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Including future climate induced cost when assessing building refurbishment performance

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A B S T R A C T

Improving energy efficiency in the existing buildings stock is essential to limit climate change and the economic assessment of measures are traditionally only based on the reduction of energy costs. However, future financial benefits of limiting climate change are rarely included in the evaluation of refurbishment investments. Although, the costs associated with global warming are expected to be extensive. This study introduces a method for the financial evaluation of energy efficiency investments that merge the reduction of life cycle energy costs with the reduction of future climate induced costs. A case study is used to exemplify the method. The case study shows that when reduced future costs due to mitigated life cycle greenhouse gas emissions are included in the analysis, the ranking between different measures can change and traditionally non-profitable measures may become financially sound investments. The introduced Economy+ indicator is shown to be an accessible performance measure to assess building refurbishment and may also be used in the design stage of new construction.

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1. Introduction

Improving energy efficiency in the existing buildings stock is essential to limit climate change [1,2] and can successfully be achieved through cost effective refurbishment investments. Refurbishment options are commonly evaluated based on operational energy reduction and the financial benefit thereof [3,4]. Awareness of the environmental impact of energy use has given rise to the increasingly common inclusion of Greenhouse Gas emissions (GHGe) as a parameter in the refurbishment evaluation [5–7]. The financial benefits of limiting climate change because of improved building energy efficiency is, however, rarely included in the evaluation.

For climate change impacts, the long-term nature of the problem is the key issue. There are social, environmental and economic advantages to limiting global warming. In a study by Warren et al. the costs associated with rectifying the consequences of global warming to the level of 1.5 °C, 2.0 °C and 3.66 °C until the end of this century is estimated to 48, 61 and 485 T€, respectively [8].

Clinch et al. early provided a publication to the field of climate economic assessment of energy efficiency investments [9]. By estimating the monetary value of 1 tonne GHGe and apply multiple climate impact discount rates, Clinch et al. presents a cost-benefit analysis of an Irish domestic energy-efficiency program [9]. Several studies have applied similar cost-benefit analyses on energy efficiency investments in buildings [10–12]. However, only Kneifel et al. [10] makes an attempt to avoid the unilateral focus on operational energy and GHGe by applying a life cycle perspective to the analysis. Energy use and GHGe are assessed from a life cycle perspective but the study does not include future damage cost of embodied GHGe. Thus, the life cycle approach is not complete, which opens up for a study on the financial performance of limiting climate impact through building refurbishment, where both embodied and operational energy use and GHGe are included.

The reviewed literature [9–12] analyze financial benefits of reducing operational energy and GHGe separately. However, future cost of global warming can become very extensive unless efforts are made to limit GHGe today. Thus, the reduced future costs should to some degree be included in the overall financial analysis of building refurbishment. This study introduces a method for the financial evaluation of building refurbishment that merge the reduction of life cycle energy use with the reduction of

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Abbreviations: GHGe, Greenhouse gas emissions; ROI, Return on investment; AY, Annual yield; EROI, Energy return on investment; NER, Net energy ratio; I, Investment; OS, Operational saving; IH, Investment horizon; TSL, Technical service life; EP, Energy price; EPC, Energy price change; EF, Emission factor; EFC, Emission factor change; DC, Damage cost; FC, Future cost; DR, Discount rate; HFA, Heated floor area; BIPV, Building integrated photovoltaics; EPD, Environmental product declarations.

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future costs due to mitigated GHGe and thus decreased climate-introduced damages.

The impact from the inclusion of future damage costs, on the evaluation of different measures are exemplified by a case study. Two refurbished residential buildings in Sweden, built during the million homes program (1965–1974) [13], will be analyzed. The buildings were refurbished with standard packages of refurbishment measures, but with different energy performance level targets, building #1 aimed for passive house standard and building #2 for 50% total energy use reduction.

2. Method

Return on Investment (ROI) and Annual Yield (AY) are used as performance measures to indicate life cycle energy use, GHGe and economic performance of building refurbishment investments. ROI is sometimes used to assess life cycle energy performance of building refurbishment, more commonly paraphrased as Energy Return on Investment (EROI) or Net Energy Ratio (NER) [14–17]. ROI and AY are chosen as performance measures since they are familiar to the construction industry, which may make the building life cycle results more accessible for the industry [18,19].

As an outcome of the refurbishments there will be, due to the investment (I), annual operational changes in terms of energy, GHGe costs (Economy). In the here presented analysis the annual Operational Saving (OS) is summed up over an Investment Horizon (IH) that equals the Technical Service Life (TSL) of the refurbishment measure with the shortest TSL and ROI and AY are thus calculated according to Eqs. (1) and (2):

$$\text{ROI} = \frac{\sum_{i=1}^{IH} \text{OS}_{\text{Energy}}} {I} \cdot \text{Energy, GHGe, Economy}$$  \hspace{1cm} (1)

$$\text{AY} = (\text{ROI}^{\text{IH}}) \cdot \text{Energy, GHGe, Economy}$$  \hspace{1cm} (2)

If the IH would be chosen longer than the shortest TSL, a reinvestment would have to take place and Eqs. (1) and (2) has to be modified accordingly.

The annual operational savings in GHGe and costs are caused by the reduced energy use, thus

$$\text{OS}_{\text{Economy}} = \text{OS}_{\text{Energy}} \times EP \times (1 + EFC)^{\text{IH}}$$  \hspace{1cm} (3)

$$\text{OS}_{\text{GHGe}} = \text{OS}_{\text{Energy}} \times EF \times (1 + EFC)^{\text{IH}}$$  \hspace{1cm} (4)

Where EP and EFC is the energy price and energy price change, respectively, and EF are the emission factors in terms of GHGe and EFC represents any changes in the emission factor due to changes in the energy mix.

The financial benefits of GHGe mitigation because of improved building energy efficiency can be assessed by valuing the damage of climate impact. The discounted present value of future climate impact, called Damage Cost (DC), is seldom included in the evaluation of suitable refurbishment investment. The economic gain of the investment based on the reduction of Future Costs (FC) is given by Eq. (5).

$$\text{ROI}_\text{FC} = \frac{\sum_{i=1}^{IH} \text{OS}_{\text{GHGe}} (1 + DR)^{\text{IH} - i}} {\text{DC} \times I_{\text{GHGe}}}$$

$$= \frac{\sum_{i=1}^{IH} \text{OS}_{\text{GHGe}} (1 + DR)^{\text{IH} - i}} {I_{\text{GHGe}}}$$  \hspace{1cm} (5)

As shown in Eq. (5) the discount rate is the influencing factor for ROI\(_\text{FC}\). Future damage costs of climate impact are challenging to estimate and appropriate discount rates to value the cost of climate change damage have been debated for decades [2]. Stern et al. argues for a Discount Rate (DR) in the range of 0–1.5% [20] while Nordhaus et al. reasons for a DR in the range of 3–5% [21]. The arguments for a higher DR, in the range of 3–5%, are that people’s actual everyday market behavior, i.e. prevailing market interest rates, should determine the DR. Thus, future GHGe mitigations are valued higher than reductions today and allows scope for economic growth. Advocates for a lower DR, in the range of 0–1.5%, values present GHGe reductions higher and include estimates of the value of social welfare of future generations into the discount rate [22]. The actual value of climate change damage, however remains a matter of disagreement, but the case for anything more than a very low DR is hard to make [23].

Refurbishment investments influence both life cycle energy use and GHGe. Therefore, both the financial benefits of reduced energy use and reduced climate induced damages should be included in the economic performance assessment. In Eq. (6), ROI are presented for situations when both the reduced cost of energy use and reduced future cost due to GHGe mitigation is considered, referred to as ROI\(_\text{Economy}\).

$$\text{ROI}_{\text{Economy}} = \frac{\sum_{i=1}^{IH} (\text{OS}_{\text{Economy}}) + (\text{DC} \times \text{OS}_{\text{GHGe}} (1 + DR)^{\text{IH} - i})} {\text{I}_{\text{Economy}} + (\text{DC} \times I_{\text{GHGe}})}$$  \hspace{1cm} (6)

3. Case buildings

The case buildings that will be studied in this paper are Passive house Stacken (building #1) [24,25], located in the city of Gothenburg in Sweden and Sustainable Alidhem (building #2) [18,26], located in the city of Umeå in Sweden. Gothenburg is positioned 1 370 km south of the Arctic Circle in Marine West Coast Climate (Cb) according to Köppen Climate Classification and Umeå is located 455 km south of the Arctic Circle in Continental Subarctic Climate (Dfc) according to Köppen. Both buildings were built during the million homes program (1965–1974) in Sweden [13] and has a typical design of that time period. The buildings were refurbished with an outspoken sustainability agenda, building #1 with a passive house standard target and building #2 with the aim to reduce total energy use by 50%. The space heating demand are estimated for the floor area that are heated to 10°C or above, called Heated Floor Area (HFA). The estimated space heating demand are 20 kWh/(m² HFA) and 72.2 kWh/(m² HFA) for building #1 and #2, respectively. More information about step-by-step refurbishment process and building design can be found in previous studies on the refurbishment of the buildings [18,19,24–26].

Comparable investments in refurbishment measures has been performed in both building #1 and #2. In addition to the refurbishment measures, investments have been done in Building Integrated Photovoltaics (BIPV) for both buildings. Table 1 shows the properties, including TSL, weight or area, specific embodied energy use and GHGe, i.e. the investment cost, for the refurbishment measures and installed BIPV in building #1 and #2. The estimated embodied energy use and GHGe include Product phase (A1–A3) and Maintenance phase (B2) [27] and are based on gathered data from various open access Environmental Product Declarations (EPD) and scientific literature, all referenced in Table 1. The weight and area has been estimated based on blue prints.

The studied IH for the refurbishment investments are 20 years, since that is the shortest TSL of the studied refurbishment investments, see Table 1. The IH for the BIPV are 30 years.

For the economic performance assessment, the building owners provided information about total investment cost, including life cycle phases A1–A5 [37], for the refurbishment measures and BIPV. Building #1 had an investment cost of about 1115 kEUR and building #2 had an investment cost of about 754 kEUR. To distinguish the BIPV cost from the total investment cost, the BIPV investment cost is estimated based on PV watt peak capacity (Wp) [32]. The investment cost per Wp is estimated to 4.2 EUR/Wp for BIPV produced in Asia [38]. This results in an estimated investment cost of
Table 1

Properties of the refurbishment measures and installed BIPV for building #1 and #2. Technical Service Life (TSL), weight in tonne (t) or area in square meter (m²), embodied energy and GHGe.

| TSL | Unit Weight or Area | Embodied Energy [GJ/Unit] | Embodied GHGe [tCO₂-eq/Unit] |
|-----|---------------------|---------------------------|-------------------------------|
|     | #1                 | #2                        | #1                           | #2                           |
| MVHR | 20°                | 0.914 t                   | 0.691 t                      | 34°                          | 34°                          | 1.9°                          | 1.9°                          |
| Attic insulation | 60°                | 330 m²                    | 256 m²                       | 0.07°                        | 0.25°                        | 0.02°                         | 0.008°                        |
| Windows | 60°                | 470 m²                    | 114 m²                       | 2.1°                         | 1.9°                         | 0.12°                         | 0.07°                         |
| Façade insulation | 60°*               | 1600 m²                   | 546 m²                       | 0.32°                        | 0.53°                        | 0.02°                         | 0.003°                        |
| Roof BIPV (multi-si) | 30°†              | 330 m²                    | 55 m²                        | 3.0°                         | 3.0°                         | 0.17°                         | 0.17°                         |
| Roof BIPV (CIGS thin film) | 30°*              | 70 m²                     |                                | 2.3°                         | 2.3°                         | 0.13°                         | 0.13°                         |
| Façade BIPV (a-Si thin film) | 30°†              | 1500 m²                   |                                | 2.0°                         | 2.0°                         | 0.12°                         | 0.12°                         |

* [28].
† [29].
‡ [30].
§ [31].
|| [32, 33].
|| [34].
|| [35].
|| [36].

Table 2

Annual operational energy and GHGe saving and energy, GHGe and economic investment cost for the refurbishment of building #1 and #2, calculated per HFA. Building #1 has a HFA of 3186 m² and building #2 of 872 m².

|       | OS₆Energy [GJ year⁻¹ HFA⁻¹] | OS₆GHGe [tCO₂-eq year⁻¹ HFA⁻¹] | ₆Energy [GJ HFA⁻¹] | ₆GHGe [tCO₂-eq HFA⁻¹] | ₆Economy [EUR HFA⁻¹] |
|-------|-----------------------------|---------------------------------|-------------------|------------------------|----------------------|
| Building #1 | 0.41                       | 0.021                           | 0.49              | 0.025                  | 0.15                 |
| Building #2 | 0.46                       | 0.025                           | 0.68              | 0.015                  | 0.79                 |

Table 3

Annual operational energy and GHGe saving and energy, GHGe and economic investment cost for the BIPV of building #1 and #2, calculated per m² BIPV.

|       | OS₆Energy [GJ year⁻¹ m⁻²] | OS₆GHGe [tCO₂-eq year⁻¹ m⁻²] | ₆Energy [GJ m⁻²] | ₆GHGe [tCO₂-eq m⁻²] | ₆Economy [EUR m⁻²] |
|-------|---------------------------|---------------------------------|-------------------|------------------------|----------------------|
| BIPV #1 | 0.23                      | 0.028                           | 2.2               | 0.13                   | 0.36                 |
| BIPV #2 | 0.30                      | 0.036                           | 2.6               | 0.15                   | 0.63                 |

643 kEUR and 67 kEUR in BIPV for building #1 and #2, respectively. Thus, the refurbishment investment cost is estimated to 472 kEUR and 687 kEUR for building #1 and #2, respectively. Twenty years of maintenance cost (B2) for the refurbishment is estimated to totally 5 kEUR for both building #1 and #2. This is based on assumed maintenance requirements of 0.25 kEUR/year for changing filters every six months in the MVHR [28]. The total maintenance cost for the BIPV is estimated to 41 kEUR and 3 kEUR over 30 years for building #1 and #2, respectively. This is based on assumed maintenance requirements of BIPV module checks by technicians annually and cleaning of BIPV modules [33] at a man-hour cost of 0.09 kEUR/hour. It is assumed that it is required 15 min per square meter to check and clean the BIPV module.

Table 2 shows the annual operational saving in energy and GHGe together with the total energy, GHGe and economic investment. The estimated annual operational energy saving is based on monitored and simulated values over time [25,26] and are assumed to stay constant over the studied IH. Thus, changes in heating and/or cooling requirements coupled with changes in climate are not considered. Emission factors and district heating prices are collected from the 2018 energy statistics of Swedenergy, a non-profit industry and special interest organization for companies involved in the supply, distribution, selling and storage of energy, mainly electricity, heating, and cooling [39]. Both the city of Gothenburg and Umeå get their district heating supply from the local CHP plant with an emission factor of 0.052 kg CO₂/MJ and 0.055 kg CO₂/MJ, respectively. The district heating price is assumed 0.020 EUR/MJ and 0.021 EUR/MJ for building #1 and #2, respectively.

Table 3 shows the BIPV energy, GHGe and economic investment together with annual operational saving in energy and GHGe. Investments in BIPV will reduce purchased electricity. The electricity prize is assumed 0.01 EUR/MJ, which is based on the mean electricity price of the Nord Pool statistics from 2018 [40]. The change in purchased electricity is assumed to affect the marginal, defined as natural gas. The emission factor for purchased electricity is assumed 0.122 kg CO₂/MJ [41].

The damage cost per tonne CO₂-eq are estimated based on the Warren et al. projected cost associated with rectifying the consequences of global warming to 1.5 °C, 2.0 °C and 3.6 °C until the end of this century which is estimated to 48, 61 and 485 T€, respectively [8]. This corresponds to estimate GHGe over the coming 80 years of about 430, 700 and 1500 Gtonne CO₂-eq for the 1.5 °C, 2.0 °C and 3.6 °C global warming scenarios, respectively, modeled with the bioclimatic MaxEnt modeling approach [42]. In Table 4 the estimated present damage cost in 2020 per tonne CO₂-eq are presented for 0.3, 1.5 and 3% discount rate.

4. Result and discussion

In this section, building refurbishment Life Cycle Assessment (LCA) results will be presented using ROI and AY as performance measures. Traditional life cycle performance indicators, including energy use, GHGe and economic performance, are used. Furthermore, the life cycle assessment will be extended with the introduced Economy+ indicator that considers reduced future damage costs due to mitigated GHGe. The consequence of assessing refurbishment investment based on solely traditional performance indi-
cators or including future climate induced damage costs as a performance indicator will be analyzed.

To enable the performance indicator analysis, two case buildings are studied from a life cycle perspective. In Table 5 the traditional performance indicators, including life cycle energy use, GHGe and economic performance are used to present the LCA result for the refurbishment and installed BIPV on the case buildings. As seen from Table 5, ROI and subsequently AY is fairly high and satisfactory for both energy and GHGe for building #1 and #2. The results for the two buildings are fairly similar except for GHGe, where ROI is much higher for building #2 than for building #1. This is explained by the fact that when striving for very low transmission losses as in building #1, the achieved reduction in operational energy use and thus reduced GHGe decreases with each layer of added insulation whereas the invested GHGe are the same. Thus, there exists a tipping point for embodied GHGe. This tipping point is influenced by geographical location, climate and the local energy mix of the building and therefor varies between different buildings. However, the result in Table 5 shows the significance of including GHGe as a performance indicator to find high performing refurbishment measures.

The economic aspects of energy efficiency measures often weigh heavily in the choice of refurbishment investments. The result in Table 5 show that the economic performance of the refurbishment investment in building #2 is non-profitable with an ROI below one and thus a negative AY. This situation is not even changed at an advantageous EPC of 6%. The refurbishment investment in building #1 is more financially sound with an ROI larger than 1, but requires an EPC of 3% to reach more normal market interest rates (3–5%). Based on these results, only the refurbishment of building #1 can be considered to be a candidate to be a financially sound investment and thus not relying on subsidies or being an investment in good will.

For the investments made in BIPV, the energy, GHGe and financial performance outcome is similar between building #1 and #2. The total BIPV investment were significantly larger for building #1, because PV-cells was not only mounted on the roof but also onto external walls. However, as seen in Table 3 where costs and savings are estimated per square meter installed BIPV, the operational saving and investment cost are quite similar for the two buildings. As seen in Table 5, neither of the BIPV investments reaches financial profit. However, at an EPC of 6% the BIPV #1 investment just breaks even.

Most economic models highlight short-term economic profit before long-term profitable investments. Therefore, it is not surprising that the traditional economic performance assessment of building refurbishment assess the immediate economic profit of the investment. The introduced Economy+ indicator, on the other hand, assess future gains from reduced damage cost of global warming. Table 6 show how the economic performance of the energy efficiency investments shifts when reduction of future climate induced costs are also included in the assessment. All calculations are based on the assumption of an annual energy price increase of 3%, i.e. EPC = 3%. The Economy+ indicator, see Eq. (6), merge the reduction of life cycle energy use with the reduction of future costs due to mitigated GHGe and are estimated for different discount rate and global warming scenarios (DR, global warming scenario). To guide the reader the reduced future costs due to mitigated GHGe for an assumed DR of 1.5%, and the traditional economic performance is also included in the table.

The result in Table 6 show that ROI for FC are considerably larger than for the life cycle energy costs. Thus, when these parameters are merged, the performance shift compared to the traditional economic analysis. The investments with a non-profitable traditional economic performance, i.e. the refurbishment of building #2 and BIPV investments, becomes a financially very sound investments when reduced future costs are included in the assessment. The Economy+ indicator show a ROI and AY well over one and zero percent, respectively, for all assessed discount rates and global warming scenarios.

The global warming scenarios and the estimated damage costs that are used in the present study are collected from a study by Warren et al. [8]. These estimates are based on assumptions about the future, which of course is a rough estimation and other studies may estimate the damage cost differently. Nevertheless, the scientific literature agrees that without actions to reduce climate impact there will be significant future climate induced costs.

By what rate these future climate induced costs should be discounted to their present value is also a matter of disagreement in the scientific community. In the present study, DR are chosen to accommodate the most influential theories within the field. However, the choice of DR will influence the Economy+ performance of the investments. Thus, there is an inherent sensitivity of the results in Table 6, due to the choice of discount rate and future damage cost, as discussed above. However, the result presented in the present study does give an indication about how the inclusion of reduced future climate induced costs influence the economic performance of energy efficiency investments.

Greenhouse gas emissions and climate induced damage cost is a global issue with shared responsibility. Thus, the estimated damage cost used in Table 6 are based on global climate impact estimates. However, as a local building owner, your interest may lay in the local effects of climate impact and the influence of damage cost on your particular company. Since increased global temperatures will influence the local climates differently and consequently the climate induced cost will differ between countries and geographical areas. Therefore, as an incentive for the building owner to include reduced future damage costs in the economic assessment of energy

| Table 4 | Estimated present damage cost in 2020 per tonne CO₂-eq (€/tonne CO₂-eq) for 0.3, 1.5 and 3% discount rate. The estimations are based on projections by Warren et al. [8, 42]. |
|----------|-------------------------------------------------|
| Discount Rate | 1.5°C Global Warming (€/CO₂-eq) | 2.0°C Global Warming (€/CO₂-eq) | 3.66°C Global Warming (€/CO₂-eq) |
| 0.3% | 68 | 87 | 250 |
| 1.5% | 26 | 34 | 96 |
| 3% | 8 | 10 | 30 |

| Table 5 | Traditional life cycle performance indicators for building refurbishment, including energy performance, GHGe performance and economic performance are used to present the LCA result for the refurbishment and installed BIPV on building #1 and #2. The economic performance are estimated for an EPC of 0, 3 and 6%. The investment horizon are 20 years for the refurbishment investment and 30 years for the BIPV. |
|----------|-------------------------------------------------|
| Building #1 | Building #2 | BIPV #1 | BIPV #2 |
| ROI | AY | ROI | AY | ROI | AY | ROI | AY |
| Energy | 17 | 15% | 13 | 14% | 3 | 4% | 3 | 4% |
| GHGe | 17 | 15% | 34 | 19% | 6 | 6% | 7 | 7% |
| Economy (EPC 0%) | 1 | 0% | 0.2 | −7% | 0.2 | −5% | 0.2 | −6% |
| Economy (EPC 3%) | 2 | 3% | 0.4 | −4% | 0.4 | −3% | 0.4 | −3% |
| Economy (EPC 6%) | 3 | 6% | 0.7 | −2% | 1.0 | 0% | 0.9 | −1% |
efficiency investments, the local effects of climate impact may be considered more relatable. Nevertheless, the future costs are only avoided if the responsibility of the GHGe are honored globally.

This study shows that the Economy+ indicator can be used to assess building refurbishment and that it changes the ranking between different measures compared to the traditional energy economic indicator. However, an Economy+ indicator that merge the traditional economic costs with future GHGe costs can also be used at an early design stage of new construction to compare and evaluate different solutions.

5. Conclusion

Refurbishment measures and energy efficiency actions are introduced to reduce energy use which leads to reduced GHGe and economic costs. However, as emphasized in this study, there are also financial benefits of the reduced GHGe, but they are rarely included in the financial evaluation of building refurbishment.

The inclusion of reduced future damage costs due to mitigated GHGe in the economic assessment of building refurbishment influence the investment profitability. Non-profitable energy efficiency investments, according to traditional economic performance assessment that considers only energy use, may become profitable when the assessment is expanded to also consider reduced future costs due to mitigated life cycle GHGe.

There is however an uncertainty in the estimated damage cost which is difficult to estimate, but the results give a clear indication about how the inclusion of reduced future climate induced costs influence the economic performance of energy efficiency investments. The introduced Economy+ indicator shows a viable method to include reduced climate induced costs in the economic assessment of building refurbishment and may also be used in the design stage of new construction.

Declaration of Competing Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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