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Research article

A cost-effectiveness assessment method and tool for assessing energy efficiency improvements in buildings

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Abstract: This paper proposes a method and a tool based on cost-effectiveness analysis (CEA) for assessing energy efficiency improvements in buildings using a case example from Egypt. Commonly used methods for economic appraisal of energy efficiency improvements have shortcomings that warrant the study of alternative methods. To offer avenues for improving the current economic assessment of energy efficiency, methods used in other fields are studied. A chain of argumentation for choosing a suitable method is developed. As a result, CEA appears to be best suited to the problem at hand. It can be used to, first, define the cost of the primary aim of saving energy and, second, allow the comparison of alternative investments in sustainable energy, not limited to energy conservation alone. A case building is studied with a calculation using a CEA method adapted for energy efficiency improvements in buildings to demonstrate the use of the method. In the case studied the CEA calculation produced costs of 0.26–0.60 USD/kWh for energy saved by the energy efficiency investments made. A systematic appraisal of cost-effectiveness of alternative energy efficiency projects would allow pointing out the most effective ones in terms of energy saved per money spent.

Keywords: energy efficiency; cost-effectiveness; economic efficiency; investment; budgeting

JEL code: Q40

1. Introduction

Energy efficiency has become a central theme in the energy policies of countries around the world with a specific emphasis on buildings as they represent the single largest end-use sector of energy consuming about 35% of total final energy globally (Moisan and Bosseboeuf 2013). In fact, ever since the 1970's, the buildings sector has remained one of the focal points for the efforts to increase energy efficiency. The residential sector in particular has had more energy-related policies put in place than any other sector in the IEA countries (Haas 1997). The results of this emphasis are starting to show, with a decreasing trend of −0.8% annually in energy consumption per household emerging globally (Moisan and Bosseboeuf 2013). After decades of rising energy consumption, this represents a meaningful change. Over time, the economic effects of this change will radiate, through the construction and energy sectors, throughout the whole economy (Tuominen et al., 2013). Therefore, the question of economic efficiency of the energy efficiency measures used to achieve this change is an important one.

In this paper a cost-effectiveness assessment (CEA) method for energy efficiency investments in buildings is presented along with a calculation tool for its application. A chain of argumentation for choosing a suitable method is developed. The aim is to offer a systematic way to assess the economic efficiency of alternative energy efficiency improvements using data that is gathered for budgeting decisions and technical planning of the building in any case. A case example from Egypt is used to demonstrate the applicability of the proposed calculation approach.

The current practice of economic appraisal of energy efficiency improvements varies a lot. A recent review of the literature by the authors found that economic appraisal is often overlooked or the methods selected tend to have meaningful shortcomings (Tuominen et al., 2015). This concurs with the findings of Kangas et al. (2018) who found that interviewed energy efficiency experts mentioned suboptimal methods, such as payback periods, in cost calculations as one of the hindering factors to improving energy efficiency in buildings. Indeed, according to Tuominen et al., (2015) the most commonly used methods are the payback period and annualized costs. Payback period does not account for the time value of money, risk and other important considerations such as opportunity costs. Annualized costs, on the other hand, are not well suited for projects with a very long or unknown lifespan. All of the methods used in the literature reviewed by Tuominen et al. (2015) were limited to the scope of the project itself, none included externalities such as climatic effects. This is the case even though many studies explicitly mentioned external effects and environmentalism as a major justification for better energy efficiency. These shortcomings suggest a need for finding a common methodology better suited to the task.

Another reason to seek to improve the methods of appraisal for energy efficiency investments pertains to decision making. There appears to be an energy efficiency gap, meaning the difference between current energy use and economically optimal energy use (Jaffe and Stavins 2003). The investment opportunities for energy efficiency improvements are numerous and include such things as efficient lights, improved insulation materials and more energy efficient appliances. Yet fewer investments are made than would be economically sensible. Past studies have presented a number of possible reasons for this phenomenon, inadequate information being one possible explanation (Jaffe et al., 2004). Better appraisal methods can help to solve the issue by providing more relevant information for investment decisions (Davis et al., 2019).

To bring the issue of costs and benefits to focus in developing energy efficiency in the building stock, the European Union requires the assessment of cost-optimality of energy efficiency measures in the recast of the Directive on the energy performance of buildings (EPBD) (European Commission 2010). The method used to define cost-optimality is a combination of net present value (NPV) for the energy efficiency investments and a forecast of energy cost savings based on expected future energy prices. The method is used by national regulators on representative reference buildings to define the level of minimum energy efficiency requirements in building regulation (Atanasiu 2013). Recent examples of the application of the method can be found from e.g., Patiño-Cambeiro et al. (2016), Karásek (2018) and Patiño-Cambeiro et al. (2019). The scope of this study is somewhat different as it deals with actual building projects instead of regulatory demands. However, some principles in the calculation process are shared, such as the use of NPV, while others are different, such as the exclusion of energy prices from CEA.

The research problem that arises from the review of literature is: What kind of methodological approach can be used to overcome the above stated shortcomings of currently commonly used appraisal methods for energy efficiency in buildings? In this paper it is suggested that cost-effectiveness assessment method has the potential to solve a number of these shortcomings. It is recognized that there are many approaches to studying the costs and benefits of an energy efficiency investment. Out of many alternatives a proposed application of cost-effectiveness assessment is presented and its suitability discussed. To demonstrate the use of this method, a case example is given based on a building studied by the authors in a previous technical study (Reda et al., 2015). The goal is to present how CEA can be used to find among given a number of investment alternatives the one producing greatest energy efficiency per money spent. This can offer novel insights in the appraisal for energy efficiency in buildings by avoiding some of the problems of currently commonly used methods.

2. Materials and methods

2.1. Method selection

Overcoming the shortcomings of the currently most commonly used methods, payback period and annualized costs, requires a more comprehensive approach to the assessment of costs and benefits of energy efficiency improvements. Therefore alternative methods currently used in other fields are examined for their suitability for assessing energy efficiency improvements in buildings.

Currently the de facto standard method in project appraisal is cost-benefit analysis (CBA), which attempts to measure the benefits and costs of a project in terms of money. The aim of assigning these monetary values is to find out what the maximum amount the society is willing to pay for the project. Because CBA uses monetary values for all costs, revenues and effects of the project, and sums them up into net present value, it gives as a result a single figure that univocally describes the net sum total of all the attributes of the project. If the NPV is positive, then the net effects are beneficial, and the project should be undertaken. In this sense, it is an extension to the social level of the NPV decision rule generally in use in corporate finance (e.g., Brealey et al., 2007).

However, considering energy efficiency in buildings the CBA approach has two major drawbacks:

- CBA gives as a result a single number that answers the yes-or-no question of whether a given project should be undertaken. This is undoubtedly very useful if that is what we are interested in. However, in the context of sustainable building projects, we are more interested in finding out how economical the project is at reaching its sustainability goals compared to the other alternatives we might have as a developer, client, authority or some other role.
- CBA requires that all outcomes of the project be given monetary values. This is not likely to be easy. The external costs of energy in general and the climatic effects of CO_2 emissions in particular are notoriously difficult to valuate monetarily. Studying energy efficiency of buildings typically concentrates heavily on both energy savings and CO_2 emissions control.

Therefore, the method suggested here is based on cost-effectiveness analysis (CEA) rather than CBA. Even though CBA has a justified role for other purposes, CEA is the preferred method when the benefits or disbenefits are difficult to value. Also, it is well suited for comparing alternative projects with the similar objectives quantified in physical terms. As an added benefit CEA is not sensitive to changes in energy prices, one of largest sources of uncertainty in evaluating energy efficiency investments, as they are excluded from the calculation.

CEA tends to be significantly less costly and time-consuming than its most obvious alternatives, cost-benefit analysis and multi-criteria analysis (OECD 2007). It can be used to identify the alternative that, for a given output level, minimizes the costs or, alternatively, for a given cost, maximizes the desired results (European Commission 2009). These qualities make CEA well suited for the appraisal of energy efficiency in buildings.

In CEA a physical quantity representing the desired outcome is selected. Then a cost for achieving the said outcome is calculated. There are a variety of methods for conducting CEA, here the three most common ones are introduced, as presented by European Commission (2009) and OECD (2007): the unit investment cost (UIC), unit annual cost (UAC), and dynamic generation cost (DGC).

Unit investment cost is the simplest and most commonly used method, where the total investment cost I is divided with the effects E_1 achieved in the first year of operation:

$$UIC = \frac{I}{E_1} \tag{1}$$

This indicator, though simple and quick to calculate, has a number of drawbacks. First, it does not account for operation and maintenance (O&M) costs. One can easily give an example that a more expensive device is preferred due to low operating and maintenance costs. Second, it does not account for differences in projects with different lifetimes. It is possible that a more expensive device will serve longer than a cheaper one; yet UIC will always give preference to the latter. Third, UIC is not sensitive to changes in the profile of the environmental effect. It may occur that a reduction in pollution will change over the lifetime of an investment. Although UIC is commonly used, OECD (2007) has recommended that UIC should not be used in professional cost-effectiveness analyses.

Unit annual cost (UAC) is a more sophisticated indicator compared to UIC that uses annualized values for investment costs, O&M costs and the outcomes. Capital costs are annualized using discounting and for O&M costs and outcomes average annual values are used. It is defined as

$$UAC = \frac{C_{avg} + I_{annual}}{E_{avg}} \tag{2}$$

where C_{avg} is the average annual O&M cost, E_{avg} is the average annual effect achieved and I_{annual} is the annualized investment cost defined as

$$I_{annual} = I \frac{d}{1-(1+d)^{-n}} \tag{3}$$

where I is the total investment cost, d is the discount rate and n is the lifetime of the project. UAC, compared with UIC, gives good estimates of the true long term average costs when the effects are distributed evenly over the life-time of the project.

UAC has, however, one major drawback in that it does not take into account the time value of the effects, even though it does that for the costs. In other words, while the costs are discounted, the outcomes are not. Dynamic generation cost attempts to overcome this drawback. It is defined as the ratio between discounted costs and discounted outcomes of the project. Even though discounting money is generally accepted, discounting non-monetary effects is seen by some as questionable. Nevertheless, non-monetary outcomes can and should be discounted for largely the same reasons as money, a matter which is discussed more thoroughly in the discussion section of this paper. Thus, despite the discounting, the outcomes are not monetised, but are expressed in physical units. DGC is expressed by Equation 4,

$$DGC = \frac{\sum_{n=0}^{N} \frac{I_n + C_n}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+d)^n}} \tag{4}$$

where I_n is the investment expenditure, C_n is O&M cost and E_n is the effect for year n, d is the discount rate and N is the lifetime of the investment. DGC is recommended by the OECD (2007) as the ideal measure of cost-effectiveness. It has all advantages of UAC and is also sensitive to changes in the distribution of the environmental effect over time. Therefore, DGC gives the best estimate of long-run average costs and it is the method selected for use in this article.

The main limitation of the method is that it only concentrates on the question of the monetary cost of achieving the desired result, in this case a reduction in energy consumption. While this is useful when the investor's interest is focused on maximising energy efficiency while minimising the costs, in most cases investors have other interests too. Thus it is clear that CEA cannot be used to replace other tools used for assessing other investment criteria. For example, if a broader view on sustainability beyond energy use only is sought, then other methods such as multi-criteria analysis may be preferable. In such cases it is recommended that other tools than CEA be used. CEA should therefore be seen as one of many tools in the toolbox of an investor, specifically it is useful for the investor who is looking the most effective energy efficiency investments in terms of energy saved per money spent. Other potential users include policy makers who are interested in finding out which are the most cost-effective energy efficiency measures available to the public.

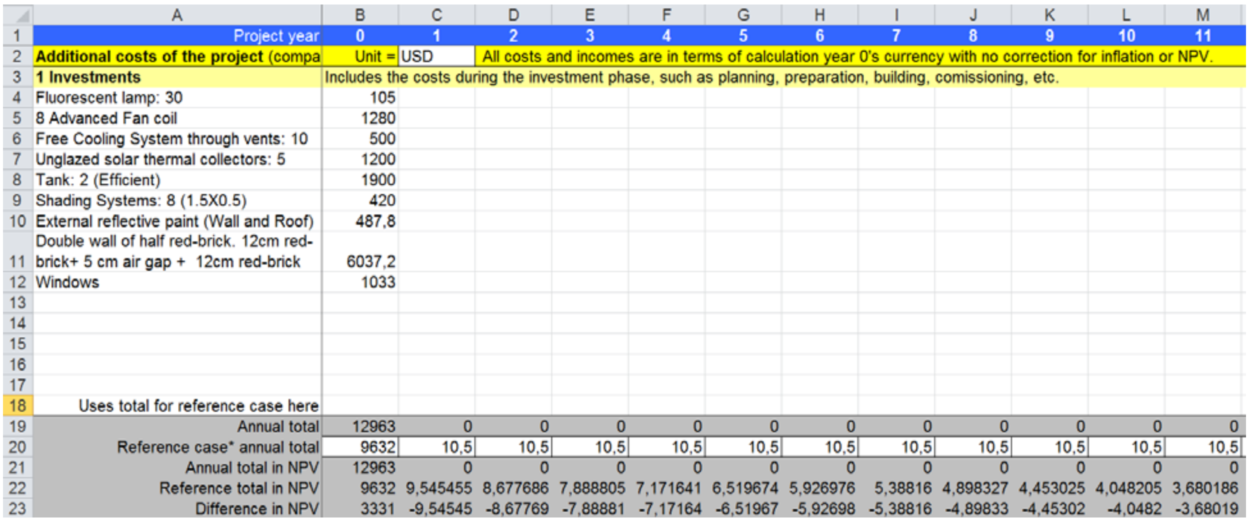
2.2. Calculation tool

To apply the DGC method to the case of energy efficiency in buildings, an Excel calculation tool by the name VTT-CEA was developed. Cost-effectiveness assessment conducted with the tool takes place in the succession of the five stages presented above, with data collected and entered to the tool. An example of a view for data input is presented in Figure 1.

The tool takes as inputs costs and energy consumption figures for each project year from three categories: (1) investment, (2) operation and maintenance and (3) renovation and refurbishment. Generally speaking, the principles of life cycle costing can be applied (see e.g., Boussabaine and Kirkham 2004; Dhillon 2009). In short, for the reliability of the calculation it is necessary that all foreseeable costs over the lifetime of the project are included. Values for the reference case are also needed, but instead of a detailed classification of costs, one figure for each category is supplied, the idea being that the current normal level of construction and operating costs is generally accepted and known.

One should use nominal prices for each year, as inflation and the time value of money are taken into account with built-in discounting. Because of discounting, the values will have to be supplied for each year. With operation and maintenance costs this can be done by using average costs for each year. Investment costs should not be annualized or amortized, but rather supplied as lump sum for the year when they are accrued.

Finally, energy costs are excluded. No costs for payments for electricity, heat, fuel or other forms of energy inflows to the case area are included in the calculation in accordance with the principles of CEA. This is to avoid counting energy twice: As a physical quantity and an expense. One must, however, include the operation and maintenance costs, excluding fuel, of any onsite equipment for energy production and conversion.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Project year	0	1	2	3	4	5	6	7	8	9	10	11
2	**Additional costs of the project** (compa	Unit =	USD	All costs and incomes are in terms of calculation year 0's currency with no correction for inflation or NPV.									
3	**1 Investments**	Includes the costs during the investment phase, such as planning, preparation, building, comissioning, etc.											
4	Fluorescent lamp: 30	105											
5	8 Advanced Fan coil	1280											
6	Free Cooling System through vents: 10	500											
7	Unglazed solar thermal collectors: 5	1200											
8	Tank: 2 (Efficient)	1900											
9	Shading Systems: 8 (1.5X0.5)	420											
10	External reflective paint (Wall and Roof)	487,8											
11	Double wall of half red-brick. 12cm red-brick+ 5 cm air gap + 12cm red-brick	6037,2											
12	Windows	1033											
13													
14													
15													
16													
17													
18	Uses total for reference case here												
19	Annual total	12963	0	0	0	0	0	0	0	0	0	0	0
20	Reference case* annual total	9632	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5
21	Annual total in NPV	12963	0	0	0	0	0	0	0	0	0	0	0
22	Reference total in NPV	9632	9,545455	8,677686	7,888805	7,171641	6,519674	5,926976	5,38816	4,898327	4,453025	4,048205	3,680186
23	Difference in NPV	3331	-9,54545	-8,67769	-7,88881	-7,17164	-6,51967	-5,92698	-5,38816	-4,89833	-4,45302	-4,0482	-3,68019

Figure 1. Typical example of a screenshot view from the VTT-CEA tool for cost data input. This picture is presented to only illustrate the user interface.

In the tool energy efficiency improvements are either assessed independently or compared with a reference case. The reference case represents the same or essentially similar project when it is realized with no particular attention to energy efficiency. This is necessary as we are measuring the value of energy *saved* and emissions *avoided*. These are defined as the difference in values between the reference case and the case being studied. It is not expected that this reference case should be modelled in detail. Rather, average levels applicable to the local conditions can be used.

As in the DGC method both energy and costs are discounted, the selected discount rate has importance. The discount rate can be set here, being actually the only adjustable parameter. The same discount factor is used both for discounting the costs and outcomes. The value for the discount rate should reflect the investor's expected return from the best alternative investment. The rate is a real rate, meaning after inflation. In accordance with the recommendation from US NREL (Short et al., 1995) when knowledge of a specific investor is unavailable the default rate is set at 10%. Because a real rate is used for discounting, the currency unit should be the first project year's currency. It should be noted that while for this example we have decided to follow the recommendation of US NREL for the interest rate, the tool does allow setting any interest rate deemed proper by the user. This matter is discussed in more length in the discussion section of this paper.

As a result the tool yields the DGC, according to Equation 4, for energy saved meaning how much money was spent in terms of NPV per kWh saved. Additionally, the tool also produces totals for energy savings and the net present value of the investment costs.

2.3. Case building and scenarios

A cost effectiveness calculation was conducted using the VTT-CEA tool to demonstrate its use on a case building. While this example presents a new building, a similar calculation could as well be conducted for a renovation or a retrofit that aims to improve energy efficiency. The case building is a typical new apartment building in New Borg el Arab City in Alexandria, Egypt. The case building is studied in three scenarios:

- Business as usual (BAU), the building is constructed following typical current construction practices in the area,
- Low investment scenario (LIS), the building is constructed including a number of selected low-investment energy efficiency measures,
- High investment scenario (HIS), the building is constructed to be close to a zero-energy building.

The case building and the scenarios are based on the technical analysis conducted by the authors in a previous article (Reda et al., 2015). The building was modelled under the different scenarios using TRNSYS3d to acquire the energy consumption figures used in this paper. For a full technical description of the studied case building the reader is referred to Reda et al. (2015). Here a brief summary of some of the most relevant main points is given.

The case building is a four-storey building, each floor having one apartment of 114 m². It is presented in Figure 2, (a) for BAU and (b) for LIS and HIS. Since people in Egypt tend to use decentralized energy systems, each household has its own energy system in the apartment and on a dedicated area on the rooftop.

In the simulations the indoor air temperature of all the apartments was kept at 26 °C during the cooling months and at 20 °C during the heating months. The energy assessment includes both heating, from November to March, and cooling, from June to September.

Occupant behaviour was considered in (Reda et al., 2015) based on the findings of an occupant survey conducted in New Borg el Arab City. This pertains to natural ventilation and domestic hot water use and is included in the modelled energy consumption figures. The results of the survey showed that occupants open the windows if the external temperature is less than the internal one, therefore allowing free-cooling. This control strategy has been implemented in the BAU based on room occupancy. On the other hand, in the others scenarios free cooling is allowed regardless of room occupancy implying a control system. People, appliance and lightings contribute to the internal loads. People and appliances were modelled based on the occupancy schedule, while lighting has its own schedule based on the time of the day. Also shown by the survey was that currently people in Egypt use mostly energy saving fluorescent bulbs, thus they have been included in the BAU scenario.

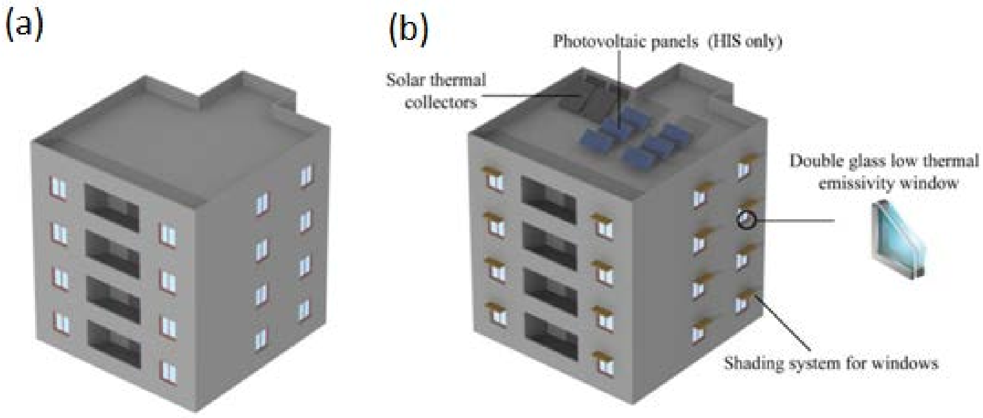


Figure 2. View of the geometry and external features of the modelled buildings in (a) BAU and (b) LIS and HIS, with photovoltaic panels only applying to HIS.

A summary of the various technologies included in the different scenarios are shown in Table 1. A detailed technical description of the case building can be found in Reda et al. (2015). For items priced in Egyptian pounds, the conversion rate of 7.15 EGP for 1 USD from 1 January 2015 was used (Bloomberg 2015). Here only technical systems that are different between the two cases are listed, otherwise the buildings are the same. The BAU scenario is based on the minimum requirements of the Egyptian energy code, while the LIS was designed to include only simple and affordable energy efficiency measures. Shading systems have been added to the windows, reflective paint to the rooftop, the envelope is better insulated and there is a solar collector system for domestic hot water.

HIS scenario is based on LIS but adds LED lighting, double glazed windows, a more efficient solar collector for domestic hot water and, most importantly, a photovoltaic system including batteries for producing electricity onsite. Although at the present cost of batteries this is likely to reduce the profitability of the system, this alternative was also calculated as Egypt suffers from blackouts due to peaks in electricity demand. Battery systems can help reduce the peakiness of electricity demand as well as provide reserve power during blackouts.

Table 1. List of technologies in the LIS and HIS scenarios and BAU including price and replacement interval estimates used in the calculation. Numbers are given per apartment.

	System name	Investment cost (USD)	Interval for replacing the system (years)	Reference
BAU	Double red brick wall with an air gap	4914	-	(Egyptian Ministry of Housing 2014a)
	Windows	1033	20	(Fiorito 2015)
	Fluorescent lights (30)	105	10	(Alliance to save energy 2011)
	Advanced fan coils (13) for air circulation	2080	20	(Alibaba 2014a)
	Regular hot water storage tank	1500	20	(Alibaba 2014b)
	Total	9614		
LIS	Insulated building envelope	6037	-	(Egyptian Ministry of Housing 2014b)
	External reflective paint	488	10	(Egyptian Ministry of Housing 2014c)
	Shading system for windows	420	20	(Egyptian Ministry of Housing 2014d)
	Windows	1033	20	(Fiorito 2015)
	Fluorescent lights (30)	105	10	(Alliance to save energy 2011)
	Free flow vents and advanced fan coils (8)	1780	20	(Alibaba 2014a)
	Efficient hot water storage tank	1900	20	(Alibaba 2014c)
	Unglazed solar thermal collector system	720	20	(Alibaba 2015)
	Total	12483		
HIS	Insulated building envelope	6037	-	(Egyptian Ministry of Housing 2014a)
	External reflective paint	488	10	(Egyptian Ministry of Housing 2014a)
	Shading system for windows	420	20	(Egyptian Ministry of Housing 2014a)
	Double glass low thermal emissivity windows	2952	20	(Albiz 2014)
	LEDs (30)	200	20	(Elwatan News 2015)
	Free flow vents and advanced fan coils (8)	1780	20	(Alibaba 2014a)
	Photovoltaic panels (18)	3960	20	(Alibaba 2014b)
	Inverter	277	10	(Om Solarlab 2015)
	Batteries (36)	9544	10	(GWL Power 2015)
	Efficient hot water storage tank	1900	20	(Egyptian Ministry of Housing 2014b)
	Glazed solar thermal collector system	990	20	(Alibaba 2014d)
	Total	28548		

Energy performance of the three PV system sizes was assessed (Reda et al., 2015). For this study the middle-sized system of those three is selected as the technical analysis showed it to be closest to the aim of achieving a net zero-energy building. The whole PV system consists of PV modules, a set of batteries and a maximum power point tracking (MPPT) inverter. The PV modules charge the battery through the MPPT and the batteries supply electricity to the loads through the inverter. The tilt angle of the PV modules has been set at 20° in order to optimize them for summer use. There are 9 strings of 2 modules, total 18, with the modules having a surface area of 1.65 m^2 each. The PV modules are placed on the rooftop so that they can without casting shadows or obstructing service access to each other provide energy to the apartments of the building according to the calculation presented here.

Energy modelling (Reda et al., 2015) gave an annual electricity consumption of 4750 kWh for each apartment in BAU and 3043 kWh in LIS. In HIS the use of PV generated electricity allows reducing net energy consumption down to 114 kWh, thus coming very close to a zero energy building.

From the point of view of the CEA calculation, the BAU scenario serves as the reference case, DGC being calculated for LIS and HIS. Table 1 gives the cost estimates used for the CEA calculation as well as the intervals for system replacements per apartment. Additionally it is assumed that in LIS on average one work day annually is used by an unskilled worker cleaning the rooftop systems and one workday by skilled professionals, such as an electrician, on system check-ups, totalling 40 USD/a using typical local costs. For HIS the amount of work is assumed to be doubled because of the addition of the PV system. The calculation is made with a 10% discount rate for 1 year of investments and 50 years of operating, maintenance and replacement costs.

3. Results

A calculation tool for cost-effectiveness assessment of energy efficiency measures in buildings was developed that adapts the dynamic generation cost method for use in energy efficiency investments in buildings. To provide a demonstration of the method in use, a calculation concerning a case building in Egypt was conducted. This calculation, based on the building model (Reda et al., 2015), provides an estimation of the economic soundness of the energy efficiency investments considered in the two scenarios analysed. The scenarios considered were LIS for low investment solutions and HIS for high investment solutions, aiming for the zero energy building level. Additionally a BAU scenario was calculated to provide the reference of a conventionally constructed building. The results of the calculations are presented in Table 2, the key result being the dynamic generation cost for energy saved, 0.26 USD/kWh in LIS and 0.60 USD/kWh in HIS, using cost data from Table 1.

Table 2. Summary of the results for the three scenarios studied.

Scenario	Investment cost (USD)*	NPV of all costs (USD)*	Total energy saved over 50 years (kWh)	Discounted total energy saved (kWh)	DGC for energy saved (USD/kWh)
BAU	9 614	10 347			
LIS	12 483	14 672	85 365	16 928	0.26
HIS	28 548	37 903	231 810	45 967	0.60

*Note: Includes only cost items different between the scenarios, see Table1.

4. Discussion

The dynamic generation cost method is sometimes questioned for discounting the effect E_n in Equation 4. As was stated, despite the discounting, the outcomes are not monetised, but are expressed in physical units. This is a source of discomfort for some. Our interest is in energy and emissions. If we measure the effect E_n in terms of energy or CO_2 emissions, how should we interpret a discounted E_n? Is it sensible at all to say that energy consumed or conserved in the future has a lesser amount of kWh's than the same amount of energy consumed today?

People nowadays generally accept with ease the implication of the time value theory for money that sums of money in the future are worth less than sums of money at present. The same is hardly true for non-monetary effects. So far it has been uncommon to discount energy and emissions but life-saving has been discounted in medical CEA for a long time now, at first with considerable resistance (see e.g., Roth et al. 1978).

It turns out that the most compelling case for discounting non-monetary effects comes from not what happens when it is done, but rather from when it is not. As Keeler and Cretin (1982) showed, health benefits, while non-monetary in nature, span over time (i.e., years spent healthy, ill or dead) and are therefore very sensitive to time value considerations. Here a reasoning similar to theirs is presented in the context of reduced CO_2 emissions.

To demonstrate the merits of DGC over the alternative methods, let us assume the following two hypothetical projects with the aim of reducing CO_2 emissions. Both projects have the same costs that are accrued over the same period of time and both projects avoid the emission of the exact same amount of CO_2. The only difference is that project 1 achieves the emission reductions evenly distributed over the next ten years, while project 2 achieves the reductions all at once at project year 10.

It can be deduced that from these two alternatives project 1 is more desirable: in project 1 some of the adverse effects taking place during project years 1–9 can be avoided and, moreover, due to the uncertainty of future developments project 2 could fail or be cancelled before its effects take place. Same is true for project 1, but then at least some positive effects would have cumulated. A rational decision maker would therefore prefer project 1 over project 2. However, from the methods discussed in method selection, UIC and UAC show these two projects to be equally desirable. Hence, a more accurate measure of cost-effectiveness should account for the distribution of the environmental effect over time, as DGC does.

It is true that the simplest explanation of time value based on money saved accumulating interest does not apply to non-monetary benefits. However, the true question is why are people prepared to pay interest for money in the first place. The example above shows that the reasons for discounting non-monetary effects, such as energy saved or emissions avoided are largely similar to those for discounting money (see e.g., NOAA 2011). These reasons include the following:

- Option value: Energy conservation achieved earlier rather than later allows the use of that energy resource to alternative purposes or not using it at all at a prior point in time.
- Uncertainty: As the future is unknown, some unexpected event may prevent the desired outcomes from materializing in the future, and the likelihood of such an event taking place grows as time goes by.
- Decreasing marginal utility: If we assume economic growth in future, positive effects (and avoided negative effects) have greater subjective value earlier as the society and people on

average are less affluent in the present than in the future, due to decreasing marginal utility of wealth.

- Preference: Humans simply tend to prefer near-term benefits to those that are distant in future.

Moreover, when there is a time component to the effect sought (such as years of lesser climate change, years of less polluted air, years lived healthy etc.), it is intrinsically more beneficial to have the effect earlier than later as that increases the total amount of that effect accrued. To overlook discounting is to overlook all these factors and, in fact, provides a distorted picture of true costs and benefits for all the reasons explained here.

Finally, there is the matter of choosing both discount rates. Even choosing one for monetary discounting is seldom clear cut. Here, the predicament seems to be doubled. However, Keeler and Cretin (1982) have demonstrated that non-monetary benefits and money should be treated with the same discount rate to avoid irrational results. In particular, Keeler and Cretin showed that with divergent discount rates neutrality of comparing investments over different time is lost so that similar investments in the future appear less or more attractive compared to present investments even if the particulars of the investments are the same. Thus using the same discount rate for non-monetary benefits as for money within a certain CEA calculation is recommended as long as there are no well-founded reasons to choose otherwise. In the example presented in this paper this recommendation is followed. In principle CEA calculations can also be done with differing discount rates if so needed.

Selecting a figure for the discount rate is particularly challenging in the residential sector, as the circumstances of each household can vary significantly. Short et al. (1995) have reported empirical observations of implicit discount rates as high as 25% and 39% for energy efficiency investments in the residential sector. Generally, the discount rates appear to be much higher than the cost of capital. Possible explanations include uncertainties in the investments, shortness of residency periods compared to investment periods, limits in income and availability of capital and noneconomic factors. Generally speaking the question of selecting the proper discount rate is far from solved but, as it is not within the scope of this paper, the recommendation of US DOE is followed, namely using the 10% rate as a satisfactory default for the residential sector (Short et al., 1995).

5. Conclusions

A case building was studied using the suggested CEA method to demonstrate its usefulness in the appraisal of energy efficiency investments in buildings. In the case building studied the low investment scenario had a cost of 0.26 USD/kWh for energy saved, whereas in the high investment scenario the cost was 0.60 USD/kWh. However, electricity prices in Egypt are heavily subsidised and Bloomberg (2017) estimates that the level of price distortions in consumer electricity markets are high. This artificially low level of energy prices means that the costs of the scenarios do not compare favourably with energy prices. The average consumer price for electricity in 2018 in Egypt was 0.03 USD/kWh (EIPR 2018). It would therefore appear that the two combinations of energy efficiency measures studied are not at present economically sensible from a pure investment calculation perspective. However, further cuts in subsidies are expected, which is likely to affect this conclusion.

To compare, in EU countries the average electricity price was 0.23 USD/kWh in 2018 (Eurostat 2018), which comes close to profitability for LIS. Out of EU countries, electricity prices in Denmark, Germany, Belgium, Spain and Ireland, would suffice to make LIS profitable (Eurostat 2018). Especially in the listed southern European countries solar irradiation levels and climatic conditions are quite similar to the location considered. It should be noted that the European example is only offered here to demonstrate what energy prices might become if subsidies are phased out in Egypt. The opposite is not inferred, meaning that these CEA calculations for the building investments are obviously not applicable to Europe due to different cost levels and building practices.

The cost level of 0.60 in HIS is high but not unreasonable considering that the measures achieve a near zero energy building level. Especially in rural areas similarly designed buildings could be studied as an alternative to electrification with a grid connection. Also, one should bear in mind that the price includes a battery system which provides the consumer energy security in a country where blackouts are not uncommon especially in the summer. The value of this service could be taken into account in a more thorough calculation, considering for instance the fact that Egyptian shopkeepers often have small-scale diesel generators in reserve. Moreover, a recent study by Nykvist and Nilson (2015) showed that battery prices have declined approximately 14% annually between 2007 and 2014. Combined with the decline in PV module prices (Feldman et al., 2012), the price of technology used in HIS can be expected to drop in the near future. Finally it should be said, concerning both LIS and HIS, that the positive effects of reduced pollution, climatic effects and consumption of non-renewable resources may indeed justify the somewhat higher cost.

The case example presented here highlights the usefulness of the CEA method in comparing the costs and benefits of energy efficiency investments in buildings. The main benefit is that it produces as an end result a single number, price of energy saved, that is understandable and concentrates to the essential issue: the cost of achieving the desired results. As it represents unit cost for energy, it can be easily compared with other alternatives as well, such as electricity prices in the grid or a renewable energy alternative, as is done in the studied case by including a PV system. It also allows follow-ups on the project by comparing the values during the planning and operation of the project. The data needed for calculating it is not markedly dissimilar from the data needed for regular project budgeting and would, therefore, mostly be collected in any case. CEA can accommodate an arbitrarily long project life-span and it includes discounting, therefore accounting for risk and avoiding common problems with many presently used appraisal methods. Finally, CEA removes the major source of uncertainty in the assessment of energy efficiency, namely future energy prices, because energy is measured in native units rather than money. These qualities would seem to allow the CEA method to solve a number of presently commonly faced problems in appraising energy efficiency investments in buildings.

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Conflict of interest

The authors declare no conflict of interest.

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