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Original Research Article

Costs, Energy Savings and Greenhouse Gas Emissions for Energy Efficiency Measures in Existing Detached Houses; A Norwegian Case Study

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ABSTRACT

Energy efficiency measures for existing buildings are some of the most important actions towards reducing energy demand and greenhouse gas emissions in society. Much is known regarding which measures provide the greatest energy savings, but this is rarely put into context with respect to costs and greenhouse gas emissions. This paper summarizes the results from a study comparing energy savings, greenhouse gas emissions and costs for energy efficiency measures in older detached houses. The paper presents and ranks the various energy efficiency measures regarding greenhouse gas emissions, energy savings and costs. The study concludes that the energy efficiency policy for existing buildings has not been successful. The study analyses why and provides recommendations on how the policy can be changed to achieve a greater effect.

KEYWORDS

Energy measures, Costs, Greenhouse gas emissions, Dwelling stock, Simple payback time, Life cycle assessments.

INTRODUCTION

Theory

The urgency to mitigate climate change has led to a global focus on reducing greenhouse gas (GHG) emissions and thus energy consumption. Furthermore, the Intergovernmental Panel for Climate Change (IPCC) emphasizes that reductions in energy demand can increase energy

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security and reduce the need for raw materials and land in the energy transition [1]. One strategy to reduce energy demand is through improving energy efficiency, i.e., reducing the amount of energy needed per unit of goods or services produced [2] . For most European countries the building sector accounts for a significant portion of total energy use and GHG emissions. Refurbishing existing buildings with energy efficiency measures is widely regarded as a crucial step towards achieving national and international climate goals[3] .
The reduction of heating energy consumption and the mitigation of GHG emissions in the building sector have been an ongoing quest, especially in countries where fossil fuel derived electricity or fossil fuels are used as the main heating solution in buildings. Numerous regulations are directed at increasing the building energy performance of existing buildings, however, there is a gap in the practical implementation of such regulations, especially in developing countries[4].

Several review articles present the status of life-cycle assessment (LCA) literature which compare various energy efficiency measures and associated GHG emissions . The most recent and comprehensive of these performed a scoping review resulting in 54 articles published between 2005 and 2022—which were then thoroughly reviewed and compared [5]. Their findings point to the majority of articles being of regional- or national case studies of specific building archetypes, typically age cohorts, covering product through construction plus operational energy respectively (A1–A5 + B6), with a lifespan of 50 years. Several studies used Environmental Product Declaration (EPD) data, towards determining GWP (96%), though few (38%) combined these results with building costs—with the authors citing this as a weakness [6].In a study of optimal energy performance packages at the lowest cost during the estimated economic lifecycle for a residential building located in three different locations in the Mediterranean climate, it was found that the optimum energy savings at the lowest cost are 23-39%. The study concludes that climatic characteristics is a very important parameter affecting the reference building definition procedure. Further, the methodology is highly sensitivity to national factors and utility rates and slightly sensitive to the discount rates, cost calculation period, and development price [6].

Since the Kyoto Protocol was adopted in 1997, international work has been conducted to identify the most environmentally- and cos- effective measures enabling European countries to meet their evolving targets on reductions in both energy demand and GHG emissions [7]. The Kyoto Pyramid was developed as a strategy for the design of low-energy buildings in Norway and has also served as a framework for energy demand reduction strategies for existing buildings. The key point of the Kyoto Pyramid is that one should start by reducing heat loss and thus heating demand, followed by reducing energy demand from appliances through energy-efficiency, before addressing the heating solution and overall energy supply [8]. The research field on energy efficiency measures for buildings has been developed over several decades and evolved from focusing on a measure's effect on energy demand to broader scopes looking at cost, payback time and lately also GHG emissions related to the measure and its estimated energy savings. However, most existing studies include only two of these aspects in their analysis. The European Energy Performance of Buildings Directive (EPBD) requires that building codes are based upon a cost-efficiency approach. And because the requirements are driven by cost, there is no inherent balance between the GWP of the energy saved and the GWP investment in the measures that impact energy use [9]. The selection of cost-effective components of the building envelope plays a significant role in a sustainable building design solution. Therefore, in terms of effective decision-making, it is important to have a complete insight into construction and operating costs throughout the lifespan of the building [10]. In a study of apartment buildings in Norway, a multi- criteria assessment approach is presented where cost, GHG emissions, energy savings, as well as social aspects, are considered for several retrofit measures combined in packages. Such packages are highly relevant for larger buildings where comprehensive renovations are more common because they are more cost-effective, but for small, detached houses in the dwelling stock, such holistic approaches are rarely conducted because of house owners' exclusive ownership and responsibility depending solely on owners' capacity. For these buildings a longitudinal approach is practiced where measures are implemented when an opportunity arises because of maintenance, etc. It is therefore necessary to evaluate individual measures towards developing knowledge on which measures are most relevant to promote for these house owners [11].

In a study of a framework for evaluating the net present global warming potential (GWP) of an energy-saving measure, emissions from materials are weighed against energy savings over a period of 60 years as defined in the Norwegian standard for GHG calculations for buildings, NS 3720:2018 [9] . There are three crucial parameters in these considerations related to; the developments in the energy mix and thus GHG emissions from energy, the carbon footprint of the materials used, and perhaps most importantly, the temporal considerations of the measure. These three parameters do, however, not consider the pressing need to reduce energy demand to limit the need for new energy production which represents economic, environmental, and sociocultural costs. These considerations lie outside the system boundary of the calculations but should be considered. This argues for a more complex evaluation framework, spanning across sectors, that promotes low-carbon materials but favours a maximization of energy savings [9].

Despite the consensus on the importance of these measures, there is a lack of comprehensive analysis that places energy savings in context with both economic costs and GHG emissions. This paper provides an extensive evaluation methodology of energy efficiency measures where potential energy savings, GHG emissions, and related costs for the most prominent measures are presented, aiming to answer the following research questions:

1. How can different energy efficiency measures be weighted based on the measures' costs, energy use reduction and GHG emissions?
2. How should energy efficiency policies change to achieve higher and more realistic energy reduction?

The Norwegian context

The case study presented in this paper analyses energy efficiency measures for detached houses in Norway. Towards developing a better understanding of the case study, and its results, a short description of the Norwegian context is provided next.

Historically, Norway has enjoyed an abundance of energy from hydropower which is considered a renewable energy source. The transition towards a low-carbon society in 2050 entails a shift from fossil fuels to renewable energy sources in all sectors. This transition can ultimately lead to an increase in electricity demand, and Norway is headed for an energy deficit in 2027. Because of hydropower, Norway has had low electricity costs and energy security, leading to building an energy supply consisting of 85% electricity [12]. Buildings account for 40% of the national energy demand, where approximately 60% of this demand is used for heating [12]. The Norwegian building regulations have since the early 2000s sharpened demands for energy-efficient buildings and renewable energy supply, and a ban on oil burners in buildings from 2020 has led to the decarbonization of the operation phase of buildings in Norway. Building regulations have now reached a "nearly zero energy"- level where stricter energy efficiency measures will have to be considered against the increase in materials and their consequences on both the environment and costs [13]. A total of 76.4% of the inhabitants own their dwelling in Norway. It is the individual homeowner who is responsible for the maintenance, adaptation, and upgrading of their dwelling [14]. A market-driven development in the dwelling sector since the 1980s has led to a lack of focus on long-term physical qualities such as energy-efficiency improvements in the dwelling stock [15]. An important challenge in housing policy therefore lies in ensuring the development of the existing housing stock so that the dwellings can satisfy new and future needs [16].

Reducing electricity demand in buildings is crucial for achieving the energy transition whilst limiting the need to establish new energy production that represents economic, environmental, and sociocultural costs [11]. In addition, a properly implemented energy upgrade of residential buildings will provide a better indoor climate and comfort, prolong building life, and reduce energy costs [17]. There have been policies promoting energy efficiency improvements in Norwegian homes ever since the energy crisis in the 1970s, and the new-built housing stock has gradually become more energy efficient [18]. The two most important contributions to this development are the stricter technical regulations for new buildings [19] and the ECO design standard, which together have reduced the energy consumption of domestic technical equipment[20]. Since the early 2000s, there has been a widespread uptake of heat pump solutions in the dwelling stock, partly due to the need for new heating solutions in preparation for the oil ban in 2020, but also motivated by comfort improvements at low cost [21]. These measures have therefore had large rebound effects and do not comply with the logic of the Kyoto Pyramid of reducing the heat loss through building envelope improvements before selecting heating solutions and energy supply. Today the most effective measures for improving energy efficiency in the Norwegian dwelling stock are considered to be insulation of the building envelope and smart control of energy use [19]. These conclusions are made solely on potential reduction of energy demand and have rarely been subjected to cost and LCA-considerations.

METHODS

This study builds upon methodology developed by Almås et al. in 2012 for the Norwegian Building Authority, integrating updated data from 2023 [22] to assess the effectiveness of various energy efficiency measures [23]. The evaluation consists of separate energy, cost and GHG emission calculations and their comparison, regarding the implementation of ten common refurbishment measures for older detached houses in Norway, which account for 48% of the dwellings in Norway [24]. The building model is a virtual detached house in Oslo, Norway. The house has two floors with a total usable area of 160 m2. The building model is built in accordance with the building regulations from 1969, with the corresponding energy technical characteristics. New building regulations were introduced in 1985, so the calculations are representative for detached houses built between 1969 and 1985, and it is assumed that the building has not been subject to major upgrades. In Norway, these houseds total approximately 300,000 buildings (approximately 20% of all detached houses). Detached houses built in this period are identified to have the largest energy-saving potential [25]. Table 1 presents the ten most prominent measures for such a detached house. For the study it is assumed that the house has an energy standard equivalent to the building code under which it was built, and that it is operated according to the Norwegian standard for energy calculations NS 3031 [26]. This assumption makes the calculations theoretical because user behaviour strongly influences energy demand. The calculated energy consumption is 46,400 kWh/year before measures.

Table 1. Refurbishment measures considered in this study

Component	Measure	Key Parameter
Outer wall	Insulating outer wall from outside	160 m^2

	150 mm mineral wool, U-value: 0.18 W/m²K	
Roof	Insulating roof from outside *200 mm mineral wool, U-value: 0.13 W/m²K*	90 m²
Attic	Insulating attic floor *200 mm mineral wool, U-value: 0.13 W/m²K*	80 m²
Floor	Insulating basement floor *Replace concrete, 200mm insulation, U-value: 0.1 W/m²K*	80 m²
Air tightness	Improving air-leakage in the building envelope *Air tightness measures around windows and doors (n50 = 0.6)*	32 m²
Windows	New windows *U-value: 0.8 W/m²K*	32 m²
Ventilation	Installation of balanced ventilation system *Heat exchanger 80%, SFP: 1.5*	160 m²
Water heater	New water heater *50% less energy consumption*	2 kW
Ground heat pump	Installation of water-based heating with heat exchanger *Water-to-water geothermal heat pump incl. installations*	160 m²
Solar PV	Installation of roof mounted solar PV system *26 standard solar panels, 44 m²*	10.7 kWp

Energy Calculations

The energy calculations are performed using the energy simulation programme SIMIEN [27] , which is the most common energy simulation programme used in the building industry in Norway today. SIMIEN is a Norwegian-developed energy calculation programme that has been validated according to EN 15265 and harmonized to NS 3031. The European standard specifies a set of assumptions, requirements and validation tests for procedures used for calculating the annual energy needs for space heating and cooling of a room in a building where the calculations are done with a time step of one hour or less. The programme performs dynamic simulations of energy needs, validates indoor climate, and sizes heating systems, ventilation systems and room cooling. The values applicable to the various technical regulations are applied to the building models in SIMIEN for the various building categories. Simulations are then carried out to obtain a theoretical potential for energy savings. The building models used are the same as those that form the basis of the framework for national energy requirements for buildings in Norway. In the model, the total window/door area makes up 20% of the usable indoor floor area. The model has windows on all facades.

Inputs into the building models are based on the Norwegian building regulations from 1969 (TEK69) and the building model represents a house built according to these requirements and the construction methods of the time. The variables, e.g., U-values (W/m²K), have been calculated thereafter. There were no requirements for air leakage in TEK69. Here, the leakage figure has been chosen after assessments concerning the construction method of the time for the individual building category. For thermal bridge values, standard values from NS3031 Table A.4 have been used, according to the typical construction method for the individual building category. For the solar factor for glass, figures based on expert judgement for the type of glass that is typical for windows that satisfy the U-value requirements of the time are used. For ventilation air volumes, a conversion has been made to what the text of the regulations corresponds to m3/(hm2) based on estimates for the number of rooms that are specially ventilated (kitchen, bathroom, laundry room, etc.) and the size of the building models. Natural ventilation is used for detached houses built according to TEK69. Cooling is not included in any of the calculations. The specific fan power factor (SFP factor) is estimated based on a typical ventilation system. As input data for power and energy requirements for lighting, equipment and hot water, as well as internal heating contribution, , figures from Tables A.1 and A.2 in Norwegian standard NS 3031 are used. These data are fixed in all calculations.

It is important to highlight that the calculated energy savings (kWh) for the various measures and their rankings apply only to ***the first energy measure*** the building owner chooses to implement. Once this measure has been implemented, the effect and ranking of the remaining measures will be affected. New calculations must then be made to find the second-best measure for energy savings, and so on. Costs and GHG emissions for the various measures are independent of this procedure.

Cost Calculations

Costs have been calculated at component level. Figures from similar projects and cost figures from external cost databases, for example "Holte" [28], are used. The total cost for the component is calculated by multiplying the unit price (total including rigging and operation) by the area or volume of the component. This calculation gives the total costs for the measure. The costs shown in the figures and tables are construction costs, including Norwegian VAT. Costs for planning/design are not included. Some of the measure costs are based on numbers from calculations in 2013 [23] adjusted for the consumer price index (increase of 38% from 2013 to 2023). Others are based on cost data from 2023.

Also, a profitability indicator that gives the total cost of a measure divided by the energy saving per year is calculated. A low value indicates the best profitability. This indicator should not be confused with the payback period, although it has similarities in its calculation methodology, though lifetimes are not taken into account. This indicator still gives a picture of which measures pay off the most.

Climate Change Impact Calculations

An environmental life cycle assessment (E-LCA) has been conducted to determine the climate change impact or GWP—measured in kilograms carbon dioxide equivalent (kg CO_2 eq.) for those measures outlined previously in this section (GWP_T), including comparison. This assessment has been conducted in accordance with ISO 14040 series [29] standard and the General Guide for Life Cycle Assessment (ILCD Handbook [30]. A cradle-to-installation assessment was conducted, i.e., emissions and consequent impacts originating during the use- and end-of-life stages are not included. Within the bounds of this paper, decision context A, i.e., micro-level decision support, and subsequent application of attributional life-cycle inventory (LCI) modelling principles have been applied. Furthermore, it was assumed that all foreground processes are uni-functional; information pertaining to the handling of multi-functionality in background processes can be found in their respective resources (Appendix 1). These impact-, method- and assumption-related decisions can limit the interpretation of results.

Primary foreground data constituting the final demand are adopted from previous cost- and energy calculations. Regarding secondary background data and life cycle impact assessment (LCIA), an important distinction has been made between passive- and active building measures. Here, passive measures are defined as those which do not require/produce energy during their use phase, and conversely active measures as those which do require/produce energy during their use phase. For passive measures (i.e., 1-6; see Table 1) secondary-background GWP impact data are based on Environmental Product Declarations (EPD) which have been determined in accordance with EN 15804 ([31]; see Appendix 1). For these passive measures (i.e., 1-6), and because of limitations in scope, emission/sequestration of biogenic CO_2 in wood-based products from cradle-to-installation (A1-A5; [31]) are not included in the results. For active measures (i.e., 7-10; see Table 1) SimaPro v9 and accompanying EcoInvent v3 database were used. For these active measures, GWP was determined using the ReCiPe (H) midpoint method [32]; see Appendix 1).

Additionally, a *simple GWP payback* time calculation was performed using Equation 1.

Equation 1

$$t_{GWP} = \frac{GWP_T}{GWP_{el.} \times E_{TA}} (years)$$

Where:

t_{GWP}	is GWP payback time (years)
GWP_T	is total GWP impact for the measure (kg CO_2 eq.)
E_{TA}	is annual energy savings for the measure (kWh/year)
$GWP_{el.}$	is the GWP intensity of electricity (kg CO_2 eq./kWh)

E_{TA} is adopted from the previous energy calculations. For $GWP_{el.}$ SimaPro v9 and accompanying EcoInvent v3 were applied to determine the GWP intensity per kWh for low-voltage electricity at the consumer level in both Norway and the EU-27, 0.026 kg CO_2 eq./$kWh_{el.}$ and 0.400 kg CO_2 eq./$kWh_{el.}$ respectively.

RESULTS

Table 2 presents the collected results of the energy-, cost- and climate change impact calculations for all measures, including simple payback calculations for cost- and GWP emissions for both Norwegian and EU-27 electricity.

Table 2. Collected energy, cost and climate change impact results, including simple payback time

Component	E_T (kWh/year)	C_T (€; incl. VAT)	GWP_T (kg CO_2 eq.)	t_C (years)	$t_{GWP, NO}$ (years)	$t_{GWP,EU-27}$ (years)
Wall	8320	37508	1046	15.0	4.9	0.3
Roof	3680	41636	1775	37.7	18.7	1.2
Attic	2944	7360	293	8.3	3.9	0.2
Floor	2880	43641	3734	50.5	50.3	3.2
Air tightness	3840	5322	94	4.6	1.0	0.1
Windows	8480	49892	2719	19.6	12.4	0.8
Ventilation	1280	6959	1850	18.1	56.0	3.6

Water heater	3016	1282	194	1.4	2.5	0.2
Heat pump	21600	36446	2816	5.6	5.1	0.3
Solar PV	9400	12821	23397	4.5	96.5	6.2

As Figure 1 shows, it is the replacement of windows that is the most expensive measure, followed by retrofitting the basement floor and external retrofitting of the roof. Retrofitting the outer wall and installing a geothermal heat pump are also relatively expensive measures. Far more affordable measures are the installation of solar cells on the roof, re-insulation of floor partitions against the attic, installation of balanced ventilation and improvement of the air tightness in the building. By far the cheapest measure is the replacement of the hot water tank.

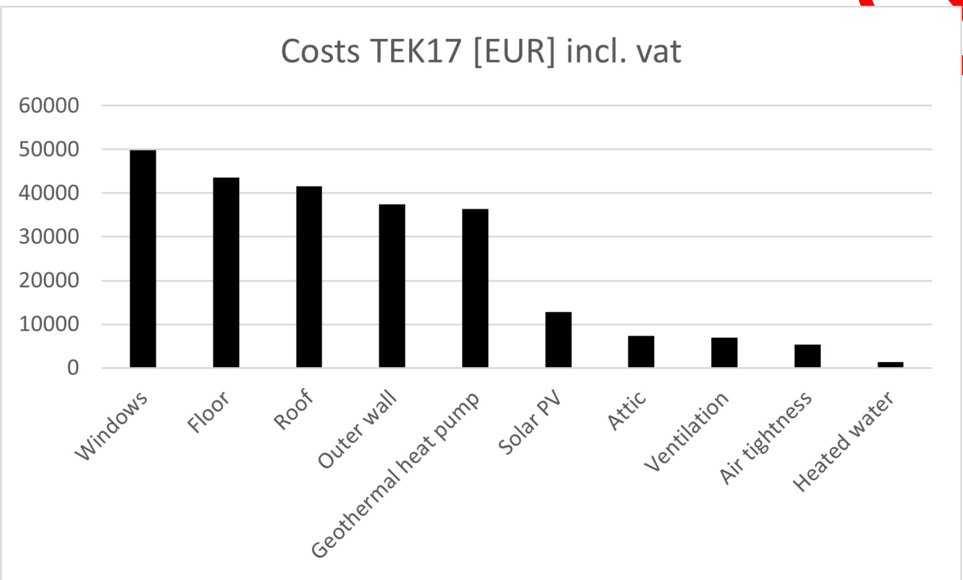

Figure 1. Costs [EUR] for each measure

When it comes to energy savings (kWh/year), the ranking is different. Figure 2 shows how the installation of a geothermal heat pump is the best, followed by solar cells on the roof, new windows, and insulation of the outer wall. Then comes a group of four measures with relatively similar energy savings, namely improvement of air tightness, replacement of the hot water tank, re-insulation of floor dividers to attics, and re-insulation of basement floors. The least energy saving is achieved by installing balanced ventilation, as shown in Figure 2.

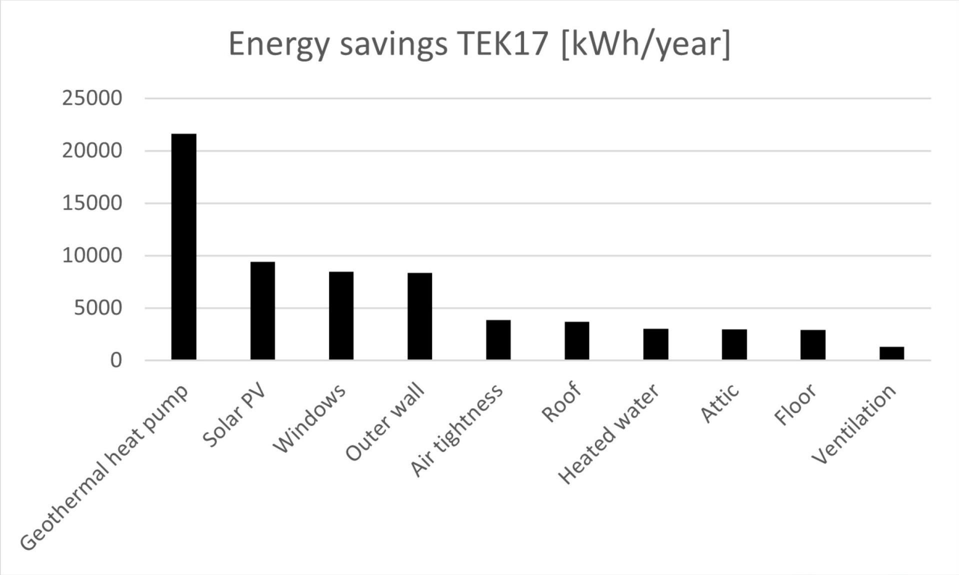

Figure 2. Total energy savings [kWh/year] for each measure

When it comes to GHG emissions (CO2), there is one measure that differs significantly from the others, namely the installation of solar cells on the roof. This measure produces more than five times as much emissions as the next measure on the list, namely improvement and re-insulation of basement floors. The latter has a relatively similar emission as a ground heat pump and replacement of windows. Somewhat lower emissions are linked to the installation of balanced ventilation, as well as post-insulation of the roof and outer wall. Much lower emissions are linked to post-insulation of floor dividers towards the attic and replacement of the hot water tank. The measure with by far the lowest emissions is the improvement of air tightness (see Figure 3).

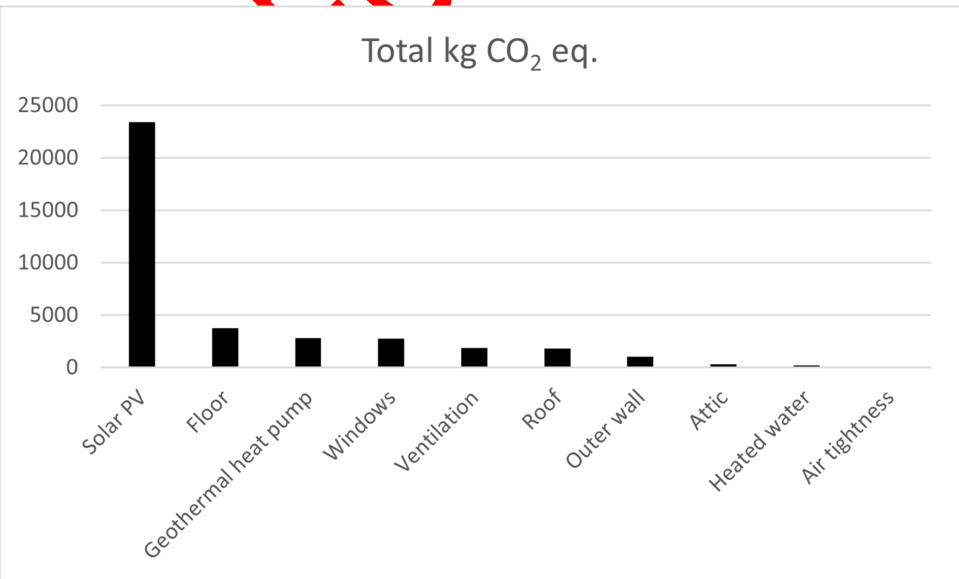

Figure 3. Total kg CO_2 eq. for each measure

But what happens when costs and energy savings are combined for the various measures? Which measures are most profitable for the building owner? Figure 4 shows a simple calculation of the payback period for the various measures where the investment cost is divided by the energy cost savings at an energy cost of 0.3 euros per kWh. A high value means low profitability. The figure shows that the least profitable measure is re-insulating the basement floor (approx. 50 years). This measure includes removing existing concrete floors, establishing draining fillers, and new concrete because there is usually not sufficient floor height to insulate directly on existing floors. Post-insulation of the outer roof is also a less profitable measure (30 years) followed by new windows (20 years), a ventilation system (18 years), and post-insulation of the outer wall (15 years). It is far more profitable to install a geothermal heat pump (6 years), improve air tightness (5 years), and install solar panels (4 years). By far the most profitable measure is to install a new hot water tank (1 year).

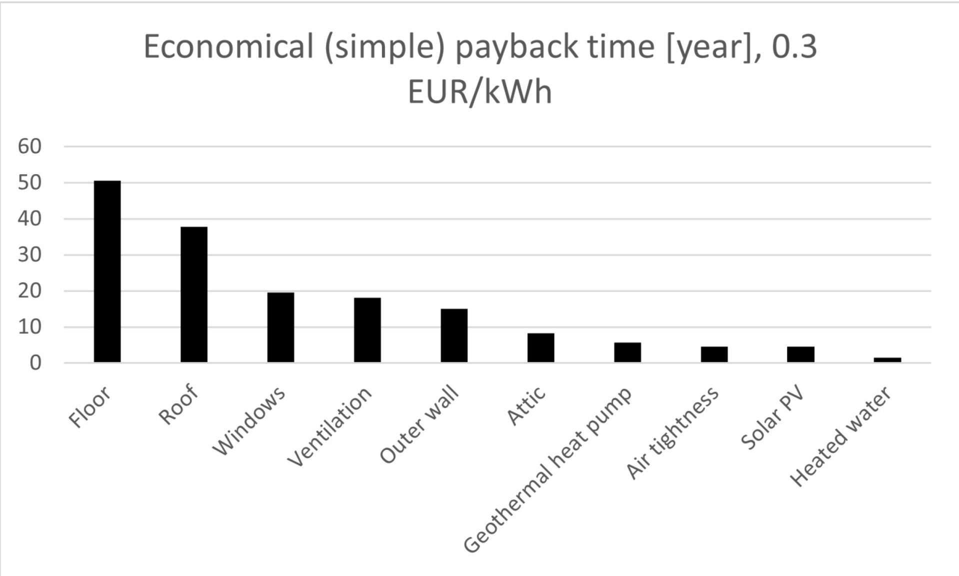

Figure 4. Economical (simple) payback time for each measure

And what happens when GHG emissions and energy savings for the various measures are combined? Which measures are the quickest to compensate for GHG emissions through energy savings? Figure 5 shows a simple calculation of "CO_2 payback time" for the various measures where the GHG emissions are divided by the energy savings reduction of GHG emissions based on the Norwegian electricity mix. A high value means a long payback period. The figure shows that by far the least environmentally friendly measure is the installation of solar cells (almost 100 years). Installation of balanced ventilation (56 years) and subsequent insulation of the basement floor (50 years) are also not environmentally friendly. The situation is much better for re-insulating the outer roof (19 years) and replacing windows (12 years), and it will be even better for the installation of a ground-source heat pump (5 years), re-insulating the outer wall (5 years) and re-insulating the floor divider to the attic (4 years). By far the most environmentally friendly measure is to improve air tightness (1 year).

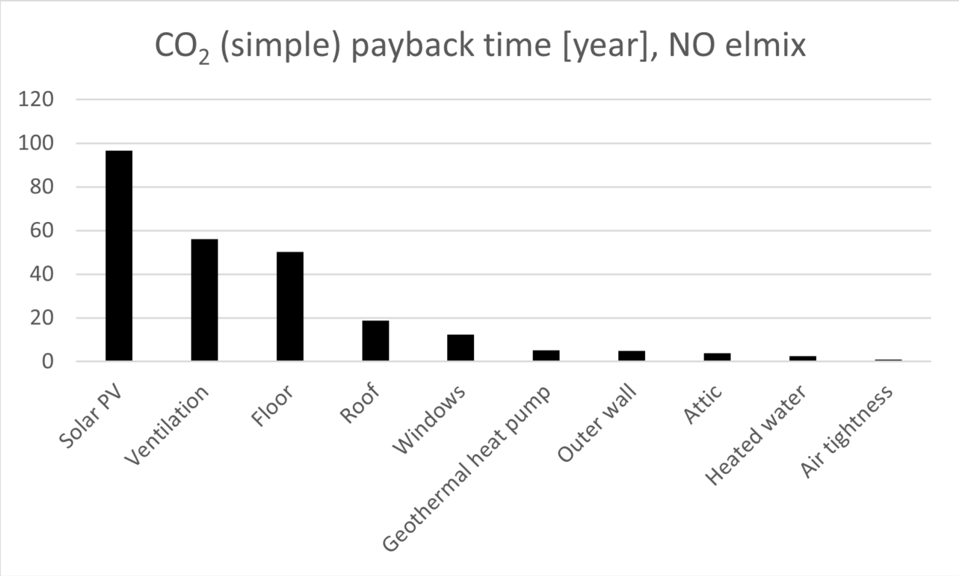

Figure 5. CO_2 (simple) payback time (NO elmix) for each measure

Electricity in Norway is mainly based on renewable hydropower. Therefore, the figures for CO2 payback time are relatively high. But if the same calculations are based on European elmix (EU elmix), the payback time is drastically reduced. The ranking for the measures is naturally the same, but now the payback period for the worst measure has been reduced to 6 years, and the best measure (improvement of air tightness) is all the way down to 0.1 years; see Figure 6.

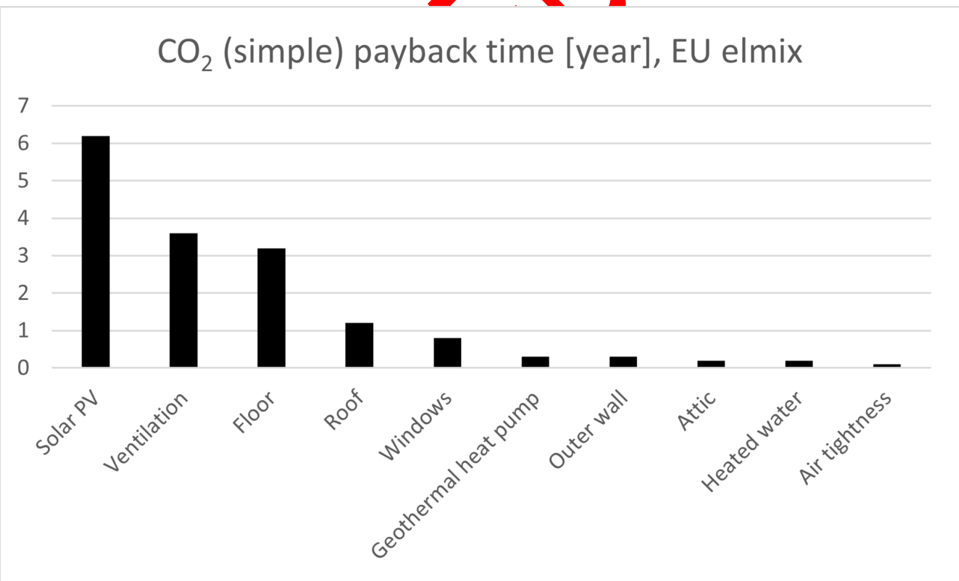

Figure 6. CO_2 (simple) payback time (NO elmix) for each measure

DISCUSSION

The key findings from the study show that there is an unfortunate correlation between the costs of the various energy efficiency measures, GHG emissions and the reduction of energy needs. The results do not correspond to the current policy for which measures are recommended and demanded. There also seems to be a big gap between ambitious governmental energy efficiency programmes based on theoretical calculations and practical life.

In the last 15-20 years, energy use in buildings has been put high on the agenda [33]. In Norway, new energy regulations for buildings have been implemented both in 2010 and 2017. Requirements have been set for energy labelling when selling property, a number of support schemes have been introduced for various energy measures and large research projects and programmes have been carried out to achieve extensive cuts in energy use to achieve national targets. But very little has happened with total energy use in buildings. Have the right measures been put in place, or must the problem be attacked in a completely different way in the future?

And what about GHG emissions? Is there a good enough connection between how the measures are prioritized in relation to costs (willingness to invest), and what climate effects the various measures have in terms of both reduced energy demand and reduced GHG emissions? As an example, in recent years there has been a large-scale investment in solar cells in Norway, and several national support initiatives have caused the number of solar panels on private homes to greatly increase. But the results from this study show that the installation of solar cells has by far the largest GHG emissions of the ten most common energy measures for Norwegian detached houses. The CO_2 payback-time is almost 100 years.

And why is energy use in buildings not drastically reduced? Our hypothesis is that theoretical calculations for the potential for energy savings do not correspond to the real world where house owners have to make judgments about which measures to focus on. The theoretical calculations and recommendations up to now largely suggest that the homes will have to go through an extensive deep renovation that includes a larger energy package which will be very expensive. But most homeowners cannot (or will not be willing to) afford it, and the volume of the measures and energy savings is therefore very limited. In our view, it will be necessary to have a completely new look at how to prioritize, finance and implement the measures. To a much greater extent, one must look at the low-hanging fruits, which are both profitable and provide rather high energy savings and reduction in GHG emissions. These measures must be communicated to a far greater extent than today. Our proposal is therefore threefold.

First, the measures that are reasonable and provide relatively large energy savings and a significant reduction in GHG emissions must be communicated to the house owners to increase the volume of energy savings dramatically. Subsequently, the costly measures that provide relatively large energy savings and reductions in GHG emissions should be heavily subsidized by the government to stimulate house owners to also choose these measures. Finally, the costly measures that provide relatively small energy savings and small reductions in GHG emissions should perhaps not be promoted, at least not as a first measure. Based on this threefold grouping of measures, the following list is suggested.

Communicate and promote:
- Improvement of air tightness
- New water heater
- Insulation of floor dividers to the attic
- Insulation of building parts that are already planned to be improved

Heavily subsidize:
- Installation of a geothermal) heat pump
- New windows
- Insulation of outer wall

Not recommend as a first measure:

- Solar PV
- Insulation of basement floor
- Insulation of outer roof
- Installation of balanced ventilation

It is important to point out that the passive measures such as insulation of the external wall, external roof and basement floor, are shown to be very expensive measures. The reason for this is the technical condition of the building, which entails large costs in addition to the insulation itself. For example, when the roof is to be re-insulated from the outside, the existing roofing, battens, etc. must be removed and demolished or reused depending on the condition and expected remaining lifetime of the components. This process results in relatively extensive extra work that requires many working hours and a large consumption of building materials. Adaptations to adjacent building parts often also have to be made when the roof structure increases in size.

However, the presented results apply only if the measures are implemented only as energy efficiency measures. If, in any case, something is to be done to the facade or the roof because of maintenance or replacement, the situation is completely different. Then it will be very sensible and cost-effective to also insulate the component. In this situation, all three measures for insulating the outer wall, outer roof and basement floor will be roughly as cheap and have as low GHG emissions as insulating the floor divider to the attic. The energy savings will of course be just as good, regardless of whether the house owners insulate as a separate measure or in combination with already necessary and planned maintenance and replacement. Consequently, insulation of building parts that are already planned to be improved will be very beneficial measures which then fall into the group of measures that should be communicated and promoted to the house owners by the authorities.

Regarding GWP_T several measures stand-out, particularly Solar PV and basement floor, see Figure 3. Contribution analysis reveals that these relatively high GWP values result from upstream processes from raw material extraction to the production of silicon wafers and concrete respectively—these findings are commonly acknowledged in the literature. These high emissions from cradle-to-installation, combined with the low energy saving/production and GWP intensity of the Norwegian elmix (26 g CO_2 eq./kWh) result in relatively long simple payback times, i.e., 96.5 and 50.3 years, respectively. The remaining measure with a relatively long simple payback time is ventilation. Here, there is not an excessively high initial cradle-to-installation GWP value or low GWP intensity of the Norwegian elmix which are the main drivers, but the low energy saving resulting from this measure. Substitution of the GWP intensity of the EU-27 elmix (400 g CO_2 eq./kWh) when determining simple payback acts as a sensitivity analysis for the results. This indicates that all results are highly sensitive to the assumed current- and expected GWP intensity of the elmix.

The study reveals significant variations in energy savings and GHG emission reductions across different implemented measures. While envelope measures are costly, they often result in substantial energy savings and GHG emission reductions, justifying their initial investment. Heating system upgrades also show promise in terms of efficiency gains, although their effectiveness is highly dependent on the existing system and building type. Ventilation improvements, despite their lower costs, offer moderate energy savings but are crucial for indoor air quality and energy recovery.

The analysis points to a need for policy revision, with a focus on incentivizing measures that offer the best balance between cost, energy savings, and GHG emission reductions while also securing a just transition. Today, the national councils for energy upgrading are very ambitious and often include a deep renovation of the home, without subsidies being given to a greater extent. The risk and the investment are therefore largely left to the house owner. Choices at the national level may not always reach all regions or inhabitants, leading to an unjust transition. Current national policies have been scrutinized for subsidizing the wealthy when improving their homes, underscoring the complexity of implementing energy efficiency policies that are both effective and equitable. Energy efficiency measures should therefore be seen together with social housing policies, and local community improvement work to reach all groups of society.

Lifetime performance is a key factor in the sustainable refurbishment of buildings. Measures that may appear costly or less effective in the short term can provide significant benefits over the building's lifetime, both in economic terms and in reducing environmental impacts. This perspective is essential for policymakers and stakeholders to make informed decisions about energy efficiency investments.

<u>Limitations</u>

The study is focusing only on Norwegian detached houses. Similar calculations are conducted for dwellings and office buildings, though not presented in this paper. The methodology and study should be expanded to include more regions/countries with different climates. This expansion could build a more robust model for generalizing the results. The study is a fully theoretical study based on simulations and thus neglects the important but challenging factor of user behaviour. There are also several parameters that involve high uncertainty, e.g., energy prices, energy mix and corresponding GHG emission, GHG emissions from materials, and general cost developments for both labour and materials. Further work should focus on integrating energy efficiency measures into general maintenance practices and promote these solutions through existing channels advising house owners. A further discussion on system boundaries for analyses like this is also needed. For this discussion, the neighbourhood level represents a promising scale for energy optimization, in addition to a more holistic approach on a regional or national scale.

CONCLUSION

This paper underscores the importance of a holistic approach to evaluating energy efficiency measures in the refurbishment of existing buildings. All considerations such as societal acceptance, biodiversity etc. cannot be converted into GWP. A combination of interventions across different building systems is necessary to maximize energy savings, reduce GHG emissions, and ensure economic viability. The findings suggest that Norway's energy efficiency policy requires significant adjustments to better promote sustainable. refurbishment practices. Recommendations for policy enhancements include increased financial incentives, more stringent regulations, and broader support for integrated refurbishment projects. Additionally, considering the lifetime performance of refurbishment measures and acknowledging the social dilemmas in policy implementation are crucial for achieving long-term sustainability in the building sector.

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APPENDIX 1

Appendix Table 1 LCI and GWP for measure 1 – Insulating outer wall

Name	LCI Value	Unit	GWP Value	Unit	Source
Output					
Insulated outer wall	1	m^2	6.53582	kg CO_2 eq.	Own Calculation
Input					
Studs	0.00784	m^3	0.51110	kg CO_2 eq.	NEPD-3923-2885-NO
Insulation	0.14216	m^3	2.06397	kg CO_2 eq.	NEPD-1696-683-NO
Air barrier	1	m^2	0.75823	kg CO_2 eq.	NEPD-3667-2612-EN
Batten	0.00256	m^3	0.16689	kg CO_2 eq.	NEPD-3923-2885-NO
Timber cladding primed & painted	1	m^2	3.03563	kg CO_2 eq.	NEPD-3924-2884-NO

Appendix Table 2 LCI and GWP for measure 2 – Insulating roof

Name	LCI Value	Unit	GWP Value	Unit	Source
Output					
Insulated roof	1	m^2	19,72442	kg CO_2 eq.	Own Calculation
Input					

Batten 1	0.01568	m^3	1.02220	kg CO_2 eq.	NEPD-3923-2885-NO
Insulation	0.18432	m^3	2.67608	kg CO_2 eq.	NEPD-1696-683-NO
Plywood	1	m^2	2.47013	kg CO_2 eq.	NEPD-3830-2785-NO
Subroof covering	1	m^2	3.65500	kg CO_2 eq.	NEPD-4148-3365-EN
Batten 2	0.00184	m^3	0.11995	kg CO_2 eq.	NEPD-3924-2884-NO
Batten 3	0.00709	m^3	0.46216	kg CO_2 eq.	NEPD-3923-2885-NO
Roofing tiles	1	m^2	7.20377	kg CO_2 eq.	NEPD-2709-1409-NO
Eavestrough	0.229	kg	0.70505	kg CO_2 eq.	EPD HUB, HUB-0245
Eavestrough flashing	0.229	kg	0.70505	kg CO_2 eq.	Proxy - EPD HUB, HUB-0245
Gable-end flashing	0.229	kg	0.70505	kg CO_2 eq.	Proxy - EPD HUB, HUB-0246

Appendix Table 3 LCI and GWP for measure 3 – Insulated attic floor

Name	LCI Value	Unit	GWP Value	Unit	Source
Output					
Insulated attic floor	1	m^2	3.66196	kg CO_2 eq.	Own Calculation
Input					
Insulation	0.2	m^3	2.90373	kg CO_2 eq.	NEPD-1696-683-NO
Air barrier	1	m^2	0.75823	kg CO_2 eq.	NEPD-3667-2612-EN

Appendix Table 4 LCI and GWP for measure 4 – Insulating basement floor

Name	LCI Value	Unit	GWP Value	Unit	Source
Output					
Insulated basement floor	1	m^2	46.67828	kg CO_2 eq.	Own Calculation
Input					
Coarse gravel	0.55	kg	3.13610	kg CO_2 eq.	NEPD-5908-5180-NO
Radon barrier	1	m^2	1.64720	kg CO_2 eq.	NEPD-5869-5145-NO
Expanded polystyrene insulation	0.2	m^3	12.26316	kg CO_2 eq.	NEPD-2796-1492-EN
Vapour barrier	1	m^2	0.29902	kg CO_2 eq.	NEPD-2809-1507-NO
Reinforced concrete	0.07	m^3	29.33280	kg CO_2 eq.	NEPD-3556-2149-EN
Flooring material (plastic/linoleum)	1	m2	4.83000	kg CO2 eq.	NEPD-2143-968-EN

Appendix Table 5 LCI and GWP for measure 5 – Improving air-leakage in the building envelope

Name	LCI Value	Unit	GWP Value	Unit	Source
Output					
Improving air-leakage	1	m²	2.94536	kg CO_2 eq.	Own Calculation
Input					
Caulking	0.616	kg	1.48826	kg CO_2 eq.	NEPD-6084-5340-NO
External trim	0.48	m²	1.45710	kg CO_2 eq.	NEPD-3924-2884-NO

Appendix Table 6 LCI and GWP for measure 6 – Exchanging windows & doors

Name	LCI Value	Unit	GWP Value	Unit	Source
Output					
Exchanged window	1	m²	84.97752	kg CO_2 eq.	Own Calculation
Input					
window	1	m²	81.20137	kg CO_2 eq.	NEPD-5606-4906-EN
Insulation push-strip	0.0048	m³	0.06969	kg CO_2 eq.	NEPD-1696-683-NO
Bottom filler strip	0.00031	m³	0.11548	kg CO_2 eq.	NEPD-2915-1608-NO
Caulking	0.616	kg	1.48826	kg CO2 eq.	NEPD-6084-5340-NO
Interior trim	4	m	1.39768	kg CO2 eq.	NEPD-2369-1107-NO
Exterior flashing	0.229	kg	0.70505	kg CO2 eq.	EPD HUB, HUB-0245

Appendix Table 7 LCI and GWP for measure 7 – Installation of ventilation system

Name	LCI Value	Unit	GWP Value	Unit	Source
Output					
Ventilation system	1	m²	11.56410	kg CO_2 eq.	Own Calculation
Input					
Ventilation system	1	m²	11.56410	kg CO_2 eq.	Adapted and scaled from: EcoInvent v3 - Ventilation system, decentralized, 6 x 120m3/h, steel ducts (CH)/production/APOS, U

Appendix Table 8 LCI and GWP for measure 8 – Installation of a smart water heater

Name	LCI Value	LCI Unit	GWP Value	GWP Unit	Source
Output					
Water heater	1	unit	194.0277191	kg CO_2 eq.	Own Calculation
Input					
Water heater	1	unit	194.0277191	kg CO_2 eq.	NEPD-5319-4616-EN

Appendix Table 9 LCI and GWP for measure 9 – Installation of water-based heating with heat exchanger

Name	LCI Value	LCI Unit	GWP Value	GWP Unit	Source
Output					
Heating	1	m^2	17.6	kg CO_2 eq.	Own Calculation
Input					
Heating	1	m^2	17.6	kg CO_2 eq.	Adapted and scaled from EcoInvent v3: Heat distribution equipment, hydronic radiant floor heating, 150m2 (CH)/production/APOS, U

Appendix Table 10 LCI and GWP for measure 10 – Renewable Energy Solar PV

Name	LCI Value	LCI Unit	GWP Value	GWP Unit	Source
Output					
Solar PV	1	kWp	2186.7	kg CO_2 eq.	
Input					
Solar PV	1	kWp	2186.7	kg CO_2 eq.	Adapted and scaled from EcoInvent v3: Photovoltaic slanted-roof installation, 3kWp, multi-Si, panel, mounted, on roof (CH)/APOS, U