Optimized Control Strategies of a HVAC System Under Dynamic Pricing Using the Building-As-Battery Concept

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ABSTRACT

The paper examines and compares the potential of dynamic pricing optimization techniques for electricity bill reduction in the office sector. The main objective is to lower HVAC operational costs of a 4 person office that is placed under dynamic Time-of-Use tariff, directly reflecting the day-ahead hourly market prices. Several situation are explored to find the most promising scenario: two office building configurations, three European cities, PV installation with additionality of battery and two different HVAC controls techniques. The performances of the different scenarios are investigated by calculating operational costs, greenhouse gases emission savings and user's comfort. The optimization with the installation of a smart controlled battery storage device is performed with a linear programming solver, while the demand response scenario is performed using Model Predictive Control nonlinear dynamic optimization. The results suggest that at the moment, a battery system with smart control produces the highest savings, at a high investments cost. If investment capital is not available the preferred solution is the MPC system that doesn't require big investments and produces noticeable savings, both in terms of operational costs and emissions.

Key words: Building Heating System, Energy Savings, Model Predictive Control, Dynamic-Optimization, Dynamic Pricing

1.INTRODUCTION

The progressive introduction of renewable energy sources for self-consumption in buildings and the consequent effort for decarbonization of the grid system have changed the way to use and manage energy. Many renewable energies, most popularly solar photovoltaic (PV) and wind power are intermittent by their nature, and this intermittency is a challenge at various levels. One particularly interesting sector in which these challenges could be addressed is the residential building sector. Together with the industrial building sector, it consumes around 40% of total energy use in industrial societies, and account for nearly one-third of greenhouse gas emissions. There is now a significant effort aimed at reducing energy costs of Heating, Ventilation and Air-Conditioning (HVAC) systems, which account for a one-third of the total building sector's energy use. The optimal management of HVAC systems is one of the most promising application to investigate, considering its high energy consumption. The main aim of controlling such systems is to guarantee the indoor comfort level while reducing the energy cost during operation. Such control problem needs then to handle contrasting objectives and its formulation often represents a complex task to be accomplished. A typical HVAC control only works as On/Off switch triggered by a thermostat that aims at keeping the internal temperature within comfort level, without efficiently optimize the moment in which you activate your system.

In this context, buildings energy flexibility has been recognized as a key resource to be exploited in Demand Response (DR) scenarios. Flexibility can be defined as the ability to manage a building according to grid requirements, climate conditions and user needs [1]. Buildings can leverage their properties such as thermal inertia, electrical and thermal storages and renewable production to provide energy flexibility by adjusting HVAC systems operations, making this sector a really promising participant in the electricity system.

2.STATE OF THE ART

In this study, PV energy production was computed using horizontal solar irradiance data and mathematically estimating the amount reaching a tilted surface with the HDKR model, which accounts for direct, circumsolar and isotropic diffuse radiation [2]. Subsequently, the photovoltaic (PV) models that forecast the power output should reproduce the solar panel's manufacturers current-voltage curves for different irradiation and temperature conditions, with a high degree of accuracy. Furthermore, the model used should take as input only commonly available data as presented in the manufacturers' datasheets. In this study the "three parameter model" is used, This model was validated to be accurate enough compared to more complex models while maintaining a simpler procedure and avoiding the computation of non-linear equations [3].

In order to simulate, and predict the thermodynamic response of a building to external conditions, a model based on an electrical circuit analogy was built. The lumped parameter models, that may be found in many studies, refers to model temperature dynamics which are simulated as a combination of resistor-capacitor network models that describe inter-zone conduction. This simple lumped capacity model, first developed by F. Lorenz and G. Masy [4], is a double time constant model, whose internal air mass and structural mass are linked to. Comparison researches show that second order model is a good choice for model structure is powerful enough to characterize the temperature dynamics within a short term timeframe just as well as a higher order model [5] [6].

Ultimately, a building HVAC control system is formulated as a Model Predictive Control (MPC) problem where energy cost and user discomfort are minimized while using the PV energy production forecast built, building parameters and the thermodynamic model, occupancy profiles, external temperature, irradiance and wind conditions predictions as inputs for control. The application of predictive optimal controllers for buildings, whose key principle is the efficient use of the thermal mass or thermal storage of a building, has been extensively studied in the past, mainly with the goal of increasing the energy efficiency [7] [8] [9]. Instead, the focus of this study is on the question how a proposed time-varying tariff can be used for load shifting and the reduction of peak demand. This type of MPC is generally called Economic Model Predictive Control and it is the one used in this study. Since the building envelope itself constitutes a thermal storage, there inherently exists the possibility to shift electricity demand. By using price signals, both current and future hourly market prices, the optimization of the energy consumption is shifted away from high price spikes, bringing cost and emission savings.

3.METHODOLOGY

The HDKR model transposes the horizontal data into the inclined ones taking into account the circumsolar diffuse and horizon-brightening components on a tilted surface. The main equation which calculates the total irradiance on the tilted surface G_T is:

$$\frac{G_T}{G} = \left[1-\frac{G_d}{G}(1-A_i)\right]R_b + \frac{G_d}{G}(1-A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + \sqrt{\frac{G_b}{G}}\sin^3\left(\frac{\beta}{2}\right)\right] + \rho_g\left(\frac{1-\cos\beta}{2}\right)$$

Where G is the total irradiance on the horizontal surface, G_d is the diffuse irradiance on the horizontal surface computed taking into account the clearness index, A_i is the anisotropy index, ratio between beam irradiance and extra-terrestrial irradiance (I_b / I_0), R_b is the view factor of beam radiation, equal to cos ϑ/cos ϑz (ϑ= angle of incidence, ϑz =zenith angle), β is the tilt angle of the surface and ρ_g is the surface reflectance of the ground (albedo).

The most important factor for the energy output of a PV system is of course the amount of solar radiation hitting the PV modules. However, other factors are important too, and they need to be taken into account when modelling PV generation starting from panel specifications and irradiance data. When the power of a PV module is measured under laboratory conditions at the factory, it is called the nominal power or peak power, and it's obtained under standardized conditions known as the Standard Test Conditions (STC), which are specified by international standards [10]. These conditions are a light intensity (irradiance) should be 1000W/m² on the whole surface of the module, module temperature should be 25°C and the spectrum of the light should be equal to the global spectrum given in [11]. When the PV modules are mounted outdoors, however, the conditions can be very different and, as a consequence, also the power output can be very different. The three parameters and one diode model makes corrections for different effects that influence PV power such as external temperature, dirt and irradiance.

The major heat transfer mechanisms involved in the room model include the following: heat conduction through external walls, window and roof; convection between the walls surfaces - internal and external- and the air mass in contact with it; heat convection with outside air due to the air supplied to and extracted from the room by the HVAC system; solar radiation through the window and external wall; heat gain from occupants, lighting and equipment; and infiltration and exfiltration.

The response of the indoor room temperature Ti to changes in the mass flow rate and temperature of the supply air is usually faster than its response to changes in the surrounding temperatures. A natural idea is to use two capacitors to reproduce the two-time scales of the process [4]. One capacitor (room capacitance C_R) is used for the low thermal mass of the air and other objects in the room, and the other (C_{wall}) is used for the heat capacity of all the walls combined. We choose to model the integrated wall as a 2R-1C element, which leads to:

$$C_R\frac{dT_i}{dt} = A_{wall}\frac{T_{wall}-T_i}{R_{wall\_i}} + A_{win}\frac{T_e-T_i}{R_{win}} + Q_{in} \pm Q_{HVAC}$$

$$C_{wall}\frac{dT_{wall}}{dt} = A_{wall}\frac{T_e-T_{wall}}{R_{wall\_e}} + A_{wall}\frac{T_i-T_{wall}}{R_{wall\_i}} + Q_{rad\_wall}$$

Where: Twall is the temperature of the wall on the external surface; Ti is the internal temperature of the room; Te is the external temperature; Awall is the area of the walls; Awin is the area of the window; Qin is the heat gained or loss due to internal sources, such as occupants, appliances, lighting, ventilation, or released in the room by solar irradiance hitting the window; Qrad_wall is the heat gain by solar irradiance hitting the external walls, defined as the irradiance hitting the vertical walls and multiplied by the absorption coefficient of the wall material; Q_{HVAC} is the heat gained/extracted by the heating/cooling system.

In order to be able to manage the energy demand peaks and make the best possible use of ToU tariffs schemes, the PV systems are frequently coupled with energy storage devices (ESD) which may undertake energy arbitrage. Therefore, ESDs are important components in Demand-Response (DR) programs as they can help in reducing peak demand and improving the utilization of renewable energy [12]. In this study the formulation of the LP algorithm for the PV+ESD scenario is presented.

Objective function:

$$Minimize \quad Cost = \sum_{h=0}^{24} (P_{grid,h} \cdot h) \cdot SpotPrice_h$$

Equality Constraint:

$$P_{grid,h} = P_{charge,h} - P_{discharge,h} + P_{HVAC,h} - P_{PV,h}$$
$$E_h = E_{h-1} + (\eta \cdot P_{charge,h} - P_{discharge,h})$$

Inequality Constraint:

$$0 \le E_h \le E_{max}$$
$$0 \le P_{charge,h} \le P_{max}$$
$$0 \le P_{discharge,h} \le P_{max}$$
$$P_{grid,h} \ge 0$$

Where, for the minimization objective function, Cost is the daily cost of the energy bought from the grid, Pgrid,h is the power bought from the grid, assumed constant during the hour h and SpotPriceh is the hourly spot price at which the energy is bought. For the power balance equality constraint, Pcharge,h is the power charged in the battery, Pdisharge,h is the power discharged from the battery, PHVAC,h is the power used for the HVAC system, PPV,h is the power produced from the PV system. For the battery state equality constraint, Eh is the state of the battery at time h and η is the roundtrip battery efficiency. The equality constraint determines that all variables are defined positive, which in the case of the power from the grid means that no energy is sold to the grid, and the battery variables are restricted by manufacturers maximum power of charge/discharge Pmax and maximum capacity Emax.

Model Predictive Controls rely on dynamic models of processes and their main advantage is the fact that they allow the current timeslot to be optimized, while keeping future timeslots in account. This is achieved by optimizing a finite time-horizon, first implementing the current timeslot and then optimizing again the whole horizon repeatedly [13]. Model Predictive Control (MPC) aims at facing the main challenges of HVAC system control such as non-linear and time-varying dynamics and disturbances through an optimization process performed over a receding time horizon. External inputs and simple weather conditions such as outdoor temperature and solar radiation are included in the model. By adding forecasts of prices and weather conditions to the HVAC system control problem, the energy consumption is optimized to be made flexible, predicting when to use the HVAC energy consumption and minimize the electricity operational cost to meet a certain indoor thermal comfort, which can be time varying. In this study the room thermal model developed according to the equation presented in previous chapters are fed in the optimization together with the cost minimization objective function.

4. MAIN RESULTS

The simulations were performed in 3 European cities with different climates: London, Lisbon and Milan. The simulations were done using irradiance, temperature and wind hourly data from 2016 from the European Commission's Photovoltaic Geographical Information System (PVGIS) [14] and hourly day-ahead spot market prices data for the 3 countries, sourced from the EntsoE Transparency Platform [15]. The solar panel chosen is a 225W Amerisolar AS-6P30 polycrystalline module, whose datasheet can be found at [16].

Two different building configurations that represent two classic typical construction methods were analyzed in this study. Model parameters, such as material transmittance for the two room considered, were calculated using standard property data for the construction materials involved [17] [18] and are listed in table 1.

Table 1 - Office room Characteristics and Thermal Parameters

Room Parameters		
Room Capacitance [J/K]		2.923×10^{8}
Wall Capacitance [J/K]		1.055×10^{8}
Bricks	Width [m]	0.12
	Conductivity [W/mK]	0.44
Internal Plaster	Width [m]	0.015
	Conductivity [W/mK]	0.9
External Plaster	Width [m]	0.015
	Conductivity [W/mK]	1.40
Glass Wool Insulation	Width [m]	0.16
	Conductivity [W/mK]	0.036
Window glass	Width [m]	0.004
	Conductivity [W/mK]	0.78
Window air cavity	Width [m]	0.01
	Conductivity [W/mK]	0.026
Internal Air Convection Coefficient $[W/m^2K]$		8.1
External Air Convection Coefficient $[W/m^2K]$	Wind speed ≤ 4 m/s	23.2
	Wind speed > 4 m/s	2.3 + 10.4 * Wind speed * 0.5
Glass transmissivity		90%
Walls absorbtivity		60%
Thermal bridge linear transmission coefficient [W/mK]		0.75
Ventilation rate [l/s/person]		30
Lamps Power usage [W]		20
Computers Power usage [W]		200
Office worker typical Metabolism [W]		139

The structure volume is s are 4 x 5 x 3 metersm3 with a 2 x 1 m2 south facing window and is surrounded by external air. The destination of use is considered to be a 4 person office space in which are in use 4 computer towers, 4 monitors, 1 printer and 4 LED lamps. The occupancy and use of appliances in the room follows the classical working timetable from 8AM to 5PM. The characteristics of the two versions of the room are as such: Room 1 is not insulated, and is built using a simple wall made of a 3-bricks layer covered on both sides by a plaster layer and Room 2 is built with insulation, and consists of a 2-bricks wall coupled with a layer of glass wool, as for the previous room, the package is covered on both sides by a plaster layer. There is the presence of an electric system with heating and cooling power of 2 kW, and the comfort interval is set between 20°C and 28°C during working hours and between 17°C and 30°C outside working hours.

For the purpose of assessing operational cost and savings of the heating/cooling load triggered by a simple thermostat, the hourly market prices, which reflect the trend and hourly cost of a ToU tariff without adding extra fixed cost such as taxes and utility fees, has been used. The load power was partly satisfied by the PV generation if time-matched, otherwise excess power generated was sold to the grid at a conservative price of 10 €/MWh.

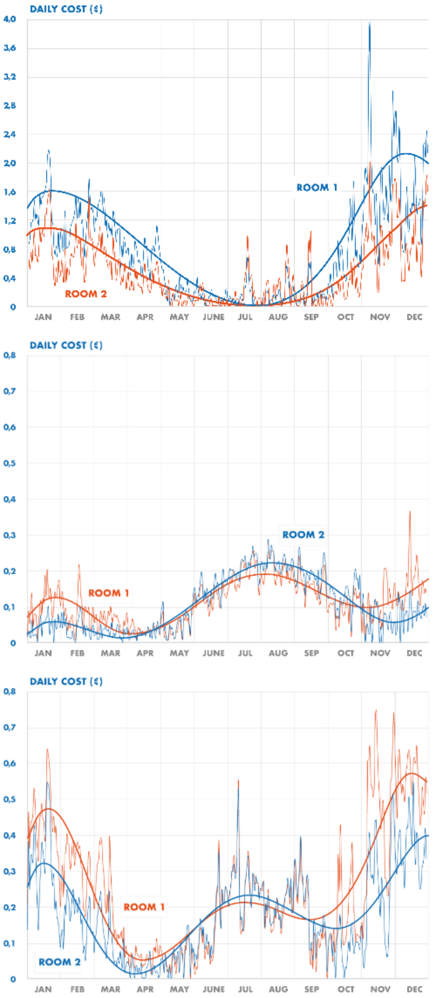
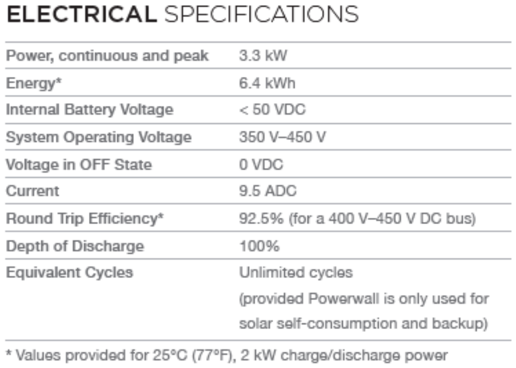


Figure 2 - Daily cost to operate the office in London (right), Lisbon (center) and Milan(left) for the two different types of room. Fine lines are the actual data and thick lines are the corresponding 6th-order polynomial fits.

In the second scenario analyzed, the rooms are equipped with a battery energy storage device. The device considered is the 7kWh lithium-ion battery Tesla Powerwall 1, launched in 2015 for the price of $3,000 [19]. The technical specifications of the products taken from the producer's datasheet are shown in Figure 2.



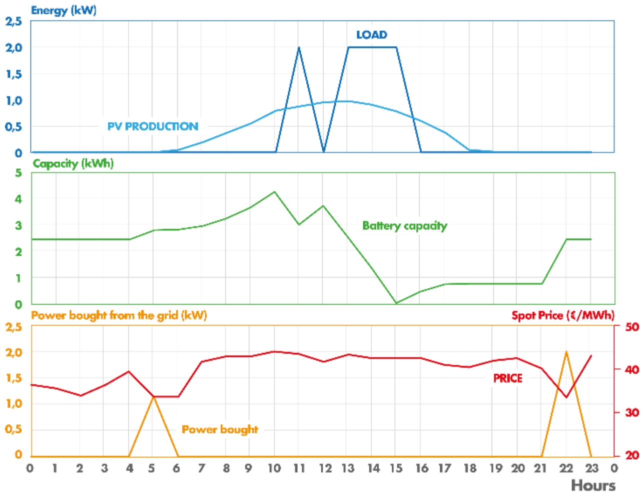
ELECTRICAL SPECIFICATIONS

Power, continuous and peak	3.3 kW
Energy*	6.4 kWh
Internal Battery Voltage	< 50 VDC
System Operating Voltage	350 V–450 V
Voltage in OFF State	0 VDC
Current	9.5 ADC
Round Trip Efficiency*	92.5% (for a 400 V–450 V DC bus)
Depth of Discharge	100%
Equivalent Cycles	Unlimited cycles (provided Powerwall is only used for solar self-consumption and backup)

* Values provided for 25°C (77°F), 2 kW charge/discharge power

Figure 2 - Technical specifications of the Tesla Powerwall storage battery

The aim of this scenario is to schedule the energy flows between PV, battery and HVAC unit in the most cost effective way. The optimization is set to be performed on a day-ahead basis, as it is longest horizon available for sufficiently accurate forecast of external temperature, and consequently heating/cooling load needs, spot prices forecast and irradiance forecast. The forecasts are assumed to be perfect. The optimization is performed on Python using the library PuLP [20], which performs linear programming problems. The algorithm calculates the optimal battery operation, such as charge/discharge schedule, and returns the total cost for the household heating/cooling operation. In Figure 3-5 examples of daily schedules.



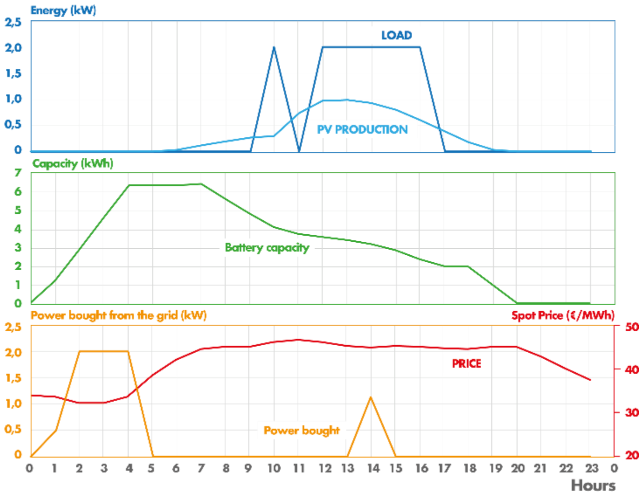


Figure 3 - Energy load (blue line), PV production (light blue line), Battery capacity (green line), Power bought from the grid (orange line) and Spot Price (red line) during 2 summer days in Lisbon for Room 1 (right) & 2 (left)

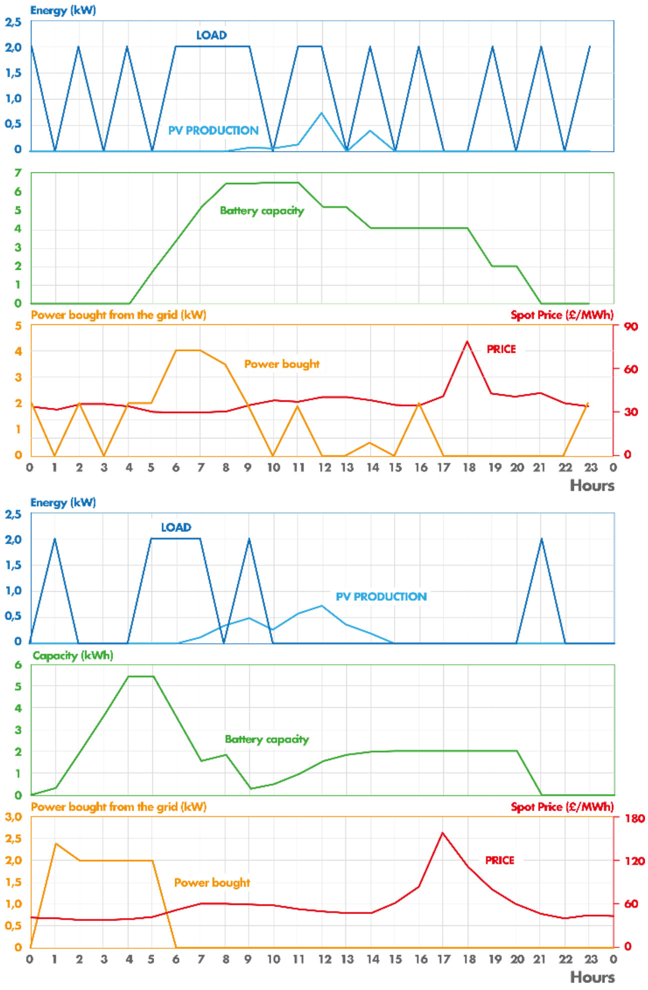


Figure 4 - Energy load (blue line), PV production (light blue line), Battery capacity (green line), Power bought from the grid (orange line) and Spot Price (red line) during 2 winter days in London for Room 1 (right) & 2 (left)

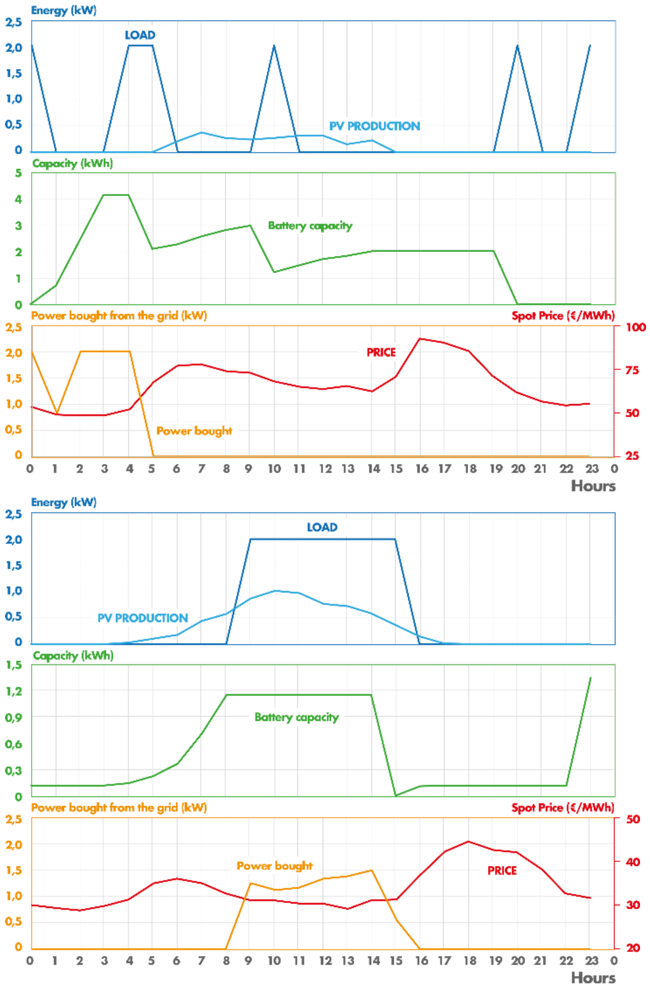


Figure 5 - Energy load (blue line), PV production (light blue line), Battery capacity (green line), Power bought from the grid (orange line) and Spot Price (red line) during 1 summer (right) and 1 winter day (left) in Milan for Room 1 (right) & 2 (left)

In the last scenario analyzed the battery is not used anymore and the rooms' heating and cooling system is equipped with a smart switch control. The purpose of this scenario is to use a Model Predictive Control load shifting technique that allows to make use of electricity in the cheap hours of the day while maintaining the thermal comfort of the room. The nonlinear control / dynamic optimization (CTL) is computed using the APOPT free solver, which is a solver that allows optimizing with integer solutions, from the GEKKO python library, by APM Monitor [21].

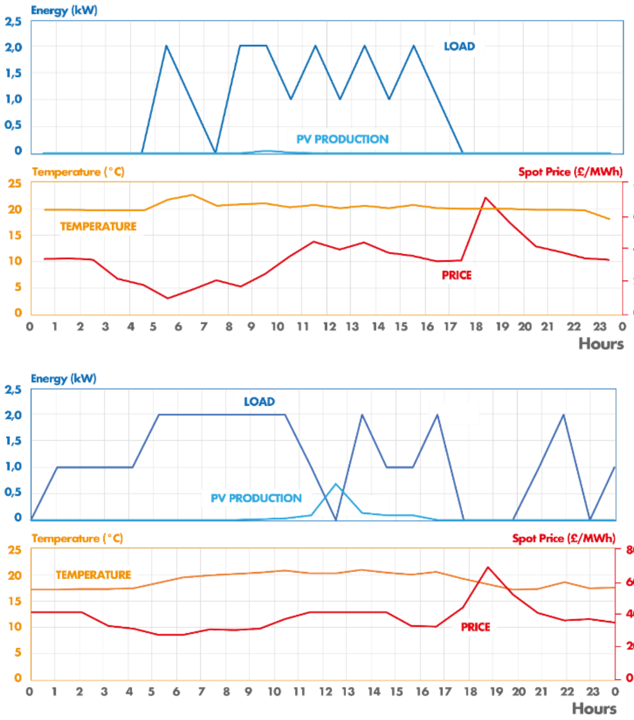


Figure 6 - Energy load (blue line), PV production (light blue line), Temperature of the room (orange line) and Spot Price (red line) using smart MPC during 2 winter days in London for Room 1 (right) and Room 2 (left)

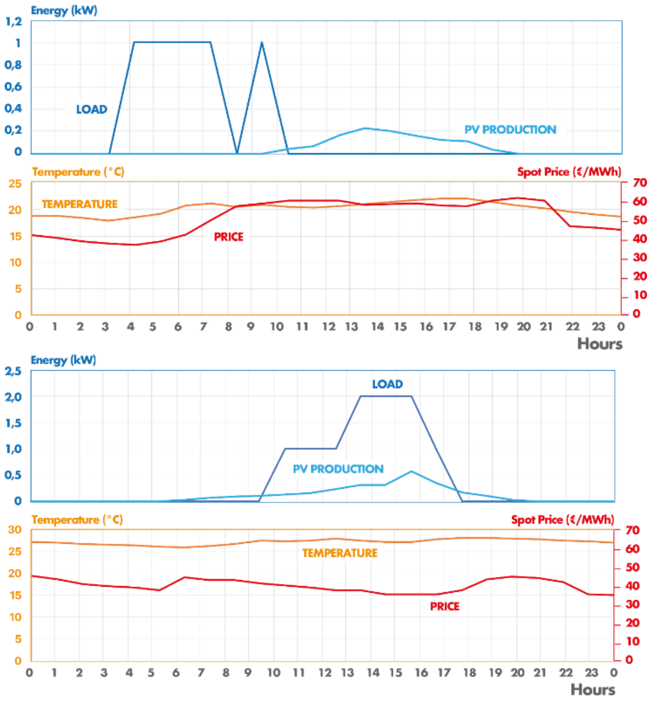


Figure 7 - Energy load (blue line), PV production (light blue line), Temperature of the room (orange line) and Spot Price (red line) using smart MPC during 2 summer days in Lisbon for Room 1 (right) and Room 2 (left)

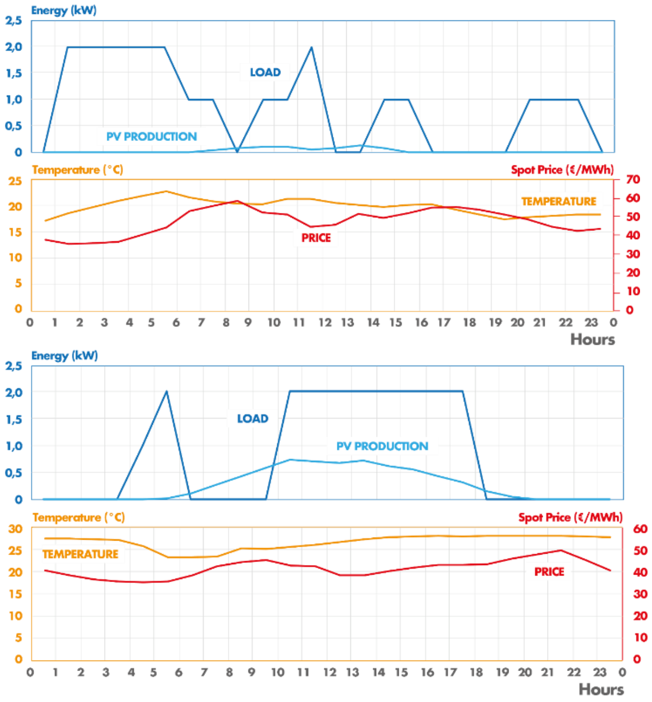


Figure 8 - Energy load (blue line), PV production (light blue line), Temperature of the room (orange line) and Spot Price (red line) using smart MPC during 1 winter day (right) and 1 summer day (left) in Milan for Room 1 (right) and Room 2 (left)

With the MPC optimization, we exploited the buildings-as-battery characteristic. The indoor temperature is always kept within comfort interval, for the exception of few days of extreme winter cold – in London and Milan - in which the MPC couldn't find a solution that could satisfy the internal temperature constraint.

5. CONCLUSION

The different scenarios and control modes are firstly compared for the total cost of the yearly operation and for the operational CO2 equivalent emissions, calculated using an emission intensity value specific per type of generation [22] and the hourly aggregated country grid generation per power source type data from Entso-E [15].

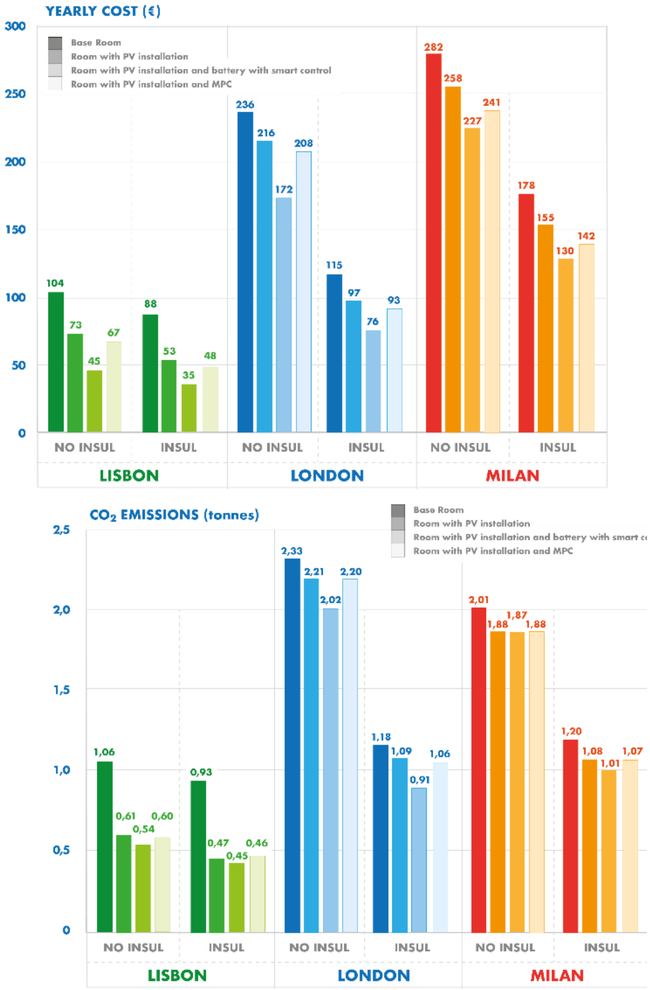


Figure 9 - Annual cost (right) and operational carbon emissions (left) comparison with different HVAC solutions for the three locations examined and rooms with or without insulation

In this study, an Economic Model Predictive Controller (Economic MPC) was simulated such that the total HVAC electricity cost is minimized, while keeping the indoor temperature in a predefined interval. Using actual electricity prices and weather conditions, we demonstrated that the Economic MPC is able to shift the power consumption load to periods with low electricity prices and, because the electricity spot prices generally reflect the amount of renewable power in the system, shifting the load to lower price periods brings a carbon emission saving as a result.

Future research will focus on the use of the proposed control strategy on building sectors with a sufficient thermal mass. A major improvement would be to validate the thermodynamic model using experimental data. Another common problem with MPC is the large computation required to implement it, which is a challenge for long period simulations. The Economic MPC concept was proofed using perfect forecasts. In the future, real forecast could be used to investigate cases with uncertainty.

References

[1] S. Ø. Jensen and al., Energy Flexibility as a key asset in a smart building future, IEA Energy in Buildings and Communities Program (EBC), 2019.

[2] J. Hay, “Calculations of the solar radiation incident on an inclined surface,” in *Canadian Solar Radiation Data Workshop*, Toronto, 1978.

[3] J. Crispim, M. Carreira and R. Castro, “Validation of Photovoltaic Electrical Models against Manufacturers Data and Experimental Results,” in *International Conference on Power Engineering, Energy and Electrical Drives*, Setubal, Portugal, 2007.

[4] F. Masy and G. Lorenz, Methode d’evaluation de l’economic d’energie apportee par l’intermittence de chauffage dans les batiments, Liege, Belgium: University de Liege, 1982.

[5] Y. Lin, Modelling the Thermal Dynamics of a Single Room in Commercial Buildings, Florida: University of Florida, 2012.

[6] M. M. Gouda, S. Danaher and C. P. Underwood, “Building thermal model reduction using nonlinear constrained optimization,” *Building and Environment,* vol. 37, no. 12, pp. 1255-1265, 2002.

[7] J. Široky´, F. Oldewurtel, J. Cigler and S. Prívara, “Experimental analysis of model predictive control for an energy efficient building heating system,” *Applied Energy,* vol. 88, pp. 3079-3087, 2011.

[8] S. Bengea, A. Kelman, F. Borrelli, R. Taylor and S. Narayanan, “Implementation of Model Predictive Control for an HVAC System in a Mid-Size Commercial Building,” *HVAC&R Research,* 2014.

[9] Y. Ma, F. Borrelli, B. Hencey, B. Coffey, S. Bengea and P. Haves, “Model Predictive Control for the Operation of Building Cooling Systems,” *IEEE Transactions on Control Systems Technology,* vol. 20, no. 3, pp. 796-803, 2012.

[10] International Standard, IEC 60904-1-1, Photovoltaic devices - Part 1-1: Measurement of current-voltage characteristics of multi-junction photovoltaic (PV) devices, IEC, 2017.

[11] International Standard, IEC 60904-3, Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data, IEC, 2019.

[12] M. Albadi and E. El-Saadany, “A summary of demand response in electricity markets,” *Electric Power Systems Research,* vol. 78, no. 11, pp. 1989 - 1996, 2008.

[13] A. Afram and F. Janabi-Sharifi, "Theory and applications of HVAC control systems - A review of model predictive control (MPC)," *Building and Environment,* vol. 72, pp. 343 - 355, 2014.

[14] EU SCIENCE HUB, "PVGIS tool - Hourly radiation," European Commission, [Online]. Available: https://ec.europa.eu/jrc/en/PVGIS/tools/hourly-radiation. [Accessed 01 04 2020].

[15] Entso-E, "Entso-E Transparency Platform," [Online]. Available: https://transparency.entsoe.eu/dashboard/show. [Accessed 01 04 2020].

[16] Worldwide Energy and Manufacturing USA Co, "WeAmerisolar," 03 2017. [Online]. Available: https://www.weamerisolar.eu/wp-content/uploads/2017/03/AS-6P30-Module-Specification.pdf. [Accessed 15 04 2020].

[17] ASHRAE, Standard Method of Test for the Evaluation of Building Energy Analysis Computer, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2010.

[18] Chartered Institution of Building Services Engineers, CIBSE guide, London: Chartered Institution of Building Services Engineers, 1986.

[19] TESLA MOTORS, "Tesla powerwall. Energy storage for a sustainable home," 2016. [Online]. Available: https://www.teslamotors.com/powerwall?redirect=no. [Accessed 15 04 2020].

[20] S. Mitchell, M. O'Sullivan and I. Dunning, "PuLP: A Linear Programming Toolkit for Python," Department of Engineering Science, The University of Auckland, Auckland, New Zealand, 2011.

[21] L. Beal, D. Hill, R. Martin and Hedengren, "GEKKO Optimization Suite," *Processes,* vol. 6, no. 8, p. 106, 2018.

[22] B. Tranberg, O. Corradi, B. Lajoie, T. Gibon, I. Staffell and G. B. Andresen, "Real-time carbon accounting method for the European electricity markets," *Energy Strategy Reviews,* vol. 26, p. 100367, 2019.

[23] Y. Chen, P. Xu, J. Gu and F. Schmid, "Measures to improve energy demand flexibility in buildings for demand response (DR): A review," *Energy and Buildings,* vol. 177, pp. Pages 125-139, 15 October Volume 177, 15 October 2018, Pages 125-139 2018.

[24] G. Parkinson, "Renew Economy," 08 05 2015. [Online]. Available: https://reneweconomy.com.au/tesla-says-battery-storage-already-makes-economic-sense-for-australia-consumers-40655/. [Accessed 01 05 2020].