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DEMAND SIDE FLEXIBILITY POTENTIAL AND COMFORT PERFORMANCE OF NON-RESIDENTIAL BUILDINGS

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Abstract. The need to create and maintain a sustainable indoor environment is now more than ever compelling. Both the legislation framework concerning the energy performance of buildings, as determined in its evolution through the EU Directives 2010/31/EU, 2012/27/EU and 2018/844/EU, and the European strategic plans towards green buildings, denote the need of sustainability and comfort of indoor environment for the occupant. Moreover, the EU Directive 2018/2001 sets the renewable energy target of at least 32% for 2030, denoting that the high renewable energy sources penetration level leads to challenges in the design and control of power generation, transmission and distribution. Demand side management may be able to provide buildings with the energy flexibility needed, in order to utilize the intermittent production of Renewable Energy Sources in a much more efficient and cost-effective way. The flexibility potential of installed building systems is investigated, while considering the effects on the indoor environment conditions and the perceived comfort. The implemented Demand Response (DR) control strategy shifts loads by changing heating system set point temperatures, based on market clearing prices of the day ahead market. The results indicated a reduction in energy consumption and energy costs, while maintaining indoor environment quality at satisfactory levels.

1. Introduction

Main goal of the European Union (EU) is to be the leader of transition to clean energy, not just to adapt to it [1], [2], [3]. For this reason, commitments have been made towards the reduction of CO_2 emissions by at least 40% by 2030, while modernizing the economy and creating growth opportunities for all European citizens [1], [3]. Main aspects in this direction are the continuous improvement of energy efficiency, the achievement of global leadership in renewable energy sources [2], the promotion of smart energy management systems and the provision of fair energy supply conditions to consumers [1], [3].

Buildings can become key players in this transition, as they account for about 35% of final energy consumption [4].The potential of building flexibility is mainly used to reduce energy costs or the cost of purchasing electricity and heat from energy grids, to increase the penetration of RES in distribution networks, or to develop real-time equalization of production and demand in order to maintain network stability [5]. In that sense, energy flexibility can be expressed as the power or/and energy that can change

over a period of time, as a reaction to an external stimulus, without compromising the indoor environment conditions and the comfort and well-being of the occupants [6].

Among the various types of buildings, office buildings are considered the most attractive option for implementing DR programs, as they are usually characterized by high energy consumption, and in most cases are better equipped than residential buildings in terms of automation infrastructure [7]. In office buildings, heating, ventilation and air conditioning systems (HVAC), lighting systems and other electrical appliances, can change their operating profile to provide energy network support services.

In the last decade, an approach has been recorded focusing on a direct connection of the occupants' needs with the corresponding installed HVAC system, utilizing data, such as the prevailing conditions inside a building to regulate the operation of the HVAC systems accordingly [8]. Particularly in terms of users' comfort as noted by Antoniadou and Papadopoulos, from 1911 until today, and especially in the last decade, a number of research studies focus on the evaluation and determination of occupants' comfort in the indoor environment. It is also noted that more than 13 models have been developed in the last 110 years trying to describe in a more detailed way such a subjective phenomenon. The developed models propose some methods to dynamically introduce the perception and feelings of users while describing comfort [9].

In order to enable the demand side management potential, there are two main types of programs that can be implemented. These are the Incentives Based Programs (IBP) and the Price Based Programs (PBP) [10,11]. PBP programs are based on the hypothesis of dynamic pricing, where the cost of electricity is not fixed, but changes following the actual cost of electricity generation. The main goal of these programs is to balance production and demand, providing high prices during periods of high demand or/and low production and low prices during periods of lower demand or/and higher production [10,11].

In order to achieve the level of controls that will allow consumers, but also utilities to benefit from demand side management, the appropriate control strategy of the systems of a building must be implemented [12]. Control strategies can be divided into two main categories, Rule-Based Control (RBC) and Model Predictive Control (MPC). RBC is a very simple method, in which the status of a variable is monitored and the system responds by changing its operation according to a predetermined strategy [12], while MPC bases its operation on predicting the energy behavior of a building. In the latter case, the optimal control strategy usually results from solving an optimization problem, with predefined constraints and a specific time horizon [12].

By combining PBP and different categories of control strategies, several investigators proposed some types of Economic or cost MCPs and RBCs. As far as economic MCPs are concerned, electricity prices from the day-ahead market in cost function type and seek of an optimized schedule that solves the derived cost-minimization problem are usually included [13], [14], [15]. On the other hand, Economic RBCs are usually based on the prediction of future electricity cost, using past electricity price data. RBCs are easier to implement and are found to provide significant energy cost decrease potential [16,17].

In several European countries consumers can choose a real time pricing (RTP) tariff for electricity [18]. When RTP policies are applied, prices are estimated near to real-time energy usage and are based on wholesale electricity prices. These tariffs are mainly composed of electricity wholesale rates plus a retail profit and in several cases are "locked" for the day-ahead several hours before midday (E.g., Finland, 2pm) [18].

In this paper, the development of a DR model and the assessment of a DR strategy is described. The demonstrated DR strategy is cost-based load shifting of the heating equipment. The main objective of the strategy is to shift the load from times with high electricity prices to times with lower electricity prices, while trying to maintain decent levels of occupants' comfort.

2. Methodology

To implement a DR model two identical offices were used, providing a test cell for the described research. The implementation is located in Thessaloniki, Greece on an office building of the Faculty of

Engineering at Aristotle University of Thessaloniki. Thessaloniki's climate is Mediterranean, is hot Mediterranean subtropical that is mild with moderate seasonality (Köppen-Geiger classification: Csa), leading to moderate heating requirements and increased cooling ones. The chosen area exhibits a building profile with a variety of space usage and occupancy patterns. The energy demand of the building is mainly met by electrical and gas energy conversion systems. The basic loads are heating, cooling and lighting.

2.1. Test cell description

The test cell is composed of two offices with the same size, orientation, interior design and equipment, that are adjacent (figure 1). The offices have a northeast orientation and border southeast and northwest with heated areas (other offices) southwest with an indoor corridor, while their northeast side is exposed to the environment. In the Typical Office, as denoted on Figure 1, a classic control method with a fixed temperature set point is applied, while on the DR Office a Rule Based Control based on the Greek Day Ahead electricity market prices, is applied.
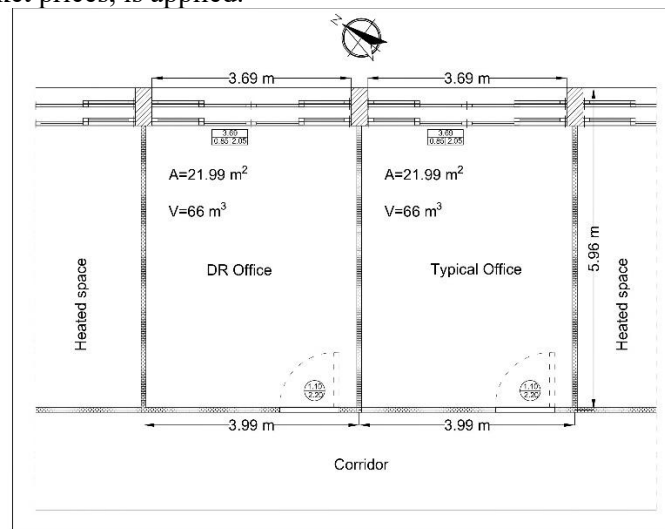

Figure 1. *Test cell floor plan*

2.2. HVAC Systems

The building has a central heating installation to meet the needs for space heating. The installation includes two gas boiler units (high temperature), with central distribution network. The distribution network has a weather compensation control system to handle part loads. A monitoring and remote control system (SCADA) helps in achieving better management of the operation of the boilers and heat distribution system, to reduce fuel consumption. The emission system for space heating consists of classic AKAN hot water radiators, with thermostatic heads mounted on each radiator. The combined power of the boiler systems is 600 kW, according to the technical specifications of the manufacturer. The flue gas analysis measured the thermal efficiency of the boiler at $n_{gm} = 90\%$.

Local air-cooled heat pumps (split type room air-conditioners) are used for cooling and are considered to cover 100% of the total cooling load of the building. The total installed cooling power is 350 kW. As there are no technical characteristics and specifications for the units, the energy efficiency ratio of the heat pumps is considered EER = 2.5 and the coefficient of performance COP=2.5, in accordance with the Greek Energy Performance of Buildings Regulation for such systems older than 5 years.

The central heating system provides heating in the winter and the air source heat pumps cooling during summer. In order to test the DR model the hot water radiators are turned off during occupancy hours and the local heat pumps are used to provide the needed heating, as they provide the capability to enforce set temperatures. The heat pumps are of old non-inverter technology, with a heating capacity of

12000 BTUs. There is no mechanical ventilation system installed, the necessary air exchanges are achieved through proper use of the office windows and following the same pattern for both offices.

2.3. Measuring Instruments

Each test room is equipped with several sensors. The Typical Office is equipped with a HOBO MX 1102 data logger for measuring indoor air temperature, air relative humidity and CO_2 concentration levels and a LogiLink EM0003 energy meter for measuring the electricity consumption. The installed energy meter does not have the capability of logging real time power data, so the total energy consumption for each hour is manually logged. The DR Office is equipped with a TESTO 480 for measuring indoor air temperature, relative humidity, CO_2 concentration levels, PMV and PPD indices and a Energenie EGM-PWM-LAN meter for measuring real time electricity consumption. Moreover, a HOBO U30 weather station is installed on the rooftop of the building, measuring the air temperature, the air relative humidity, the wind speed/direction and the solar irradiance.

2.4. Occupancy Schedule

Most office buildings in Greece provide basic HVAC services during normal business hours. Normal business hours for the described building are from 8:00 a.m. to 5:00 p.m. In regular conditions the average occupancy rate exceeds 50% during office hours. However during the COVID 19 pandemic, the profile of energy consumption in the building sector has changed, as traffic restrictions have led to mass teleworking and distance learning, leading to a reduction in activity in office buildings and a shift towards the residential building sector [19].

A direct consequence of this change is the increase in energy consumption of residential buildings. In addition, most non-residential buildings should be able to adjust their spatial and temporal operating characteristics, to cope with fewer employees per surface unit and rolling or flexible occupancy schedules [19]. In this context, it should be noted that in the under evaluation building, the occupancy rate considerably reduced to levels below 20%, while the existing energy management system can not provide adequate control over the operation of HVAC systems to meet the change in space usage and load shape.

2.5. Demand Response Method

The case of real time pricing (day ahead), where prices vary hourly on a daily basis is considered. The main problem while implementing a demand response program based on day ahead market data, is that prices change during the day and fluctuate even until the end of each hour that they refer to.

Greek Day-Ahead market data are obtained [20] and the Market Clearing Price (MCP) data are used as price signals. MCP is the price that refers to the equilibrium point between supply and demand of electrical energy.

Based on the information about the variation of electricity price, new set-point temperatures for space heating are defined. The heat pump operation in DR Office is switched from temperature-controlled to price-controlled. The temperature-control approach considers a predefined set point temperature to maintain satisfactory comfort levels, while the price-control manipulates the predefined set-point temperatures in order to shift loads from high price periods to lower price periods.

A Rule based control (RBC) is implemented aiming at covering the building's heat demand by optimal use of the air source heat pump, taking into consideration the next 24 hours forecast (day-ahead) energy price using 1 hour time-steps.

The hot water radiators are thermostatically controlled, so they can be turned on and off. The central heating system is used during the hours when no occupancy occurs. During occupancy the hot water radiators are turned off and the local heat pumps provide the needed heat. The heat provided by hot water radiators is not measured, but its effect on temperature levels is easily noticeable in the diagrams that follow.

3. Results

The initial step of the analysis is to choose the set point temperature for each office. The setpoint for the typical office is set to 21 °C and for the DR office fluctuates between 19 and 23 °C depending on the MCP values. Setpoint temperature increases when price decreases and vice versa.
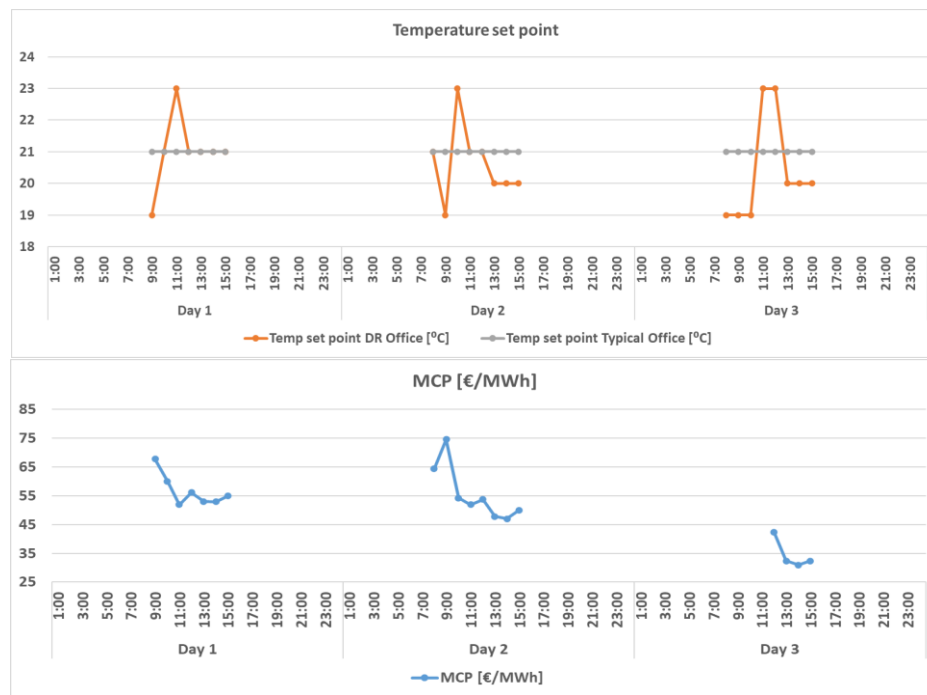

Figure 2. *Market Clearing Price values and temperature set points of Heat Pumps*
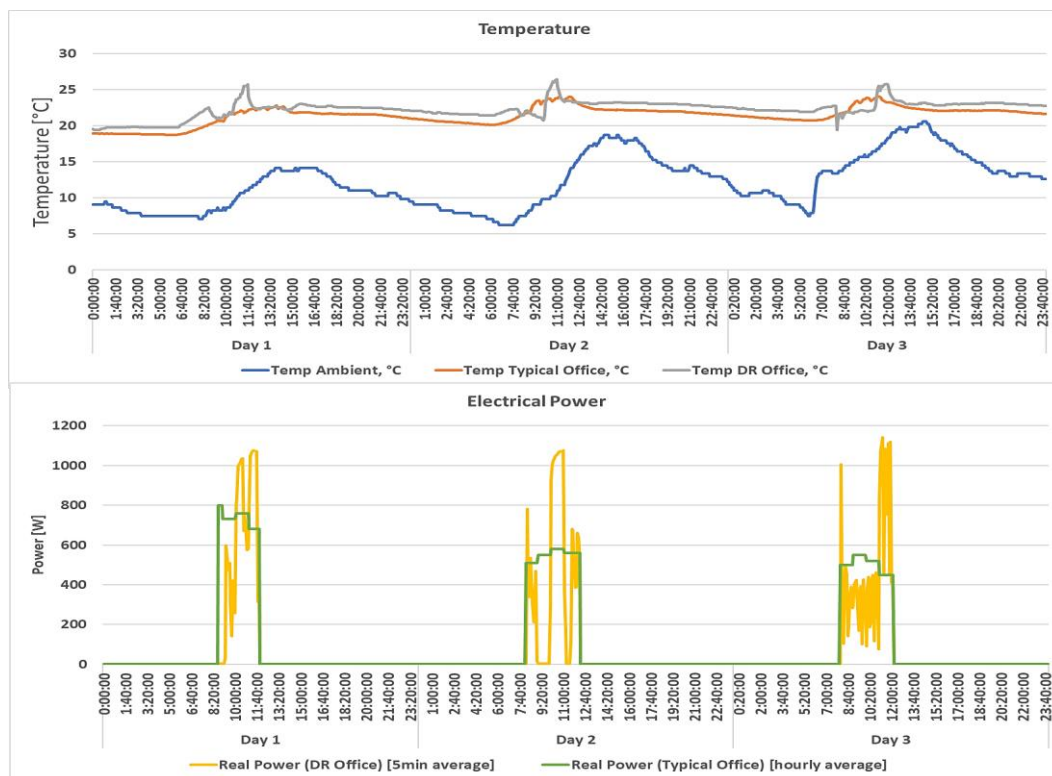

Figure 3. *Temperature of offices and ambient air and heat pumps electrical power rates*

The results of the application of DR strategy are depicted in Figure 3. The indoor air temperature and measured power for normal control (Typical office) and price-based control (DR office) and the ambient air temperature are presented. Due to the variable set point temperatures, there is a significant temperature and power variation for the DR office. The instability of temperature during the operation of the local non-inverter heat pumps is also prominent. In all three days high levels of ambient temperature are observed. The operation of heat pumps stops at around 12:30, because of low thermal loads due to high ambient temperature. The temperature differences observed between the two offices over the course of the measurement period could be due to deviations in the measuring instruments' accuracy or in the performance of the installed HVAC systems.

As displayed in Table 1 the DR strategy results in a slight reduction of total energy consumption at days 1 and 3, but a slight increase during day 2. The total difference is relatively low and may be due to deviations in the accuracy of the measuring instruments or to the variation in space occupancy or/and the efficiency of local heat pumps. In terms of energy costs, it is noted that the absolute difference is only about a few cents of euro. However, the percentage reduction in energy costs is significant.

Table 1. *Total energy consumption and energy costs for the different office scenarios*

Total energy	Day 1	Day 2	Day 3	Total	Energy cost	Day 1	Day 2	Day 3	Total
DR Office (kWh)	2,092	2,13	1,98	6,202	DR Office	0,122 €	0,119 €	0,087 €	0,327 €
Typical Office (kWh)	2,38	2,11	2,02	6,51	Typical Office	0,143 €	0,128 €	0,100 €	0,372 €
Difference (kWh)	-0,288	0,02	-0,04	-0,308	Difference	-0,022 €	-0,010 €	-0,014 €	-0,045 €
Percent change	-12%	1%	-2%		Percent change	-15%	-8%	-14%	

As it is known, the Fanger method [21] utilizes a 7-point predicted mean vote (PMV) index to determine thermal comfort. In this line of approach, the determination of PMV and PPD indices have been denoted for the DR Office as the indoor conditions were expected to note more intense variation compared to the typical office area. Based on the conducted analysis the PMV-index values for the DR Office are noted in Figure 4. PMV-index values vary in our analysis from -0.40 to +0.50, noting however values ranging from +0.50 to +1.00 only for a very short period of time. Considering that PMV values between -1 (slightly cool) and +1 (slightly warm) are considered acceptable [21], our implementation strategy keeps the PMV-index not only within acceptable bounds but in neutral levels of comfort in most cases.
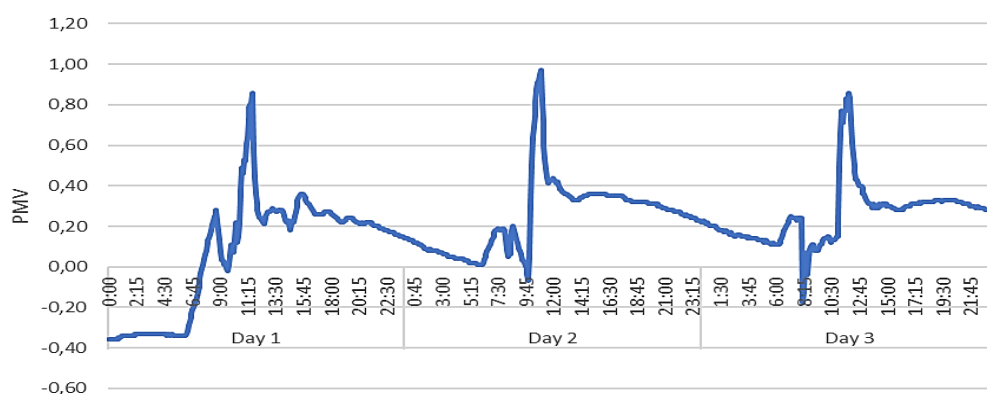

Figure 4. *PMV values in DR Office*

4. Conclusions

The need to create and maintain a sustainable indoor environment is now more than ever compelling. The flexibility potential of installed building systems needs further investigation, while considering the

effects on the indoor environment conditions and the perceived comfort in cases of non-residential buildings leading towards energy efficient buildings with high indoor environment conditions.

In the present work, the implementation of a DR strategy in an office located in Greece was evaluated. Its energy efficiency is compared to an identical office in which a standard heat pump control strategy is applied. The DR control strategy shifts loads by changing set point temperatures, based on dynamic energy prices and specifically on the market clearing price of the Greek day ahead market. Main goal is the reduction of the induced cost of energy, while still managing to maintain indoor comfort. The results indicated a small reduction in energy consumption and absolute energy costs, but at the same time a significant percentage reduction in energy costs. The impact of the application of the DR strategy on the indoor air temperature was found to be negligible.

The quality of the indoor environment was maintained at satisfactory levels throughout the DR strategy implementation. High outdoor air temperatures, on the other hand, lead to a reduction in thermal loads, which aids maintaining indoor comfort and thus slightly distorts the quality of results. On the other hand, it provides a good example for rather warm winter days, which are frequent in Mediterranean climate. Future works include application of the strategy in typical winter or/and summer conditions and the development of an automated methodology for robust determination of temperature set points according to energy prices.

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