# Optimal Control Strategy for HVAC Systems Promoting Building Inertia with and without RES

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November 18, 2020

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## Abstract

In recent years, the shortage of energy supply has become very important with the significant increase in energy consumption in the industrial, commercial and residential sectors. The energy consumption and $CO_2$ emissions of the building sector account respectively for 50% and 60% out of related totals. As a major energy-consuming sector, the adoption of energy efficiency building measures for energy savings and peak demand reduction is a must while maintaining indoor thermal comfort. A technical and adequate approach consists in providing an appropriate thermal mass to store the delivered energy and use it when necessary in addition to investigating real-time energy management strategies for the building. Hence, a case study of the thermal mass impact on a building in a Mediterranean region is developed using DesignBuilder. It takes into consideration five inertial signatures where the heavyweight thermal mass reveals to be the most profitable in terms of energy consumption and Greenhouse gas emissions. Besides, optimal control strategies are implemented using the MOPSO on Matlab, with and without RES for the control of the HVAC system aiming to maintain comfort with high energy efficiency. Simulations show savings up to 25% in energy consumption without RES and up to 50% with RES.

## Keyword

Multiple Objective Particle Swarm Optimization, Building Inertia, PV, Net Metering, U-Value.

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## 1. Introduction

Over the past 50 years, the global energy consumption of primary energy has steadily increased by around three times. Buildings account for around 50% of the total energy consumption in the World with a responsibility of approximately 60% of the Greenhouse gas emissions [1]. The primary electric end-uses in buildings are lighting, cooling, heating, equipment, and ventilation. As green buildings are proliferating worldwide, the demand for sustainable energy with building designs is highly increasing and the concept of energy efficiency measures is gaining the utmost attention. Many studies were conducted in the domain of building energy management systems. Several alternatives can be implemented for building design and can be divided between passive and active design methods. Passive methods refer to the effect of the thermal mass of the building, its envelope and structure elements, while active ones take into consideration the use of HVAC systems along with their control and the integration of RES.

On one hand, as known, different inertial signatures and envelopes can be used for a building. In [2], A. Goreishi has studied the effect of exterior thermal mass in terms of its location and depth. In [3], E. Siu Wing Wong, and Z. Liao have proved that thermal mass has no significant impact on energy consumption in high rise buildings in cold climates. In [4], [5], and [6], the authors incorporate layers of PCM for different buildings and prove the efficiency of such material in energy savings.

On the other hand, the control algorithms, the performance strategy, and the control system hardware impose the performance control of the HVAC system. In [7], R. Yang and L. Wang have implemented an optimal control strategy for the HVAC system while maintaining comfort. In [8], the authors presented an automated building control system management using sensors.

In this paper, a new model combining active and passive measures, and ensuring the cost-effective control strategies for HVAC systems while promoting building inertia, with and without the use of RES is implemented. It is applied for an office in Lebanon (a hot and humid climatic region) where a high shortage in electricity occurs due to the lack of power generation suiting the demands. Thus, the use of a generator in conjunction with EDL based on a 50% ratio is required.

Our study takes charge of the control of the supply/return air volume flow rate and the supply air temperature by using the MOPSO algorithm to generate different optimal solutions for the control of the HVAC system. The impact of the thermal mass on the heating and cooling loads is investigated. The building and HVAC models are presented and then, the formulated multi-objective functions are minimized for decision making with and without the use of RES. The presented results consider a case study of an office located in Beirut, Lebanon (33° 53′ 13″ N, 35° 30′ 47″ E).

This paper is divided into three sections. Section 2 presents a literature review of all the elaborated topics. Section 3 presents the models studied and the mathematical model used for optimal control without the integration of RES. Section 4 presents the results of the impact of the thermal mass on the energy audit of the building using Design Builder software and of optimal control strategy without RES. Section 5 presents a study of the optimal control strategy with the integration of RES. Finally, a conclusion states the present and future works.

## 2. Literature Review

The existing works in energy building management focused on two main areas separately. The first one treated the thermal mass while the second one elaborated on the optimal control strategy.

Thermal mass is the ability of a building envelope to absorb, store, and radiate heat [9]. It can be divided into three categories: lightweight, mediumweight, and heavyweight. It is not a substitute for insulation, but they are complementary. When correctly used, it moderates internal temperatures by averaging out the diurnal extreme temperatures. This system is called Passive Solar Design [10]. During winter, the thermal mass absorbs heat during the day from direct sunlight or radiant heaters. It re-radiates this warmth back into the house at night. During summer, cool night breezes pass over the thermal mass, drawing out all the stored energy. Each thermal mass's performance is characterized by its high density, good thermal conductivity, and an appropriate thermal lag. The use of concrete is very common in buildings. Several materials can be added to increase the effects of the thermal mass. For example, magnetite can be added to the concrete to increase its thermal conductivity. Furthermore, layers of PCM could be used too; commonly used ones include paraffin wax and a variety of benign salts. PCM can reduce the daily indoor temperature by at least 4 °C on a summer day. Its use in buildings depends on several parameters such as PCM configuration, the melting temperature as well as the thermal energy storage capacity. The findings indicated that PCMs with higher thermal energy storage capacity has a minimal heating load, cooling load, and electricity consumption. It is proven that PCMs with higher melting temperatures perform better in warmer areas [10]. Besides, its best location is near the innermost layer. Thermal mass must be located inside the building on the ground floor for an ideal summer and winter efficiency and many studies were established in different types of buildings (high-rise buildings, single houses …). Numerous studies demonstrated that the placement of the inertial mass on the internal side of the building envelope is recommended, both for energy saving and for comfort [11].

Energy management and optimal control strategy are important for the occupants to cut the electricity bills and improve the quality of life. The energy consumed by HVAC equipment has the highest percentage. Therefore, energy efficiency measures of the HVAC system shall take place to provide thermal comfort and indoor air quality comfort [7]. Indoor air quality can be valued by the concentration of carbon dioxide in the building space coming from the occupants and other pollutant sources. Demand-controlled ventilation systems are used to reduce energy consumption. They improve the air quality by controlling the amount of outside air brought to the buildings based on the number of occupants. Therefore, the VAV system could be used in which the supply air volume flow varies to match the reduction of space load during part-load operation.

## 3. Application Model

The office selected is situated at sea level (Latitude: 33.82°, Longitude: 35.48°); it is composed of two big offices, two conference rooms, two corridors, WCs, a cafeteria, an IT Room, and an entrance with a total area of 1,500 m$^2$. The walls are formed of concrete blocks in a double layer of 10 cm each, and a 5cm air space. The windows are double glazed and a layer of the concrete slab of 15cm is observed. The retrofit of this office was achieved by varying the type of envelope, from the lightweight to the heavyweight thermal mass. Four cases, other than the base case, were observed: LW, TF, MW, and ICF represented in table 1.

| | **Inner Layer** | **Middle Layer** | **Outer Layer** |
|---|---|---|---|
| **LW** | 1.25cm plasterboard | 9cm EPS | 6cm metal cladding |
| **TF** | 20cm Rockwool, 1cm plywood | 5cm air gap | 11cm break outer leaf |
| **MW** | 25cm concrete | 2.5cm PCM | 30cm brick, 2cm coating |
| **ICF** | 1.25cm plasterboard | 22cm extruded polystyrene | 0.5cm rendering |

**Table 1 – Different Envelopes**

### *3.1 Optimal Control Strategy without RES Integration*

Controlling the HVAC system in the office refers to reducing the energy consumption while maintaining the thermal indoor comfort, using the VAV system where the supply air volume flow varies to match the reduction of load. This variation has an impact on indoor temperature and $CO_2$ concentration. Therefore, the multi-objective problem is solved using the MOPSO with proper energy dispatching for each HVAC equipment.

The temperature variation, which changes accordingly to the loss or gain of energy, is shown as follows:

$$mc_p \frac{dT_{in}}{dt} = Q_{internal} + Q_{convection} + Q_{HVAC} + Q_{infiltration}$$

$$mc_p \frac{dT_{in}}{dt} = \alpha . N + \beta + \sum_{i=1}^{n_{surfaces}} h_i S_i (T_{out} - T_{in}) + \dot{m}_{supply} c_p (T_{supply} - T_{in}) + \dot{m}_{inf} c_p (T_{out} - T_{in}) \quad (1)$$

Where N: Number of occupants, $\alpha$ and $\beta$: Coefficients related to internal loads generation rate, $h_i$: Internal convective coefficient for the walls and ceiling ($W/m^2.^oC$), $A_i$: Area of the heat surfaces ($m^2$), $T_s$: Surface temperature ($^oC$), $\dot{m}_{supply}$: Mass flow rate (kg/s), $c_p$: Specific heat capacity of the supply air ($J/kg.^oC$), $T_{supply}$: Temperature of the supply air ($^oC$), and $\dot{m}_{inf}$: Mass flow rate of the infiltration air (kg/s)

On the other hand, the mass balance of $CO_2$ concentration is as follows:

$$A = A_{supply} + \frac{N.L}{G_{supply}} + \left( A(0) - A_{supply} - \frac{N.L}{G_{supply}} \right) . e^{-I.t} \quad (2)$$

Where $A_{supply}$: $CO_2$ concentration in the supply air, $L$: Average $CO_2$ concentration generation rate per person, $I = \frac{G_{supply}}{V}$: Space air change rate, and $G_{supply} = \frac{\dot{m}_{supply}}{\rho}$: Volume flow rate of the supply air.

For a whole system's energy simulation, the energy models of the primary components must be established:

$$E_{fan} = \frac{\delta_{air} \times {X_G}^3 \times G_0 \times H_0}{\eta_{motor} \times \eta_{VFD} \times \eta_{trans}} \quad (3)$$

$$E_{heating} = \frac{\dot{m}_{supply} c_p (T_{supply} - T_{mix})}{COP1} \quad (4)$$

$$E_{cooling} = \frac{\dot{m}_{supply} c_p (T_{supply} - T_{mix})}{COP2} \quad (5)$$

Where $E_{fan}$ is the energy model of the fan, $E_{heating}$ is the energy model of the heating unit, and $E_{cooling}$ is the energy model of the cooling unit.

The objective functions shall be minimized and are resumed as follows:

$$E = E_{fan} + E_{heating} + E_{cooling} \quad (6)$$

$$Q_{total} = Q_{internal} + Q_{convection} + Q_{HVAC} + Q_{inf} \quad (7)$$

$$A = A_{supply} + \frac{N.L}{G_{supply}} + \left( A(0) - A_{supply} - \frac{N.L}{G_{supply}} \right) . e^{-I.t} \quad (8)$$

Under the following constraints :

$$T_{set} - 1 \leq T_{in} \leq T_{set} + 1 \quad (9)$$

$$15 \leq T_{supply} \leq 30 \quad (10)$$

$$20 \leq T_{mix} \leq 38 \tag{11}$$
$$7.5 \leq \dot{m}_{supply} \leq 15 \tag{12}$$

This paper treats multi-objective optimization through MOPSO while in the previous literature individual objectives are treated separately. Multiple weights are assigned to the various objectives to determine the optimal solution (Leader). For this paper, all the simulated weights are equal, and considering various ones for the objectives is the subject of future works.

When implementing control on the HVAC system, the control variables ($T_{supply}$, $T_{in}$, $T_{mix}$, and $\dot{m}_{supply}$) should be adjusted according to the real-time environmental condition. The building is continuously controlled by implementing the proposed control strategy in the HVAC system for one year. The control time step for decision making is 15 minutes. The maximum number of iterations is 100 iterations and the population and repository size are respectively 30 and 20.

The simulation of the MOPSO on Matlab was performed as developed on Yarpiz and adapted to our case [12]. The flowchart of the MOPSO algorithm is represented in figure 1 where the parameters are set, and the velocity and position are initialized. Then, the domination between the particles is determined and the leader is selected, and thus the position and velocity are updated. After determining the domination of the new repository members, the grid and its indices are updated. The leader is selected finally after the convergence of the solution. The optimal solution is obtained hourly for the five cases all over 2019.

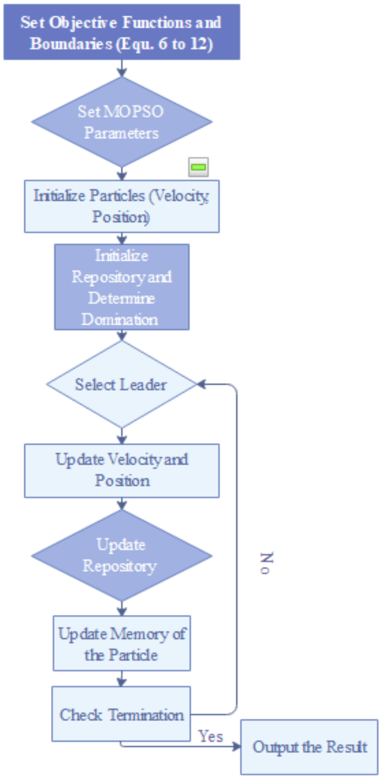

**Fig.1 – MOPSO Flowchart**

### 3.2 Optimal Control Strategy with RES Integration

High-performance buildings and related energy optimization are considered one of the most efficient ways of reducing Greenhouse gas emissions. Therefore, the use of RES is necessary for the successful implementation of such optimization.

Rooftop solar PV is used, in this study, to lower the peak demand by shifting the electrical use of energy from on-peak to off-peak period. Major support for the expansion of solar PV array and helping to accelerate the payback period of PV investment is the Net Metering and the Feed-in Tariffs.

Under net metering, the utility provides credits for the energy sent to the grid by the inverter. The credits are accumulated at a full retail value. It requires a bi-directional power meter. It has been introduced in Lebanon by EDL in 2011. It has technical advantages (like free installation of the meter by EDL). The end of month bill is the difference between the energy consumed from the grid and the one injected into it. In case of any surplus, it will be added to the next month and subtracted from the subsequent bill. For the feed-in tariff, the electricity consumption and generation costs are different. It is not yet introduced in Lebanon because it needs stability and credibility of the grid which is under development.

In this case study, the PV array will work alternatively with EDL and generator (when EDL is cut off). In case the RES can suit the load, the Diesel generator is off, and the excess energy will charge the batteries (according to their state of charge). Otherwise, the Diesel generator will operate when the RES cannot serve the load and EDL is off.

The system, formed of PV modules, inverter, and cables, is a 20-year project and would cost around 205,000 $, including its maintenance over the considered period. The 85 kWp solar station is formed by PV panels that will be oriented towards the South and to maximize the annual energy produced, PV panels will be inclined 30˚. To calculate the energy produced by an 85 kWp PV system per year, we have considered a sun peak hour SPH = 6.13h by taking March as an average month. The daily solar radiation (kWh/m$^2$) for every month was taken from the

NSRDB and for a tilted angle of 30°, the PVWATTS calculator was used to calculating the daily solar radiation. The annual PV energy generated was calculated in table 2.

| **PV Energy Generation** | |
|---|---|
| **PV ($kW_p$)** | 85 |
| **Peak Sun Hours (hrs/day)** | 6.13 |
| **Energy Produced (kWh/day)** | 521.05 |
| **Energy Produced (kWh/month)** | 15631.5 |
| **Energy Produced (kWh/year)** | 187578 |

**Table 2 – PV Energy Generation**

In parallel, an ABB central inverters PVS800 was adopted that can handle the PV's generated power. By respecting the voltage range defined in the inverter's datasheet we were able to specify the PV System Voltage (500 VDC). Then, the number of PV is calculated according to table 3.

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| **PV Sizing** | |
|---|---|
| **$P_{MPP}$ (W)** | 300 |
| **$V_{MPP}$ (V)** | 54.7 |
| **$V_{OC}$ (V)** | 64 |
| **$I_{SC}$ (A)** | 5.87 |
| **Efficiency (%)** | 18.4 |
| **Number of PV** | 283 |
| **Number of PV in parallel** | 31.00 |
| **Number of PV in series** | 9.14 |
| **Width (m)** | 1.05 |
| **Length (m)** | 1.56 |
| **Area ($m^2$)** | 1.63 |
| **Total Area ($m^2$)** | 463 |
| **Vout total (V)** | 500.00 |
| **Price per Module ($)** | 300 |
| **Total Price ($)** | 75083 |

**Table 3 – PV Sizing**

The goal of the objective function is to minimize the operational cost of the system. It is represented as follows:

$$M = \min \sum_{i=1}^{24} (e_{EDL}.E_{EDL} + e_{Gen}.E_{Gen} + e_{PV}.E_{PV}) \qquad (13)$$

Where $e_{EDL}$: EDL Tariff in Table 4, $E_{EDL}$: Electrical energy by EDL, $e_{Gen}$: Generator Tariff, 400 L.L, $E_{Gen}$: Electrical energy by the generator, $e_{PV}$: PV Tariff, equal to 78 L.L. and $E_{PV}$: The electrical energy consumed by the PV array.

Under the constraint $E_{total} = E_{optimal} = E_{EDL} + E_{Gen} + E_{PV}$ (14)

Where $E_{total}$ is the optimal energy already calculated in the first phase with the MOPSO. PSO flowchart is represented in figure 2. In this part, we considered that the previous optimization is performed and within this paragraph, we used its output to optimize the cost with the presence of various source, thus a multistage optimization is performed.

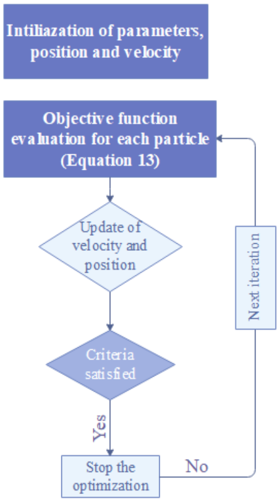


Fig.2 – PSO Flowchart

| Summer Season (April 1 – September 30) | | Winter Season (October 1 – March 31) | |
|---|---|---|---|
| **Night Rate<br>(From 00:00 to 07:00)** | 80 | **Night Rate<br>(From 00:00 to 07:00)** | 80 |
| **Day Rate<br>(From 07:00 to 18:30)** | 112 | **Day Rate<br>(From 07:00 to 16:30)** | 112 |
| **Peak Rate<br>(From 18:30 to 21:30)** | 320 | **Peak Rate<br>(From 16:30 to 20:30)** | 320 |
| **Day Rate<br>(From 21:30 to 23:00)** | 112 | **Day Rate<br>(From 20:30 to 23:00)** | 112 |
| **Night Rate<br>(From 23:00 to 24:00)** | 80 | **Night Rate<br>(From 23:00 to 24:00)** | 80 |

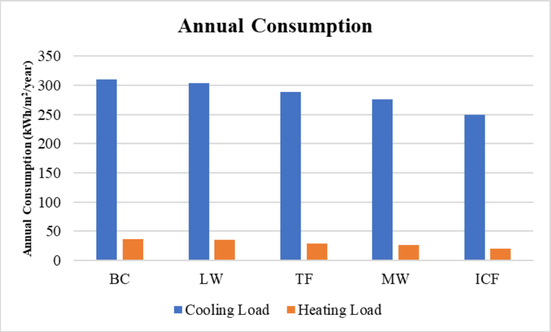
Table 4 – EDL Tariff

## 4. Results

Energy efficiency measures adopted focused on two main areas. They include a) Impact of the thermal mass, b) Optimal control strategy without RES integration.

### *4.1 Thermal Mass' Impact*

The impact of thermal mass was studied using Design Builder software. The results of the annual energy consumption and $CO_2$ emissions for the five cases are represented in figures 3 and 4.



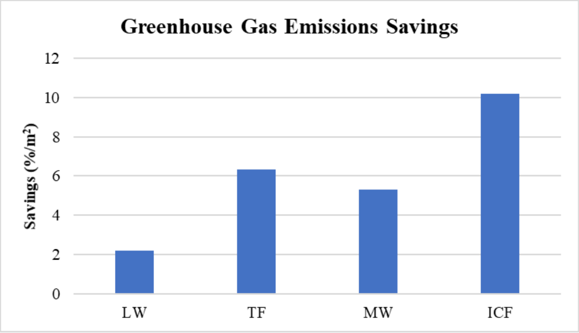


Fig.3 – Annual Energy Consumption

Fig.4 – Greenhouse Gas Emissions Savings

From figure 3, the most profitable building in terms of energy performance is the ICF which is a heavyweight building providing lower heating and cooling loads. Furthermore, this study has shown that, when compared with an equivalent lightweight construction (TF), the ICF offers a significant advantage in terms of energy performance (in both cases, the same U-value is observed). A reduction of 20% of the heating load and 7% of the cooling load are observed, in this case.

As for the carbon footprint of the building, the following coefficient was taken into consideration in the calculations: kg.$CO_2$/kWh = 0.65 according to the IPCC Guidelines for National Greenhouse Gas Inventories. Figure 4 shows the savings in Greenhouse gas emissions between the base case and the rest, in terms of the total area office. The ICF case provided higher greenhouse gas emissions savings.

### *4.2 Optimal Control Strategy without RES Integration*

For good thermal comfort, the temperature must vary between 21 and 23 °C in the winter season and 23 and 25 °C in the summer season. Therefore, two days were taken into consideration, 20 January and 22 June 2019. The results obtained, for the ICF, are represented in figures 5 and 6. As shown, the temperature is well maintained between the limits of both days. The same results were obtained for the rest (BC, LW, TF, MW).

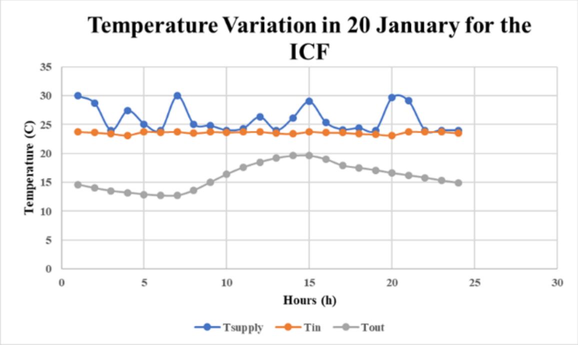


**Fig.5 – Temperature Variation on 20 Jan. for ICF**

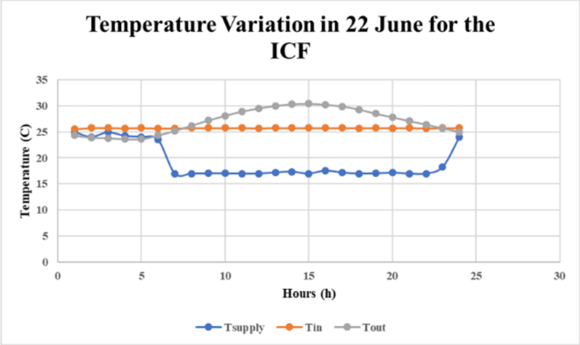


**Fig.6 – Temperature Variation on 22 June for ICF**

The simulation results of the variation of the indoor $CO_2$ concentration for 20 January and 22 June are shown in figures 7 and 8 which confirm that the concentration of $CO_2$ is controlled between the limits.

$600 \leq A_{winter} \leq 1050$ for the winter season.

$800 \leq A_{summer} \leq 1050$ for the summer season.

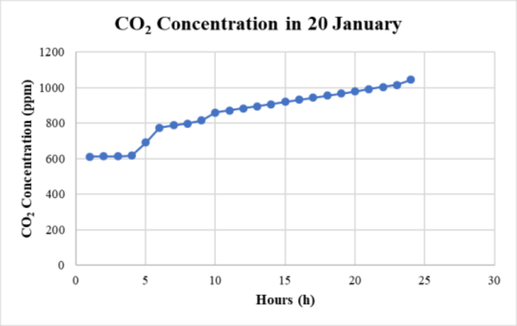


**Fig.7 – $CO_2$ Concentration on 20 Jan.**

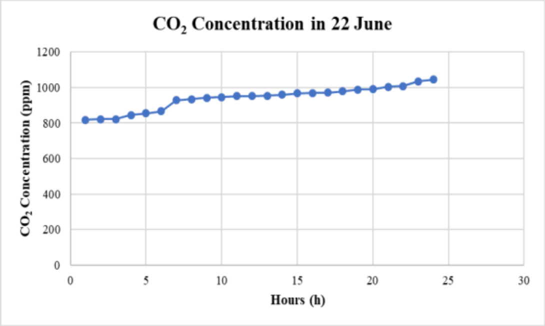
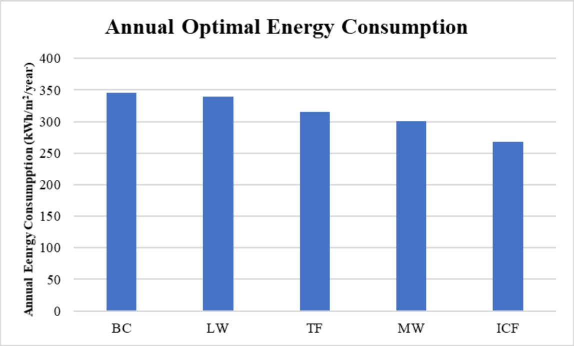


**Fig.8 – $CO_2$ Concentration on 22 June**

Figures 7 and 8 show the results of the optimal energy consumed for the five cases as well as the greenhouse gas emissions. The results obtained confirm Design Builder's results, the ICF is the best-case in terms of energy and greenhouse gas emissions savings.



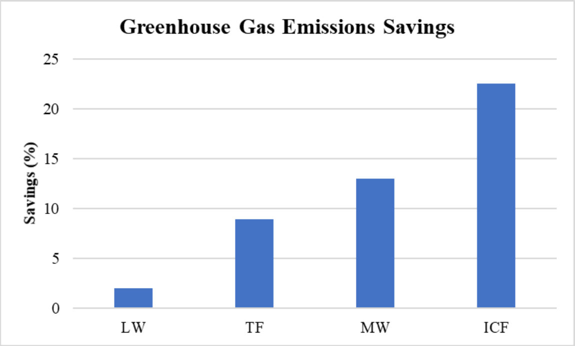


**Fig.9 – Annual Optimal Energy Consumption**

**Fig.10 – Greenhouse Gas Emissions Savings**

Suppose that the office will be supplied by electricity 24 hours per day with a ratio, as mentioned before, of 50% EDL, 50% Generator. The office has its generator; the kWh price is approximately 400 L.L. As for EDL, the prices are represented in table 4. The savings, in total cost paid, are represented in figure 11.

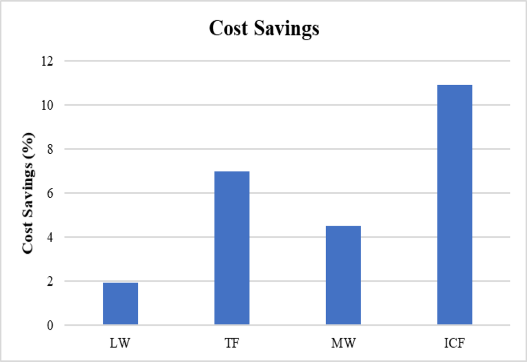
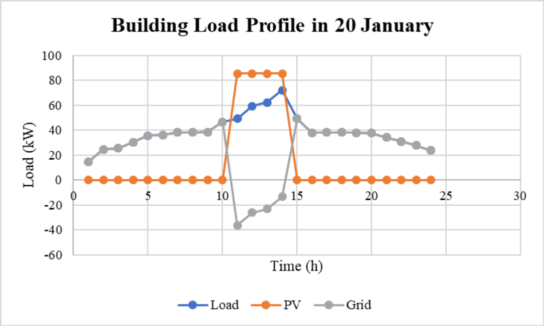


**Fig.11 – Cost Savings**

## *4.3 Optimal Control Strategy with RES Integration*

The same two days were retaken into consideration. Figures 12 and 13 represent the building load in these two days, the PV output, and the grid/building energy.



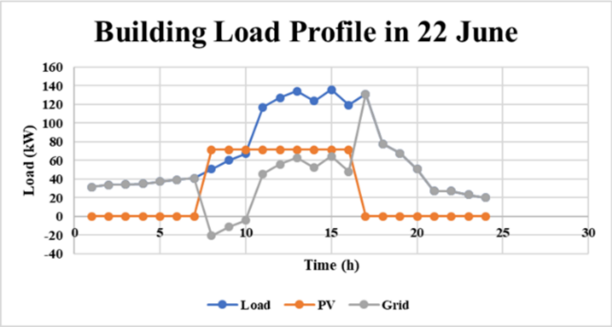


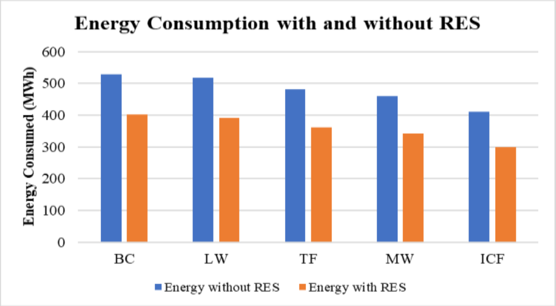
**Fig.12 – Building Load Profile on 20 Jan.**

**Fig.13 – Building Load Profile on 22 June**

Daylight hours affect the duration of the solar PV power output, which longer in Summer than in Winter, and reduce the daily building energy consumption. With the deployment of PV, there are imported and exported energy.

Exported energy happens when the PV power output is greater than the load at a given time and will be injected to the grid (represented as negative in Figures 12 and 13).

Total annual energy consumption before and after using the rooftop PV is represented in figure 14; as noticed, the yearly energy consumption has been decreased after using the PV array by 47% for the ICF. Figure 15 shows the monthly building energy consumption with and without the deployment of solar PV. The most remarkable reduction is shown in the Summer season (June, July, and August). The reason is that the peak, in Winter, is mainly in the morning and the PV fails to satisfy these demands due to the weather conditions.



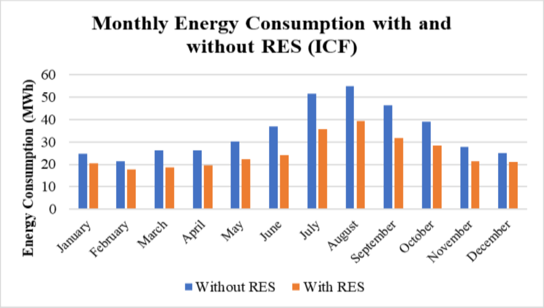
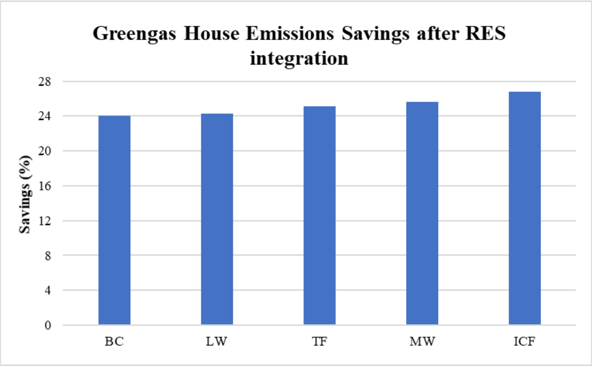


**Fig.14 – Energy Consumption with and without RES**

**Fig.15 – Monthly Energy Consumption**

Greenhouse gas emissions savings, as well as cost savings before and after RES integration, is represented in figures 16 and 17. The results prove the importance of integrating RES in buildings for savings. Savings up to 26% and 39% for the ICF case are observed for the greenhouse gas emissions and energy cost respectively.



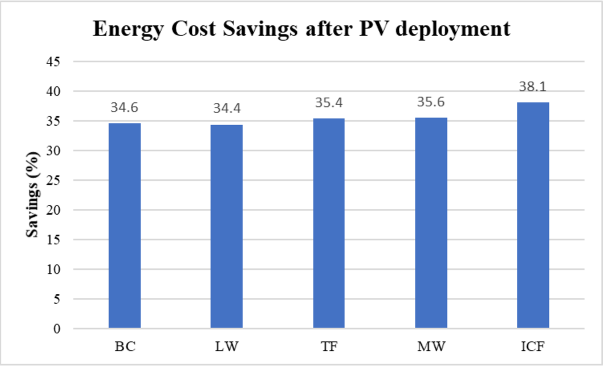


**Fig.16 – Greenhouse Gas Emissions Savings**

**Fig.17 – Energy Cost Savings**

The benefit of generating electricity from PV and injecting it into the grid will be evaluated according to the net metering. There is a decrease in the annual total cost by 38.1% for ICF.

The PBP for the five cases is represented in table 5 showing the lowest PBP for the ICF case.

The results prove that the most profitable case is the one having the lowest PBP which the ICF; in fact, PBP = 8.6 is good according to the lifetime of the project which makes the choice more suitable.

| | **PBP (years)** |
|---|---|
| **BC** | 10.4 |
| **LW** | 10.2 |
| **TF** | 9.7 |
| **MW** | 9.4 |
| **ICF** | 8.6 |

**Table 5 – PBP**

## 5. Conclusion

Major researches and studies have been conducted in the domain of building energy management systems. But still, it is yet to be fully commercially incorporated. As shown in this paper, the impact of the thermal mass on the energetic behavior of a building was treated, a multistage optimal control strategy for the control of the HVAC system was investigated with a maintain of the thermal comfort of the occupants with and without the integration of PV array on the roof of the office. For the first part, the results have shown the highest energy savings for the ICF case (up to 35%) and thus greenhouse gas emissions (up to 24%) and cost savings (up to 11%). As for the second, the integration of RES has been proven as one of the most efficient ways in energy, greenhouse gas, and cost savings; savings up to 47%, 27%, and 38% were observed for the ICF case for energy, greenhouse gas, and cost respectively. This result was also verified by calculating the PBP of each case which shows that the ICF case is the most suitable one (PBP = 8.6 years).

The future work can be summarized below and not limited to:

- The dynamic control of the setpoints, which is proven to be related to the decrease of the HVAC system's energy consumption.
- The study of the stability of the system and its requirements, after integrating RES can be an interesting area to look after.

## Conflict of interest statement

Declarations of interest: none

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