Energy Proceedings
Vol 31, 2023
ISSN 2004-2965

Technoeconomic Comparison of Retrofitting Options towards Green Buildings

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ABSTRACT

Building retrofit is one of the most effective ways to improve the energy efficiency of buildings. Many studies on building retrofit have been done in the literature. However, the methods provided in these studies are mostly specialized, which means they are suitable for professional building project decision makers and not for ordinary building owners. As we know, the main force to promote green buildings is ordinary building owners. Therefore, this paper studies the effects of retrofitting each individual facility in a building and simulations are done using EnergyPlus to ensure the accuracy of results, thereby, providing a simple and intuitive retrofit guide for ordinary building owners. Through this guideline, building owners can comprehensively understand the energy and economic benefits brought by the retrofit of each individual facility in the building. Based on this, building owners can easily make appropriate retrofit plans according to their buildings' situation without paying for professional consultation.

Keywords: building retrofit, EnergyPlus, building energy simulation, energy efficiency, payback period

NONMENCLATURE

Abbreviations	
COP	Coefficients of performance
HVAC	Heating, ventilation, and air conditioning
OITs	Optimum insulation thicknesses
PV	Photovoltaic
Symbols	
C(t)	Total cost in year t ($)
$Cf(N)$	Absolute value of the cumulative cash flow at the end of the N-th month ($)
$Cf(N+1)$	Discounted cash flow during the (N + 1)-th month ($)
d	Discount rate
E_{pre}	Total energy consumption of the building before retrofit (kWh)
E_{post}(t)	Total energy consumption of the building after retrofit in year t (kWh)
$ES(t)$	Energy savings after retrofit in year t (kWh)
N	Number of months with last negative cumulative discounted cash flows
p(t)	Electricity price in year t ($/kWh)
Tp	Payback period (month)

1. INTRODUCTION

Energy shortage and emission reduction are great challenges faced by humans. The building sector is responsible for a large proportion of the total energy consumption in the world [1-3]. In order to reduce energy consumption, many countries develop energy conservation policies and methods to improve the energy efficiency of buildings [4-6]. One of the most effective ways is to retrofit the inefficient facilities of buildings with energy-efficient ones [7-9].

Many studies have been done on building retrofit problems in the literature. These studies can be categorized into two aspects, building envelope systems and indoor facilities [10-12]. For the building envelope systems, Saikia et al. presented a dynamic optimization model for designing a multi-retrofit building envelope. The results showed that up to 33.5% of diurnal heat gain can be resisted in the hot Indian climate [13]. Fan et al. proposed a multi-objective optimization model for building envelope retrofit, aiming at maximizing the energy savings and minimizing the payback period [14]. Muddu et al. investigated the OITs for typical walls in 25 regions of Ireland to inform decisions about building envelope retrofit through insulation optimization [15]. Seghier et al. proposed a building information model (BIM) based method for green building envelope retrofit, aiming at reducing the energy consumption of a building while ensuring the indoor thermal comfort [16]. Pérez-Carramiñana et al. studied the influence of retrofitting building envelope components on the energy efficiency of buildings in Mediterranean climate [17]. For the indoor facilities, Belany et al. investigated the retrofit of three different lighting systems and analyzed the resulting economic cost and environmental impact [18]. Mukhtar et al. analyzed and summarized the energy and environmental benefits of retrofitting the existing electric heaters for hot water and ordinary air conditioners for space heating with energy-efficient alternatives [19]. Amjath et al. summarized the implementation process of energy retrofit and different types of energy retrofit related to HVAC and lighting systems with the purpose of providing a reference for project decision makers [20]. Wang et al. presented a multi-objective optimization model for retrofitting planning of building indoor facilities to help decision makers to make the best use of the available budget [21]. Ye et al. proposed an energy retrofit and maintenance optimization model for the lighting system of a building, which aims at maximizing energy savings [22]. These studies provide feasible and effective building retrofit strategies, which are suitable for professional building decision makers. However, it is well known that most of building owners are not professional in building retrofit and they even do not have a basic understanding of building energy-efficient retrofit. This phenomenon hinders the development of green buildings. Therefore, it is necessary to provide convenient guidance for general building owners so that they can make building energy-efficient retrofit plans by themselves without consulting a professional. In this way, building owners will be happy to retrofit their buildings because of the economic benefits resulting from the retrofit and the absence of consulting fees, thereby, promoting the energy efficiency of the building sector.

Therefore, this study analyzes and summarizes the energy savings and economic benefits of retrofitting each individual facility of the whole building, aiming at allowing building owners to intuitively understand the energy and economic benefits of retrofitting each facility, thereby, guiding them to make a reasonable retrofit plan according to the situation of their buildings. In this study, the windows, walls, roof, lightings and the chillers and heat pumps in the HVAC system are considered to be retrofitted. A roof-top PV system is considered to be installed. To obtain accurate building retrofit results, the EnergyPlus software is used to simulate the energy performance of a target building before and after retrofit. Based on this, the economic benefits resulting from retrofit are analyzed with the life-cycle method.

The remainder of this paper includes four parts. The physical model of a target building is built in Section 2. After that, the detailed information on building retrofit simulation is presented in Section 3 and the results are analyzed in Section 4. Finally, conclusions are drawn in Section 5.

2. BUILDING ENERGY MODELLING

In this section, the physical and energy models of an office building in Pretoria, South Africa are built with Sketch up [23-24], OpenStudio [25] and EnergyPlus [26-27].

Firstly, a 3D modeling software, Google Sketch Up, is used to build the physical model of the target building, as shown in Fig. 1. The building has two floors and each floor has eight private offices and a common office area. Then, the 3D model is introduced into the OpenStudio software so that it can be simulated in EnergyPlus. In EnergyPlus, detailed information of the target building should be input first, such as the types of lightings, HVAC and windows, the materials of walls and roof, the location and orientation, the time schedule, and the zone temperature and humidity, etc. After this, the building can be fully mapped in EnergyPlus and the energy performance of the building before and after retrofit can be simulated accurately. The simulation shows that the net site energy and energy use intensity of the building are 212858 kWh and 255.3 kWh/m^2 per year, respectively.

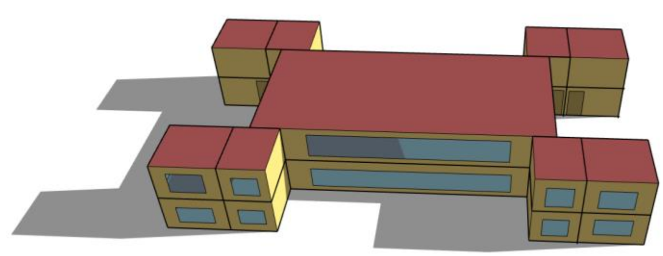

Fig. 1. Physical model of an office building

3. BUILDING RETROFIT SIMULATION

In this section, the retrofit of each individual component in a building, including the walls, roof, floor, windows, lightings and the HVAC system, and the installation of a roof-top PV system are detailed. Then the energy performance of the above retrofit scenarios will be simulated using EnergyPlus and the economic benefits brought by the retrofit are calculated with the life-cycle cost method. It should be noted that the budget is assumed to be sufficient for each individual retrofit.

3.1 Building retrofit strategies

3.1.1 Wall retrofit

The walls of the target building consist of three layers, which are one-inch stucco, eight-inch concrete and one-half-inch gypsum from outside to inside, respectively. An insulation system is considered to be installed between the one-inch stucco layer and the eight-inch concrete layer to reduce the heat transfer between the building and the environment. There are three kinds of insulation materials available for the wall retrofit. And their information, including thickness, conductivity and density, and the total cost of retrofitting the walls with these materials are detailed in Table 1.

Table 1. Detailed information of wall retrofit

Option	Thickness (m)	Conductivity (W/mK)	Density (Kg/m^3)	Cost ($)
1	0.034	0.042	91	1608
2	0.045	0.042	91	2158
3	0.056	0.042	91	2702

3.1.2 Roof retrofit

The roof of the target building consists of three layers, which are roof membrane, one-half-inch gypsum board and metal decking from outside to inside, respectively. An insulation system is considered to be installed between the layers of roof membrane and one-half-inch gypsum board. There are three kinds of insulation materials available for roof retrofit. Their detailed information, including thickness, conductivity and density, and the total cost of retrofitting the roof with these materials are given in Table 2.

3.1.3 Window retrofit

The windows of the target building are single-panel glass and the U value of the windows is 6.64, respectively. In this study, the inefficient windows are considered to be replaced with new ones. There are three alternatives available for the window retrofit and their detailed information, including thickness and conductivity, and the total cost of retrofitting the windows with these alternatives are given in Table 3.

Table 2. Detailed information of roof retrofit

Option	Thickness (m)	Conductivity (W/mK)	Density (Kg/m^3)	Cost ($)
1	0.016	0.048	264	3496
2	0.021	0.048	264	4347
3	0.026	0.048	264	5432

Table 3. Detailed information of window retrofit

Option	Thickness (m)	Conductivity (W/mK)	Cost ($)
1	0.003	2.04	4673.12
2	0.003	0.04	3909.16
3	0.003	0.018	3555.21

3.1.4 Floor retrofit

The existing floor of the target building consists of four-inch concrete floor and carpet pad. There are two sets of alternatives to retrofit the floor and their detailed information and related cost are presented in Table 4.

Table 4. Detailed information of floor retrofit

Option	Type	Cost ($)
1	CPO2 carpet pad	4966
	Reinforced concrete	
2	Typical carpet pad	6112
	4 in normal concrete	

Table 5. Detailed information of lighting retrofit

Option	Type	Number	Cost ($)
1	LED 20W	32	3259
	2-lamp 36W	32	
	CFL 20W	60	
2	LED 17W	32	3471
	2-lamp 18w	32	
	CFL 14W	60	
3	LED 12W	32	2168.36
	2-lamp 14W	32	
	CFL 7W	60	

3.1.5 Lighting system retrofit

There are three types of lightings in the target building, which are 2-lamp T8 fixture 65W, incandescent 70W and incandescent 100W, the numbers of which are 60, 32 and 32, respectively. The three types of lightings are considered to be retrofitted with new ones and three sets of alternatives are available for retrofitting the lighting system. The information of the lighting alternatives and the total retrofit cost of the lighting system are shown in Table 5. For instance, option 1 means that the three types of old lightings are retrofitted with LED 20W, 2-lamp 36W and CFL 20W with a cost of \$3259, respectively.

3.1.6 HVAC system retrofit

The chiller and heat pump in the HVAC system are considered to be retrofitted with energy-efficient ones. The COP of the original chiller and heat pump of the target building are 3.7 and 3.5, respectively. There are two sets of alternatives for the chiller and heat pump retrofit. The information of the alternatives and the total cost of retrofitting the whole HVAC system are provided in Table 6.

Table 6. Detailed information of HVAC retrofit

Option	Type	COP	Cost (\$)
1	Chiller	3.7	9344
	Heat pump	4.1	
2	Chiller	3.9	13440
	Heat pump	4.3	

3.1.7 PV system installation

A PV system is considered to be installed on the roof to reduce the energy demand of the target building. There are three solar panel alternatives for the PV system installation. The information of the alternatives and the total installation cost are given in Table 7. The parameter, Area, is the effective area of the roof for the PV system installation.

Table 7 Detailed information of PV system installation

Option	Efficiency	Area (m^2)	Cost (\$)
1	0.2	60	16131
2	0.2	80	21510
3	0.226	80	28718

3.2 Energy and economic benefits calculation

The annual energy consumption of the case building before and after retrofit is simulated using EnergyPlus. The energy savings of the building after retrofit can be calculated by

$$ES(t) = E_{pre} - E_{post}(t) \quad (1)$$

The payback period is the point at which the net present value of the cumulative benefits of energy savings exceeds the net present value of the retrofit cost [28]. It can be calculated by

$$Tp = N + \frac{|\overline{Cf}(N)|}{Cf(N+1)} \quad (2)$$

The cash flow considering the discount rate in year t of the retrofit is calculated by the following equation:

$$Cf(t) = \frac{-C(t) + p(t)ES(t)}{(1+d)^t} \quad (3)$$

4. RESULT AND ANALYSIS

Table 8. Results of retrofitting different facilities individually

Type	Option	ES (kWh)	Tp (month)	Ep
Wall	1	3288	42	1.5%
	2	3588	50	1.6%
	3	3813	58	1.7%
Roof	1	12236	26	5.7%
	2	12503	31	5.8%
	3	12600	38	5.9%
Window	1	3836	90	1.8%
	2	3341	87	1.5%
	3	3072	87	1.4%
Floor	1	3886	94	1.8%
	2	2858	137	1.3%
Light	1	24967	13	11.7%
	2	29039	12	13.6%
	3	31812	7	14.9%
HVAC	1	6736	100	3.1%
	2	9994	97	4.7%
PV	1	25109	53	11.8%
	2	40415	45	18.9%
	3	45146	53	21.2%

The results of retrofitting each individual facility of the target building are presented in Table 8. In Table 8, the type and option indicate the facilities to be retrofitted and the alternatives chosen for the retrofit. The parameters, ES, Tp and Ep, denote the energy savings per year, payback period and percentage of energy savings compared to the energy consumption of the building before retrofit, respectively. For instance, the data in the fifth row means that the roof of the building is retrofitted with its first alternative and 12236 kWh energy savings can be achieved with a payback period of 26 months and the roof retrofit saved 5.7% energy.

In terms of energy savings, it can be found from Table 8 that the energy performance of retrofitting the building indoor appliances is basically better than that of retrofitting the building envelope system. In comparison, installing a PV system on the roof of the building results in the most energy savings. For instance, the PV system can reduce the energy consumption of the building by 21.2%. Retrofitting the lighting system and the HVAC system of the building can achieve 14.9% and 4.7% energy savings, respectively. Retrofitting the walls, windows, floor and roof of the building can achieve about 1.7%, 1.8%, 1.8% and 5.9% energy savings, respectively.

In terms of economic benefits, the rule is basically that retrofitting building envelope components takes longer time to pay back the investment in comparison with installing a PV system. The payback period of the lighting system retrofit is the shortest. For instance, the payback periods of retrofitting the walls, windows, floor and roof of the building are about 50, 87, 94 and 31 months, respectively. The PV system takes about 45 months to pay back the investment. The payback period of retrofitting the lighting system is about 12 months while that of retrofitting the HVAC system is about 97 months.

Therefore, retrofitting the lighting system and installing a roof-top PV system should be considered first if the budget is not sufficient. With enough budgets, the retrofit priorities are basically the indoor appliances, the PV system and the envelope components. If only the indoor appliances need to be retrofitted, the priority should be given to the lighting system first as retrofitting the lighting system results in more energy savings with a shorter payback period compared to retrofitting the HVAC system. This is because the cost of the chiller and heat pump in the HVAC system is much more than that of lightings while the energy savings achieved by the HVAC system is less than that of the lighting system. If only the envelope components of a building need to be retrofitted, the priority should be given to the roof as the energy and economic benefits obtained by retrofitting the roof are better than those of retrofitting the walls, windows and floor. This is because the roof receives more direct sunlight than other envelope components.

In Table 8, it also can be found that retrofitting a facility with different alternatives results in different energy savings and payback period. For instance, retrofitting the walls with its first alternative can obtain 3288 kWh energy savings per year with a payback period of 42 months. In comparison, more energy savings can be achieved with a longer payback period if its third alternative is chosen for retrofit. For the lighting retrofit, the third option chooses low wattage lamps for retrofitting and achieve more energy savings with a shorter payback period, which however may sacrifice illumination comfort. Therefore, it is necessary for building owners to understand the conditions of their own building and their preferences on different needs, such as energy savings, payback period, net present values, thermal comfort and so on, so that they can get a desired retrofit plan.

5. CONCLUSION

The energy savings and economic benefits of retrofitting each individual facility in a building are systematically and comprehensively investigated to provide ordinary building owners with an intuitive guideline for building energy-efficient retrofit planning. In this study, the facilities of a target building, including the walls, windows, roof, floor, lightings, and HVAC system are considered to be retrofitted with energy-efficient alternatives, and a solar panel system is considered to be installed on the roof. The energy performance of retrofitting each facility of the target building is simulated with EnergyPlus to ensure the accuracy of the results. And the corresponding economic benefits are calculated with the life-cycle cost method. The results show that the lighting system should be retrofitted first with insufficient budgets. When sufficient budget is available, the order of priority for retrofit should be the indoor appliances, the PV system, and the envelope components.

ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundation of China (Grant No. 61903140).

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