to the baseline. Figure 6 displays the month-by-month comparison between the calculated baseline and the monitored energy consumption.

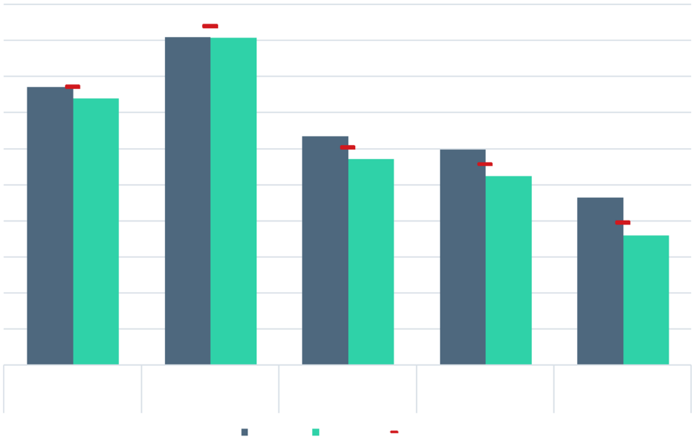

Figure 6. Gas consumption for space heating from baseline and measured vs. Heating Day Degrees (period 02/12/2020 - 29/04/2021).

Once again, it is worth mentioning that space heating figures refer to the whole hospital, while the retrofit measure was implemented on 40% of the heated area only. Therefore, if considered only on the perimeter object of the optimization intervention on the hospital, the energy saving mentioned above would reach approximately 20% of heating consumption.

4.4 Comfort conditions

In a stand-alone 13-floors building hosting a heterogeneous mix of functions and HVAC components, maintaining homogeneous and constant indoor conditions 24/7 is a tough challenge to face.

The provision of IoT environmental sensors equipped the facility management team with a user-friendly web-based tool to monitor in real-time indoor temperature, relative humidity, and CO2 levels, and thus verify if and when minimum comfort conditions of 22±1°C were met across the building.

The data monitored by the newly installed sensors were also the starting point for the commands to the HVAC system elaborated in cloud, acting to maintain the agreed comfort conditions while saving energy.

The box and whiskers plot in Figure 7 report the hourly temperature data recorded in November 2020 (HDD=357), a month before the activation of the new control system, by the IoT sensors in the various areas. Figure 8 reports the hourly temperature data recorded by the same sensors in March 2021 (HDD=335). The comparison between the two figures reveals that, while the indoor comfort requirements were met both before and after the retrofit measure, the implementation of an automated control system using adaptive and predictive control logics allowed to reduce temperature fluctuations and to stabilize them closer to the desired 22°C set-point.

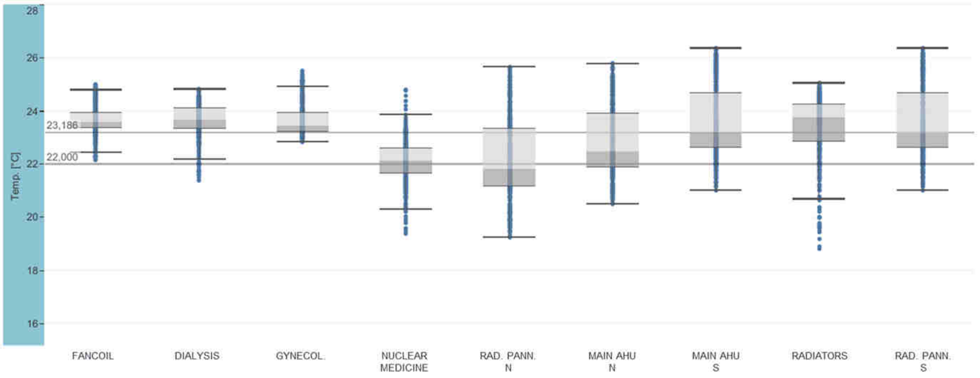

Figure 7. Distribution of hourly indoor temperatures monitored from 01/11 to 30/11/2020, before the activation of the new control system, by the 65 IoT environmental sensors installed in the various areas of the main pavilion.

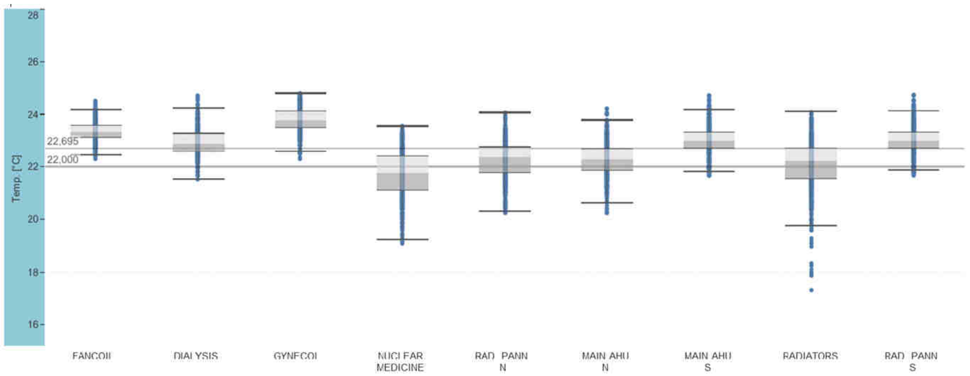

Figure 8. Distribution of hourly indoor temperatures monitored from 01/03 to 30/03/2021, with the new control system active, by the 65 IoT environmental sensors installed in the various areas of the main pavilion.

Conclusions

The paper presents the results of upgrading the control features of the existing HVAC system serving the main pavilion of a large hospital facility. The solution offered, installed with no interruption to the building services and no changes to the existing plants configuration, led to tangible energy savings at the hospital level with no consequences on the indoor environmental quality. The energy savings amounted to over 5% reduction in natural gas consumption in COVID period, that rise to 8% if calculated on energy use for space heating only, and to approx. 20% if considered on the perimeter object of the optimization intervention; these remarkable results confirm the crucial role of the advanced BACS system in improving hospitals' environmental sustainability while meeting short-term financial KPIs.

Besides the achieved results, the retrofit project represented a meaningful testing ground for the joint management of complex projects. Indeed, the proposed intervention ensued from the common initiative of Edison, the hospital energy services provider, who put in field its well-established expertise in the energy management of complex sites, and of Enerbrain, the solution provider who designed and implemented the technological solution.

Lessons learnt in the process tackle a wide range of topics, which demonstrate the complexity of the issue faced: from the optimal operating values for each heating circuit, to the strategies to improve the occupants' perceived comfort, to the most reliable method to assess the pre- and post-retrofit building performances. The common factor that led the team to win these challenges is trusted cooperation, that enriched, in a virtuous circle, the technological solution with hands-on experience and the facility management team with an enhanced control system, leading to the achieved energy savings results.

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