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*Article*

# An Indicator Framework for Evaluating Building Renovation Potential

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**Abstract:** Implementation of a new European Union directive on energy renovation in Denmark can be expected to have a strong impact on the country's energy renovation requirements. Accordingly, an indicator framework has been developed with the aim of identifying and quantifying the energy renovation potential of a specific Danish municipality. We identified and selected four indicators—energy consumption, $CO_2$ emissions, heating costs and current energy labels—specifically for detached dwellings. The physical renovation potential was then quantified based on the indicator results, and an average score for the four indicators was calculated for each of the 10,228 detached dwellings in the municipality. All four indicators were weighted equally in the calculations of the total renovation potential score. The methods used in this study can be applied more widely as they rank detached dwellings according to their renovation potential. However, we also found that more detailed data are necessary to determine the specific renovation potential of detached dwellings. A greater effort to collect more data on the part of the municipalities would improve the accuracy of analyses.

**Keywords:** energy efficiency; energy renovation; retrofitting; municipal heat planning; sustainable indicator frameworks



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## 1. Introduction

Europe's buildings are responsible for 40% of its energy consumption and 36% of its greenhouse gas emissions [1]. This means that upgrading its building stock is one of the most important solutions to some of the challenges the continent faces in addressing climate change. Renovating buildings has a very significant impact on a house's energy consumption: for example, a 1 °C increase in room temperature generates a 6% increase in energy consumption [2]. A specific indoor air temperature is often targeted, but different people find different temperatures comfortable [3]. The reality is that with better insulation it becomes easier to maintain a desired room temperature.

Denmark's building stock is complex, consisting of buildings of different ages and different sizes built with different materials and for different purposes. The majority, however, are residential dwellings, this is because we must all live somewhere, whether in a single-family dwelling or a multi-story building with apartments. When we then want to reduce the energy consumption of Denmark's building stock, we do not find it easy to decide how to go about it and which buildings to target. In some countries like Denmark, basic data for each building are collected in a common national database. Denmark has a building registry database (BBR), which is described in detail in [4]. It contains basic data about the buildings in relation to their size, age and heating source. However, as entering data in the database is voluntary on the part of the building's owners, the data are not necessarily up to date. This is a critical problem, but it is the only detailed data we have on Denmark's building stock. The BBR data cover the physical data which describe the building, and the data are often used to categorize archetypes of buildings, which are then used to evaluate the demand for energy. This reduces the complexity involved in modelling the buildings.

When, therefore, the BBR data are used to calculate a specific room temperature, such as 21 °C, it is based solely on the physical data of the buildings and the building statistics. No account is taken of the likelihood that the inhabitants of a building may heat it to below or above 21 °C, thus changing the building's actual heating demand. Actual energy consumption data are now more readily available due to the installation of individual smart meters [5]. All things being equal, these data may give a more precise result than the calculation based on the BBR data and the archetype categories. However, actual consumption then depends on who is living in the house, and its energy consumption will probably change when a new family moves in with different heating requirements. It also only covers buildings which have a smart meter.

In this study, we use the data from the BBR database together with sustainability indicators to evaluate the renovation potential in each detached dwelling in Rudersdal municipality, Denmark, which amounts to 10,228 buildings. We do not use actual energy consumption data, nor cluster the buildings into archetypes. We evaluate the energy renovation potential of each building using its BBR data. The aim is first and foremost to identify the buildings which we consider to have the highest renovation potential based on four sustainability indicators.

The energy-saving potential of a building depends on how the heat is supplied to it. Across Denmark, on average 65% of buildings are supplied by district heating (DH). The DH cover in Rudersdal municipality is lower than average, and one of the municipality's goals is to expand it. We will address the supply parameter by applying different energy-supply scenarios.

Building regulations have become much stricter over the last thirty years, with the aim of making new buildings much more energy efficient. The new building stock is therefore much more energy efficient than the old building stock, which is achieved either by adding new buildings to the existing stock or replacing the latter entirely. The country's building stock grew by 1% per year from 1970 to 2010. If we maintain the same rate of growth, we will still have 70–80% of the 'old' buildings and 20–30% new buildings in 2050 [6]. Introducing regulations for old building stock is difficult, but this stock is nonetheless being addressed strongly in a new proposed regulation, whereby the least energy efficient houses will have to be upgraded. [7].

The European Union (EU) drew up a target of a 20% improvement in energy efficiency by 2020, which was achieved across the EU [8] with the help of low energy consumption in 2019/2020. The target for the residential sector was 26% [9]. New EU legislation has established a legally binding target by which to reduce the EU's final energy consumption by 11.7% by 2030 (relative to the 2020 reference scenario) [10]. The present annual increase in energy savings of 0.8% should increase to 1.3% (2024–2025), then to 1.5% (2026–2027) and finally to 1.9% from 2028 onwards, amounting to an average of 1.49% of new annual savings for the period 2024–2030 [9]. The new Energy Efficiency Directive is part of the 'Clean Energy for all Europeans' package, which went through significant amendments in 2018. An updated energy efficiency target was adopted of at least 32.5% in savings by 2030, based on 2007 projections. On 14 March 2023 the European Parliament also adopted a new version of the Energy Performance of Buildings Directive (EPBD) to address the problem [7]. This new version includes ambitious energy efficiency requirements, which will lead to an upgrade of Europe's buildings.

In a proposal to the European Parliament the worst-performing residential buildings will need to reach at least class F by 2030 and class E by 2033. According to an analysis by Jyske Bank, the new EPBD initiative will have consequences for 800,000 Danish families, who will need to spend a total of EUR 16 billion on energy-efficient upgrades to their homes. The initiative might lead to some houses being declared illegal by 2030 because homes with an energy label of G would have to be renovated to reach at least an energy label of F before 2030. Moreover, by 2033, these houses will have to be renovated to a minimum energy label of E. The initiative will be enforced on the building's owner, who will not be able to sell the property without a valid energy label [11], which should be less than ten years old [12]. Moreover, it will become difficult to sell these properties before 2030, as buyers will not be interested in buying houses that do not meet these energy label requirements. It may not make sense to renovate older houses, especially in rural areas, and some homeowners cannot afford to do so. This raises the possibility that the initiative may end up trapping property owners in a situation in which they are able to neither renovate nor sell [11]. However, the proposed use of energy labels has not been agreed upon. The agreement is that each member state will adopt its own national trajectory toward the reduction of average primary energy use of residential buildings by 16% by 2030 and 20–22% by 2035 [13]. In this study we will still use the original idea behind the proposal to the European Parliament of using energy labels.

The energy efficiency gap [1,14,15] is described as the technical optimum of carrying out energy efficiency projects, despite their absence [14]. Ref. [16] calculates the profitable space-heating savings potential as applying to about 80% of Danish residential building stock up to 2050. Although the barriers [16] identified are not technical or economic but due to a lack of knowledge and interest, [17] finds that barriers can be technical, economic or behavioural. Then there are perceived barriers, where people delay retrofitting until a more extensive renovation of the house is carried out [15].

We use Rudersdal municipality as our example in this study. It is situated north of Copenhagen and has its own goal to reduce $CO_2$ emissions by 85% by 2030 compared with 1990 [18]. Denmark's goal is to reduce $CO_2$ emissions by 70% by 2030 compared with 1990 [19]. Rudersdal municipality is mostly residential, with little industry or farming. Therefore, its biggest contributor to $CO_2$ emissions is the heating of buildings, which accounts for 36% of its $CO_2$ emissions. One of Rudersdal's largest plans for reducing $CO_2$ emissions is to phase out oil and gas heaters by expanding DH [18].

This study investigates how a municipality and its residents can prepare for the new possible energy efficiency initiative. According to BBR data extracted in July 2023, 57% of the buildings in Rudersdal municipality are detached dwellings, which are therefore the focus of the study. In addition, there are more data on detached dwellings compared with other types of buildings, and they are easier to analyse because they do not share walls or floors with neighbours [20].

Our contribution consists in developing a specific indicator framework with the goal of evaluating the energy renovation potential of residential dwellings in Rudersdal municipality in Denmark using both environmental and economic criteria. The framework can easily be used in other countries. Our method requires access to specific data regarding each house in the municipality. This article therefore contributes to a better understanding and visualization of the renovation potential of the municipality's building stock. It provides a background for the complex decision to design the coming energy renovation strategy in the municipality.

This paper is structured as follows: Section 2 describes the methodology for selecting and developing the indicator framework. Section 3 describes the overall methodology for developing the indicator framework and Section 4 describes the specific methodology used for quantifying each of the indicators. Section 5 presents the findings, and Section 6 discusses the results. The paper concludes in Section 7.

## 2. Methods: Developing an Indicator Framework

### *2.1. Developing an Indicator Framework*

The indicator framework was developed using the steps in the urban sustainability reporting process suggested by Virginia McLaren [21]. There are a total of nine steps, shown in black in Figure 1. The first four are involved in scoping and defining the goals, framework and selection criteria for the indicators. After establishing the boundaries and methods by which to find the indicators, identification of the latter begins, resulting in a final set of indicators. These can then be used to obtain results that can be analysed. In this step, the idea is to decide whether the indicator results show development either towards or away from sustainability. The last two steps consist in presenting the indicators in the most favourable light, assessing the indicator's performance, and deciding whether they work adequately and measure what they are meant to measure. The nine steps are as follows:

(1) define sustainability goals;
(2) scoping;
(3) choose indicator framework;
(4) define selection criteria;
(5) identify potential indicators;
(6) choose a final set of indicators;
(7) analyse indicator results;
(8) prepare and present report;
(9) assess indicator performance.

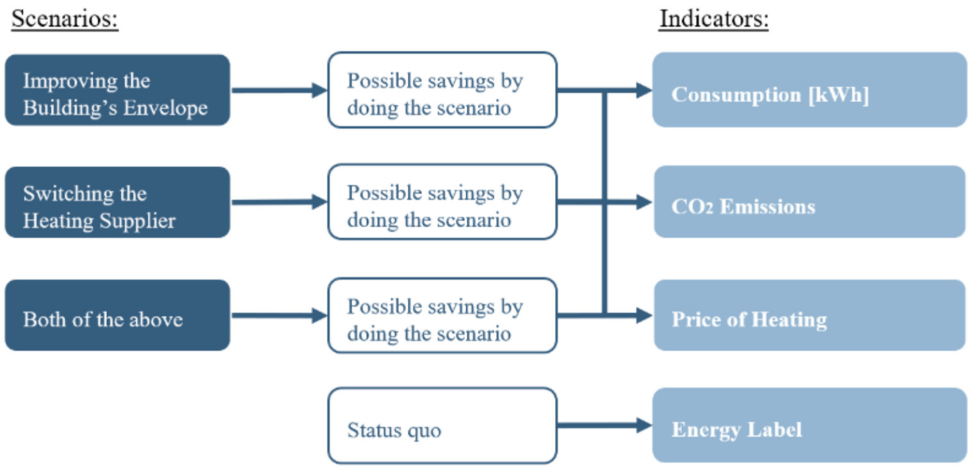



**Figure 1.** Potential scenarios and indicators identified in wave three.

The first four steps were used in the initial process to select the criteria. The next three steps, identifying potential indicators, choosing a final set of indicators and analysing the indicator results, in addition to the first step (defining goals), were conducted through loops going back to the information gathering phase in order to find more literature and search for more available data. The following subsections will go through the first six steps, as well as the eighth step on how to present the indicator results in the best possible light, starting with defining the sustainability goals. The reason for doing this is to explain the method used in both developing the indicators and presenting each of them before reaching the seventh step, the indicator results and their analysis. The last step, assessment of the indicator's performance, is discussed in Section 5.

### *2.2. Step 1: Define Sustainability Goals*

The first step is to define the sustainability goals the indicators should target. This can be achieved either by goals that are already defined in other planning documents or by developing goals suitable for the specific case [17]. The following goals from different political agendas would affect Rudersdal municipality in addition to the energy labels' aim. Our findings from this literature review are listed below:

- The Paris Agreement [22];
- The Sustainable Development Goals [23];
- Rudersdal's Plan for the Sustainable Development Goal no. 13, Climate Action [24];
- Energy Performance of Buildings Directive III [25];
- Energy Performance of Buildings Directive IV [26].

Among the goals in Rudersdal's Climate Action Plan are the following: (a) Rudersdal's intermediate target for 2030 is a $CO_2$ reduction of 85% compared with 1990, (b) Rudersdal should be climate neutral by 2040, (c) realization of the potential for energy savings in existing buildings (both private and public) of approximately 7% towards 2030, (d) an increased focus on guidance for citizens and businesses about energy savings in private buildings, and (e) an increased focus on guidance for citizens and businesses about green heating solutions [24].

- Energy labels: 'The aim is to promote energy savings by visualising the amount of energy that a building consumes and by outlining the energy saving possibilities' [27].

Finding inspiration from the literature review, and combining the goal of the study and the information gathered from the literature review, the following sustainability goals were defined:

- Help the municipality and its residents prepare for the Energy Performance of Buildings Directive IV.
- Help the EU, Denmark and Rudersdal reach their goal of reducing $CO_2$ emissions and becoming climate neutral by making them aware of the renovation potential.
- Promote energy efficient building renovations in Rudersdal municipality and help the municipality guide their residents towards energy efficiency.
- Help the municipality in further sustainable city planning and improve the building application process.

### *2.3. Step 2: Scoping*

The next step was to scope the indicators to make sure that they target the correct audience, have the correct level of detail and are still realistic within the timeframe of the study, in addition to considering the temporal and spatial boundaries. Before doing this, the purpose behind the indicators was defined, as seen in the sustainable goals.

The scope of the indicators can be summarised as follows: (i) 3–8 indicators should be developed (ii) using the newest possible data, no older than from 2019, and which should (iii) cover energy renovations for detached dwellings in Rudersdal municipality, thus (iv) limiting the indicators so that they consist only of data for before and after the renovation, and not for the renovation process itself.

### *2.4. Step 3: Choosing an Indicator Framework*

Maclaren [21] lists six types of frameworks that can be used for the development of sustainability indicators: domain-based, goal-based, sectoral, issue-based, causal, and combination frameworks. Instead of explaining all of these, this subsection will focus on those chosen for this study. There are advantages and disadvantages with all the types of frameworks; however, by choosing the combination framework, which combines two or more of the other five frameworks, it is possible to overcome many of the disadvantages. This is because many of these disadvantages are solved through the advantages of another framework, allowing the combination framework to consolidate their advantages while overcoming their weaknesses. The combination framework was therefore chosen as the overall framework for this study, combining the domain-based, goal-based and issue-based frameworks.

### *2.5. Step 4: Define Selection Criteria*

To define the selection criteria that were used to choose the final set of indicators (step 6), we took inspiration from [21,28]. The selection criteria that were defined for the indicators in this study are as follows:

- specific
- measurable;
- achievable;

○ timely;
○ cost-effective to collect and use;
○ based on raw and available data;

- relevant;
- valid;
- reliable;
- sensitive;
- transparent;
- unambiguous;
- ethical.

### *2.6. Step 5: Identify Potential Indicators*

The first four steps identified eight overall sustainability factors that may influence whether a detached dwelling should be renovated. These include (1) heating consumption, (2) heating supply, (3) building parts, (4) materials, (5) BR18 rules of profitability and minimum energy requirements, (6) energy labels, (7) indoor climate and (8) level of obsolescence and dangerous materials and gasses. From this activity, multiple issues were dismissed due to a lack of data, including 3, 4, 5, 7, and 8. Heating consumption, heating supply and energy labels were the only sustainability factors remaining from which we could develop indicators.

#### Feedback Loops to Develop Scenarios

Several feedback loops were made before choosing the final indicator set. In identifying the potential dataset in step 5, we went back to the overall definition of the sustainability goals and realized that none of the potential indicators took into account the social dimensions of sustainability. We therefore developed a survey and carried it out using the municipality's Facebook page. The results of that survey are not included here but are available in [20].

The second feedback loop took us back to step 3, where the indicator framework was chosen. The average heating consumption, depending on the year of construction and area for detached dwellings, is given in [29]. These were the most precise data on energy consumption by detached dwellings we found for this study, and so we decided to develop an indicator from this. Furthermore, two indicators were developed regarding heating supply, namely $CO_2$ emissions and heating costs. Ref. [29] also gives information on how much $CO_2$ a building emits depending on the heating supply, which can be used in the indicator, covering the environmental pillar of sustainability.

In addition to the four indicators, three scenarios were developed: (1) improving the building's envelope, (2) switching the heating supplier and (3) both. These three scenarios were developed based on [29], the results of which differ depending on whether the building envelope was improved or the heating supplier was switched. It was felt to be of interest to determine whether the difference was between the scenarios, and from this conclude which scenario was the best. The residents could also choose to carry out only one of the scenarios, which can influence the renovation potential. However, the energy label indicator was taken out of the scenarios and treated as a stand-alone indicator.

The renovation potential is investigated by observing the possible savings, which was in turn accomplished by undertaking the different scenarios. This is achieved by comparing the status quo with the values calculated after a scenario is complete. There is a total of four indicators: (1) consumption, (2) $CO_2$ emissions, (3) heating costs and (4) energy labels. The three scenarios work as sub-indicators for indicators 1–3, giving a total of nine sub-indicators. The scenario set-up is illustrated in Figure 1.

The final potential indicators are then identified by completing the feedback loops. Feedback loop 1 starts with the simple question of what the overall contributors to energy are in a detached dwelling. Loop 2 comprises continued work on the results from loop 1 and their combination with sustainability factors (issue-based framework), the domain-based framework, and the heat savings potential in existing buildings [29].

### *2.7. Step 6: Evaluate the Indicators and Select the Final Set*

Using the indicators identified in loop two, evaluating the results and going back in a loop to revise the indicators, we arrive at the final potential indicators. Finally, the identified indicators were compared with the sustainability goals (goal-based framework) under the assumption that the potential indicators would contribute to all of the goals defined in step 1. Step 6 evaluates each potential indicator identified in step 5 against the selection criteria, which are defined in step 4 [21].

## **3. Methodology: General Background for All Indicators**

We will now describe each of the four indicators in more detail and how they were developed. As well as describing each indicator, the overall scale and overall data processing of each will be explained, including how the data for each indicator were collected and how the scale works for each indicator.

### *3.1. Methodology: The Overall Scale*

We have chosen to use a five-point scale for all of our indicators, with grade one representing the lowest renovation potential and grade five the highest. A five-point scale is sufficiently detailed to show differences and makes it possible to draw conclusions. The data found on the detached dwellings are expressed as an average for the whole of Denmark, and there is therefore no reason to choose a more detailed scale.

However, a sixth grade was needed when we saw the results of the scenarios, including that of switching the heating supplier. This was because grade one represented the lowest renovation potential, meaning that a renovation potential exists, but when we looked at the results there were no potential savings. This includes energy consumption for the same scenario, where the difference in consumption before and after the renovation would be zero. A grade representing no renovation potential, labelled grade zero, was therefore added for the three indicators that consist of scenarios as sub-indicators, giving them a six-point scale.

### *3.2. Methodology: Overall Data Processing*

All of the data processing for the four indicators was undertaken in Excel (2019). The BBR data on detached dwellings were downloaded from KMD Cognito Access 2.1.0 on 18 July 2023 as CSV files and imported to Excel. Then, 686 protected and conservation-worthy buildings were removed. Additionally, duplicates consisting of six buildings that have been demolished, but not yet removed from BBR, were removed, resulting in a total of 10,228 detached dwellings used in this analysis.

### *3.3. Methodology: Grading Method for the Indicators Consisting of Scenarios*

We used percentiles as the grading method when distributing the detached dwellings among the indicators consisting of scenarios. Percentiles are generally used to show a proportion or ranking by comparing one case with several others. The percentile is given as a number between zero and one, and represents a percentage of values found within specific values. An example of this would be if ten people had taken a test, one of the subjects answered 80% of the questions correctly, and the other nine answered more than 90% correctly. Though the first subject had scored 80% on the test, they are ranked in the bottom 10th percentile among the other participants. The grading scale is described further in [20].

The percentile method assigned the bottom 20% of detached dwellings to grade five, the highest renovation potential. This fits neatly with the sustainability goal of helping the municipality and residents prepare for the new EPBD initiative. This is because the new possible labelling system puts the bottom 15% of energy efficient residences in label G, and buildings with both labels G and F need to be improved by 2033.

### 3.4. Methodology: Assigning Which Heating Supplier to Switch to

The scenario involving just switching the heating supplier and the scenario involving both switching the heating supplier and improving the building's envelope, each include the switch to a different heating supplier. This was used to check the impact of Rudersdal's Heating Plan on preparations for the EU initiative.

The heating plan consists of three phases. Buildings within phase one will be offered DH in 2023–2025, and those in phase two in 2026–2027. Phase three has not yet been decided, but the plan will be developed in 2028–2029 and will hopefully be able to supply DH between 2028–2035. The following was therefore decided regarding the switching of heating suppliers:

- Detached dwellings within phases one and two switch to DH. Detached dwellings within phase three that are not included in the plan switch to HPs.
- Detached dwellings that already have DH or heat pumps (HP)s keep this as their heating supply.

The result of doing this was that the detached dwellings had either DH or a HP after the change. The reason for not including phase three in DH was because this has not been planned as yet. This means that, to have buildings ready for the initiative's mandatory date of 2030, the building's owner should look for another alternative. As detached dwellings with DH or HPs are both seen as sustainable solutions, owners have no reason to change. Connecting as many detached dwellings as possible to DH is the plan for Rudersdal. HPs are in general new to the market, and all HPs should therefore be able to give five to ten years of service or more.

## 4. Methodology: Individual Indicator

### 4.1. Methodology—Indicator 1: Energy Consumption

The energy consumption indicator was developed from Figure 2, which shows the consumption of a detached dwelling today, and Figure 3, which shows the consumption after improving the building's envelope, including increased comfort levels. Both figures use the unit kWh/m$^2$ p.a., depending on the year built. By using the year built and area extracted from BBR, consumption before and after improving the building's envelope in kWh p.a. was found. To find the possible savings by improving the building's envelope, the following formula was used:

$$\Delta EC = EC_{before} - ECi_{after} \quad (1)$$

where $\Delta EC$ represents possible savings of energy, $EC_{before}$ represents the energy consumption before interventions and $ECi_{after}$ represents energy consumption after the intervention, which in this case is improving the building's envelope.

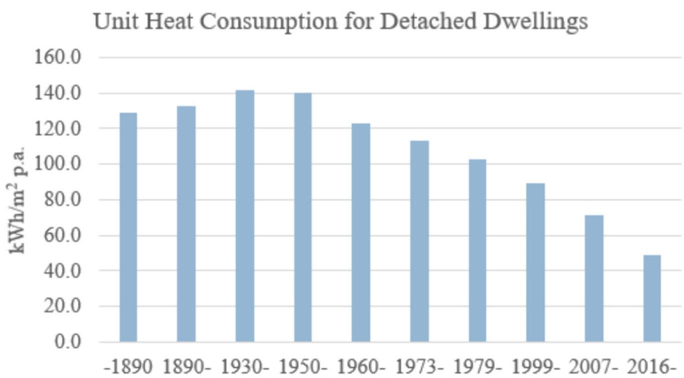



**Figure 2.** Heat consumption for detached dwellings in kWh/m$^2$ per year for different time periods. Data extracted and translated from [29].

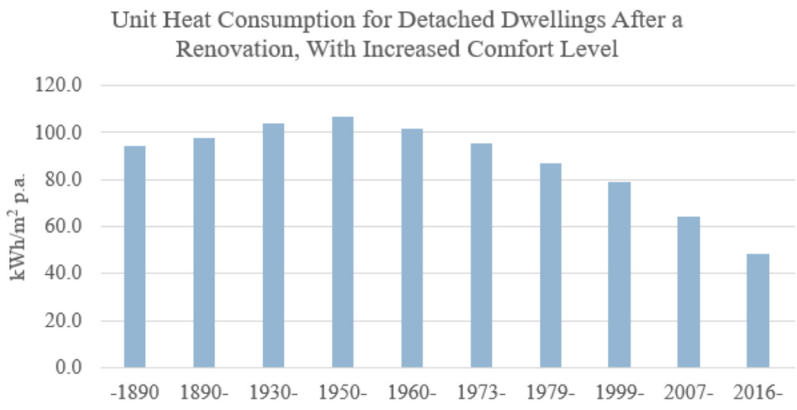



**Figure 3.** Heat consumption for detached dwellings after renovation in the different time periods in kWh/$m^2$ per year. Data extracted and translated from [29].

This was the explanation for the scenario for improving the building's envelope. The scenario involving switching the heating supplier is zero for all detached dwellings. As a result the last scenario, involving both switching the heating supplier and improving the building's envelope, can utilise exactly the same formula and offer the same results as in the scenario involving improving the building's envelope.

### *4.2. Methodology: $CO_2$ Emissions*

The $CO_2$ emissions indicator was developed from Table 1, which shows the $CO_2$ emissions for detached dwellings, depending on the different heating suppliers, using the unit kg $CO_2$/MWh. The first scenario, involving improving the building's envelope, was developed using energy consumption before and after improving the building's envelope, calculated in the energy consumption indicator, dividing that by 1000 to go from kWh to MWh, and then multiplying it with the kg $CO_2$/MWh values found in Table 1, depending on the heating supplier registered in BBR.

**Table 1.** $CO_2$ emission factor for detached dwellings for the different heating suppliers. Data are from *Energistatistikken*. Emissions are given in kg $CO_2$/MWh. Data extracted and translated from [29].

| | DH | Gas Boiler | Electricity | Oil Boiler | Heat Pump | Biomass |
|---|---|---|---|---|---|---|
| Detached dwellings | 75 | 196 | 175 | 148 | 73 | 3 |

The following two formulas are used to calculate the $CO_2$ emissions:

$$E_{before} = EC \times F \tag{2}$$

where $E_{before}$ represents the $CO_2$ emissions before the intervention, EC represents the energy consumption before the intervention and F represents the fuels emission factor.

$$E_{after} = EC_{after} \times F \tag{3}$$

where $E_{after}$ represents the $CO_2$ emissions after the intervention, $EC_{after}$ represents the energy consumption after the invention and F represents the fuel emission factor.

To find the possible savings by improving the building's envelope, the following formula was used:

$$\Delta E = E_{before} - E_{after} \tag{4}$$

where $\Delta E$ represents the possible savings of $CO_2$ after the intervention, $E_{before}$ represents the $CO_2$ emissions before the intervention and $E_{after}$ the $CO_2$ emissions after the intervention.

The second scenario, involving switching the heating supplier, represents a combination of Table 1 and the change of heating supplier, as explained in the section describing determining which heating supplier to switch to. This was achieved by using formulas (2) and (4) and:

$$E_{after} = EC_{before} \times F \quad (5)$$

where $E_{after}$ represents the $CO_2$ emissions after switching the heating supplier, $EC_{before}$ represents the energy consumption before switching the heating supplier and F represents the fuels emission factor.

It can be seen that the first formula for switching the heating supplier is the same as that for improving the building's envelope. The difference between the first and second set of formulas is in the change of heating supplier and indicates the possible savings for $CO_2$ emissions after switching.

The last scenario, involving both switching the heating supplier and improving the building's envelope, is a combination of the two earlier scenarios. We use (2) and the following two formulas:

$$E_{total} = Es_{after} + Ei_{after} = ECi_{after} \times F \quad (6)$$

where $E_{total}$ represents the total $CO_2$ emissions of both switching the heating supplier and improving the building envelope, $Es_{after}$ represents the $CO_2$ emissions from switching the heating supplier, $Ei_{after}$ represents the $CO_2$ emissions after improving the building's envelope, $ECi_{after}$ represents the energy consumption after improving the envelope and F represents the fuels emission factor.

$$\Delta E_{total} = \Delta Es_{after} + \Delta Ei_{after} = E_{before} - \sum(Es_{after} + Ei_{after}) \quad (7)$$

where $\Delta E_{total}$ represents the possible total $CO_2$ emission savings, $\Delta Es_{after}$ represents the $CO_2$ emission savings from switching the heating supplier, $\Delta Ei_{after}$ represents the $CO_2$ emission savings after improving the building's envelope, $ECi_{after}$ represents the energy consumption after improving the envelope and F represents the fuels emission factor.

It can be seen that the first formula is the same as the other two scenarios, and that the second formula is a combination of the two scenarios, resulting in the discovery of the possible savings of switching the heating supplier and after improving the building's envelope.

### *4.3. Methodology: Cost of Heating*

The cost of heating indicator was developed using the prices taken from Bolius's continuously updated website [30], as shown in Table 2. It can be seen that DH has, in addition to a price per kWh, a fixed charge. Bolius lists two prices for electricity, one called electricity and another called electric heating.

**Table 2.** Cost of different heating supplies [30], eurocents in brackets.

| **Heating Supplier** | **Cost [DKK (Eurocents/kWh)]** |
| --- | --- |
| DH | 0.6390 (8.58) |
| Gas boiler | 0.7610 (10.2) |
| Electricity | 1.8626 (25.0) |
| Oil boiler | 1.2472 (16.7) |
| HP | 0.7104 (9.53) |
| Biomass | 1.11989 (15.0) |
| DH fixed charge | 3774 (506.6) |

This indicator uses electric heating, whereas electricity is assumed to refer to other uses of electricity beyond heating. Prices for different HPs can also be seen in Bolius, where an air-to-water HP is chosen which represents the worst-case scenario (most expensive) and the most typical. Lastly, there are two types of biomass to choose from, beechwood and wood pellets. Beechwood was chosen for the same reasons as the HP.

To find the possible savings in the costs for each scenario, the same formulas as in the $CO_2$ emissions indicator have been used, but with $CO_2$ emissions changed in accordance with the price of heating and divided by 1000, due to the cost unit being in DKK/kWh. The costs are matched with the type of heating supplier, bearing in mind that DH has a fixed charge, which is added at the end of both the first and second formula of each scenario, before the possible savings for the cost of heating are calculated at the end for each scenario.

### *4.4. Methodology: Energy Label*

The energy label indicator investigates the status quo and does not include any scenarios. A username and password were provided by Rudersdal municipality, which made it possible to collect data on detached dwellings in Rudersdal by downloading a CSV file and importing it into Excel. The data included three buildings without any addresses and 23 buildings that were not included in the BBR data, which were assumed to have been demolished, and were therefore removed from the dataset. Additionally, protected and conservation-worthy buildings were removed, amounting to 299 buildings.

Twelve duplicates were found and removed from the dataset. These duplicate buildings have been demolished, but still have a valid energy label, probably because they received an energy label before being sold and then demolished by the new owners. This resulted in a total of 3973 energy labels used in this analysis.

To be able to give all of the 10,228 detached dwellings a grade and later to map them, the data from the building analysis had to be connected to the data from the BBR. This was achieved by using the VLOOKUP function in Excel, connecting 'ADG ID' from the BBR with Access-ID from the building analysis, which both represent the same value and have the same value for each detached dwelling. The result was a column in Excel showing whether a detached dwelling had an energy label, and if so which one.

How each detached dwelling received its grade can be seen in Table 3. For the indicator energy label, decimals were introduced. Today, the energy labelling system has a total of nine energy labels, which cannot be divided by five and thus fitted into the indicators' five-point scale. The decimals solved this problem and ensured that all energy labels were weighted equally. Energy labels are today required for all new buildings. This requirement has been law since 2010, which means that buildings built in the last thirteen years have been labelled. A label is valid for ten years, resulting in all new buildings that have been built in the last ten years being a part of the data provided by the building analysis.

**Table 3.** Grading scale for the indicator energy label.

| **Grade** | **1** | **1.5** | **2** | **2.5** | **3** | **3.5** | **4** | **4.5** | **5** |
|---|---|---|---|---|---|---|---|---|---|
| Energy Label | A2020 | A2015 | A2010 | B | C | D | E | F | G and none |

Based on this information, it was decided that detached dwellings without an energy label would be given a grade five, representing the highest renovation potential with regard to energy labelling. In addition, this ensured that buildings built in the last ten years were not given a grade five.

### *4.5. Methodology: Evaluation of the Potential Indicators*

As explained above, all four indicators were fully developed and were made ready for evaluation based on the selection criteria defined in Step 4. The result of this evaluation can be seen in Table 4, where all of the selection criteria can be seen to be fulfilled except for the 'based on raw and available data' criterion, which was almost fulfilled for three of the indicators. All three indicators were based on the available data, but one could argue that they were not based on raw data for each detached dwelling. The energy consumption indicator, the $CO_2$ emissions indicator, and the cost of heating indicator use data from [29], which is an average of detached dwellings with an energy label in all of Denmark, depending on the year of construction. This means that it has an achievable renovation potential, from which [29] has calculated how much a building can save by renovating its energy supply. This is the most likely condition for buildings today, but as it does not represent raw data, it does not describe the true condition of the detached dwelling. Unfortunately, no data were available on this.

**Table 4.** Evaluation of the potential indicators based on the selection criteria defined in step 4. Symbol explanation: X = fulfilled and / = almost fulfilled.

| Indicator | Energy Consumption | $CO_2$ Emissions | Price of Heating | Energy Label |
|---|---|---|---|---|
| Specific | X | X | X | X |
| Measurable | X | X | X | X |
| Achievable | X | X | X | X |
| Timely | X | X | X | X |
| Cost-effective to Collect and Use | X | X | X | X |
| Based on raw and available data | / | / | / | X |
| Relevant | X | X | X | X |
| Valid | X | X | X | X |
| Reliable | X | X | X | X |
| Sensitive | X | X | X | X |
| Transparent | X | X | X | X |
| Unambiguous | X | X | X | X |
| Ethical | X | X | X | X |

## 5. Results

A challenge in presenting the results is the huge dataset of 10,228 buildings per sub-indicator. It was not possible to show the results for each detached dwelling, and it was therefore decided to give statistics for all of the indicators for the municipality, followed by illustrations of the average grade, the number of dwellings with each grade and their age.

### *5.1. Results: Energy Consumption*

The results for the energy consumption indicator are not as interesting as the other three indicators because there is no renovation potential for the scenario describing the period after switching from a heating supplier. This can be seen in both Tables 5 and 6. Table 5 shows the grade ranges and the percentages of how many detached dwellings there are in each grade for the three different scenarios. Table 6 shows the grade distribution between the three scenarios and the total number of buildings in each grade. Both tables show that 100% of the buildings in the scenario describing the period after switching a heating supplier have a grade of zero. Consequently, as seen in Table 5, the two other scenarios have the same percentage of buildings in each grade, around 20%, as only the improvement of the detached dwelling's envelope influences the indicator. In Table 6, it can be seen that the other two scenarios divide each grade above zero equally. Note that the total sum of all the grades is $3 \times 10{,}228$, due to there being three scenarios. It can be seen that 100% of the buildings that have grade 0 are in the scenario involving switching a heating supplier, and the total amount in grade 0 is 10,228, corresponding to all of the buildings in this indicator.

The upper and lower values for each grade in kWh p.a. can be seen in Table 5. The upper and lower values were found using percentiles, meaning that every building's value above zero would be distributed evenly into grades one to five for the three different scenarios. Grade zero indicates that there is no renovation potential. When looking at the grade ranges for grades one to five, it can be seen that grade five has the biggest difference between upper and lower values, with a 16,351 kWh p.a. difference. This large difference in grade five is due to a number of very big and old detached dwellings in Rudersdal, where the buildings are over 400m$^2$ and were built before 1960. The smallest difference between the upper and lower values is in grade two, with a 690 kWh p.a. difference.

**Table 5.** Grade ranges for the indicator energy consumption after applying the three different scenarios and the percentage of detached dwellings in each grade for the three different scenarios.

| Grade Ranges for Energy Consumption After Applying Different Scenarios | No Potential | Lowest Potential | | | | Highest Potential |
|---|---|---|---|---|---|---|
| Grade | 0 | 1 | 2 | 3 | 4 | 5 |
| Lower value [kWh p.a.] | | 27.43 | 2591.56 | 3281.25 | 4138.13 | 5651.38 |
| Upper value [kWh p.a.] | 27.43 | 2591.56 | 3281.25 | 4138.13 | 5651.38 | 22,002.69 |
| Percentage of buildings in each grade (after improving the building's envelope) | 0.00% | 20.05% | 20.01% | 19.80% | 20.20% | 19.94% |
| Percentage of buildings in each grade (after switching the heating supplier) | 100.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Percentage of buildings in each grade (after switching the heating supplier and improving the building's envelope) | 0.00% | 20.05% | 20.01% | 19.80% | 20.20% | 19.94% |

**Table 6.** Grade distribution between the three different scenarios when looking at the indicator energy consumption, and the total amount of buildings in each grade.

| Grade | After Improving the Building's Envelope | After Switching the Heating Supplier | After Switching the Heating Supplier and Improving the Building's Envelope | Total Number of Buildings |
|---|---|---|---|---|
| 0 | 0.00% | 100.00% | 0.00% | 10,228 |
| 1 | 50.00% | 0.00% | 50.00% | 4102 |
| 2 | 50.00% | 0.00% | 50.00% | 4094 |
| 3 | 50.00% | 0.00% | 50.00% | 4050 |
| 4 | 50.00% | 0.00% | 50.00% | 4132 |
| 5 | 50.00% | 0.00% | 50.00% | 4078 |

### *5.2. Results: $CO_2$ Emissions*

Table 7 shows the grade ranges for the $CO_2$ emissions indicator. The upper and lower values in kg $CO_2$ p.a. are shown for each grade, as well as the percentage of detached dwellings within each grade. Table 8 shows the grade distribution between the three different scenarios and the total number of detached dwellings within each grade for the three scenarios.

**Table 7.** Grade ranges for the indicator $CO_2$ emissions after applying the three different scenarios and the percentage of detached dwellings in each grade for the three different scenarios.

| Grade Ranges for $CO_2$ Emissions After Applying Different Scenarios | No Potential | Lowest Potential | | | | Highest Potential |
|---|---|---|---|---|---|---|
| Grade | 0 | 1 | 2 | 3 | 4 | 5 |
| Lower value (kg $CO_2$ p.a.) | | 2.17 | 502.32 | 1093.72 | 2063.21 | 2730.50 |
| Upper value (kg $CO_2$ p.a.) | 2.17 | 502.32 | 1093.72 | 2063.21 | 2730.50 | 11,671.49 |
| Percentage of buildings in each grade (after improving the building's envelope) | 0.00% | 35.26% | 49.93% | 14.04% | 0.64% | 0.14% |
| Percentage of buildings in each grade (after switching the heating supplier) | 22.92% | 0.00% | 2.00% | 24.69% | 28.53% | 21.86% |
| Percentage of buildings in each grade (after switching the heating supplier and improving the building's envelope) | 0.42% | 20.08% | 3.36% | 16.63% | 26.16% | 33.34% |

The biggest difference between the upper and lower values is in grade five, with a difference of 8941 kg $CO_2$ p.a. Furthermore, 59.5% of detached dwellings within the scenario describing both the period after switching a heating supplier and improving the building's envelope have a grade of four or higher, meaning that this is the renovation scenario where most detached dwellings will save the most $CO_2$ if renovated. The least potential, not counting grade zero, comes from the scenario describing the period after improving the building's envelope, in that 85.2% of detached dwellings have a grade of two or lower.

**Table 8.** Grade distribution between the three different scenarios when looking at the indicator $CO_2$ emissions, and the total number of buildings in each grade.

| Grade | After Improving the Building's Envelope | After Switching the Heating Supplier | After Switching the Heating Supplier and Improving the Building's Envelope | Total Number of Buildings |
|---|---|---|---|---|
| 0 | 0.00% | 98.20% | 1.80% | 2387 |
| 1 | 63.71% | 0.00% | 36.29% | 5660 |
| 2 | 90.29% | 3.62% | 6.08% | 5656 |
| 3 | 25.36% | 44.60% | 30.04% | 5662 |
| 4 | 1.15% | 51.56% | 47.29% | 5659 |
| 5 | 0.25% | 39.51% | 60.25% | 5660 |

There are a few buildings that have no potential in the scenario describing the period after switching a heating supplier, which is due to the detached dwellings that already have a HP or DH. They were assumed to keep their heating supplier, so their potential would be zero. The scenario describing both after switching a heating supplier and improving the building's envelope also have small numbers of detached dwellings with a zero grade. This is due to the buildings that have biomass as a heating supplier, where the $CO_2$ emissions are lower than DH and HPs, which means that, when switching to these, there is an increase in $CO_2$ emissions.

Table 8 confirms the findings of Table 7. It is shown that 60% of the detached dwellings that received a grade five were in the scenario describing the period after switching the heating supplier and the scenario involving improving the building's envelope. This would therefore mean that the renovations that would save the most $CO_2$ are to switch the heating supplier and improve the building's envelope. It can also be seen that the smallest improvement on $CO_2$ savings would come from the scenario describing the period after improving the building's envelope, where 90.29% of detached dwellings received a grade two, and 63.71% received a grade one. Furthermore, the scenario describing the period after switching a heating supplier has the most detached dwellings in the middle grades, with 44.60% receiving a grade three, but most of the buildings in this scenario are in the higher grades. Note that the total sum of all the grades is 3 x 10,228, due to there being three scenarios.

From these two tables, it can be concluded that the type of heating supplier has a large impact on $CO_2$ emissions. The two scenarios where the heating supplier is changed result in more detached dwellings with a higher grade, meaning that they have the highest renovation potential and therefore the highest potential to save $CO_2$. This is caused by most detached dwellings in Rudersdal being supplied by gas, thereby switching to either DH or HPs, which in turn leads to a decrease in $CO_2$ emissions.

### 5.3. Results: Cost of Heating

The upper and lower values found for the cost of heating indicator are shown in Table 9. Like the two other indicators, these were found by percentiles. The biggest difference between the upper and lower values is again in grade five, with a difference of 104,871 DKK p.a. The scenario describing both the period after switching a heating supplier and improving the building's envelope has the highest potential to save money, where 19.67% of detached dwellings in this scenario have a grade of five. It can, however, be seen that for the scenario describing the period after improving the building's envelope, more buildings are in the higher grades, where 69.87% of detached dwellings in this scenario received a grade three or higher. Additionally, the scenario describing the period after switching the heating supplier and the scenario involving improving the building's envelope have 51.44% and the scenario describing the period after switching the heating supplier has

12.03% of detached dwellings, with a grade of three or higher. The lowest potential cost saved after a renovation comes from the scenario describing the period after switching a heating supplier and that involving improving the building's envelope, where 22.08% of detached dwellings have received a grade of one. Thus, this scenario includes both the highest potential and the lowest potential when looking at the percentage of buildings in grades one and five. The scenario with the least potential among detached dwellings, a grade of zero, is again that describing the period after switching a heating supplier, where 68.02% of detached dwellings have no potential to save money after switching the heating source. The increasing and decreasing nature of the grade ranges is illustrated in Figure 4.

**Table 9.** Grade ranges for the indicator cost of heating after applying the three different scenarios and the percentage of detached dwellings in each grade for the three different scenarios.

| Grade Ranges for cost of Heating After Applying Different Scenarios | No Potential | Lowest Potential | | | | Highest Potential |
|---|---|---|---|---|---|---|
| Grade | 0 | 1 | 2 | 3 | 4 | 5 |
| Lower value (EUR p.a.) | | 0.98 | 166.8 | 313.7 | 446.2 | 702.1 |
| Upper value (EUR p.a.) | 0.98 | 166.8 | 313.7 | 446.2 | 702.1 | 14,778 |
| Percentage of buildings in each grade (after improving the building's envelope) | 0.00% | 7.61% | 22.43% | 28.61% | 27.59% | 13.77% |
| Percentage of buildings in each grade (after switching the heating supplier) | 68.02% | 14.85% | 5.09% | 0.31% | 0.70% | 11.02% |
| Percentage of buildings in each grade (after switching the heating supplier and improving the building's envelope) | 9.56% | 22.08% | 16.92% | 15.45% | 16.32% | 19.67% |

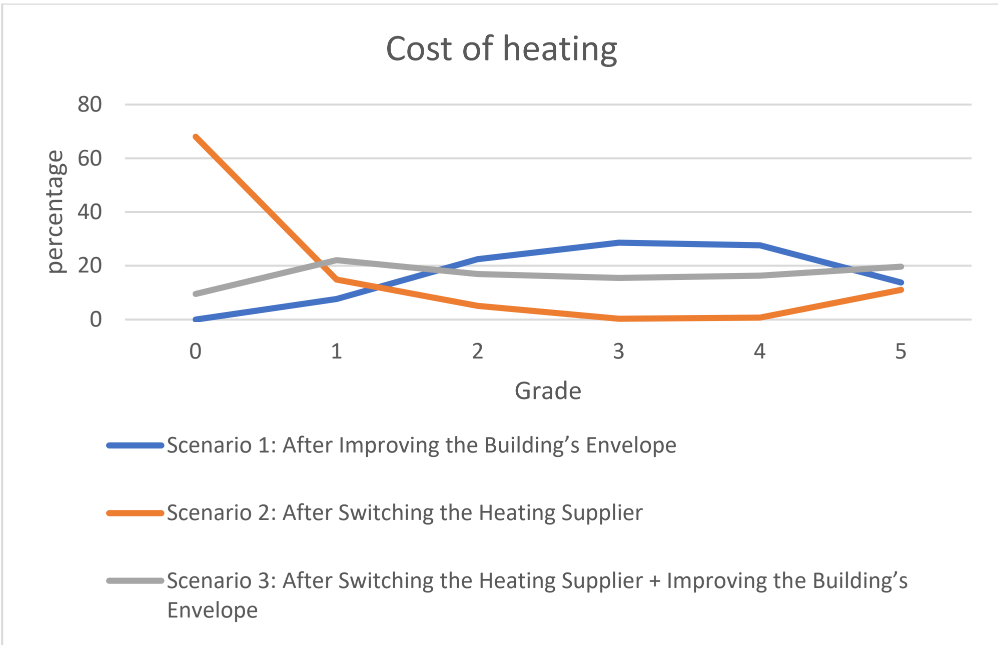



**Figure 4.** Cost of heating: the percentage of dwellings in each grading category for each scenario.

An overview of the grade distribution between the three different scenarios, and the total amount of buildings in each grade, can be seen in Table 10. It can be found that the highest percentage, 44.25%, of detached dwellings in grade five belongs to the scenario describing both the period after switching a heating supplier and improving the building's envelope, while most detached dwellings in grades two, three and four belong to the scenario describing the period after improving the building's envelope. It can be seen that 87.67% of the buildings that have grade 0 are in the scenario involving switching the heating supplier and that the total amount in grade 0 is 7935, corresponding to all of the buildings in this indicator.

**Table 10.** Grade distribution between the three different scenarios when looking at the indicator price of heating, and the total amount of buildings in each grade. Note that the total sum of all the grades is 3 × 10,228, due to there being three scenarios.

| Grade | After Improving the Building's Envelope | After Switching the Heating Supplier | After Switching the Heating Supplier and Improving the Building's Envelope | Total Number of Buildings |
|---|---|---|---|---|
| 0 | 0.00% | 87.67% | 12.33% | 7935 |
| 1 | 17.08% | 33.35% | 49.57% | 4555 |
| 2 | 50.46% | 11.46% | 38.08% | 4546 |
| 3 | 64.48% | 0.71% | 34.82% | 4538 |
| 4 | 61.85% | 1.58% | 36.58% | 4563 |
| 5 | 30.97% | 24.79% | 44.25% | 4547 |

*5.4. Results: Energy Label*

Figure 5 shows the percentage of detached dwellings for each energy label in Rudersdal municipality. Sixty-one percent of detached dwellings in Rudersdal do not have an energy label. Most detached dwellings in Rudersdal that do have one have a D label, including 14% of all buildings in Rudersdal. The second highest percentage of detached dwellings have a C energy label, followed by energy label E. There are only 4% of detached dwellings that have an energy label lower than F, 3% F and 1% G. Only 5% of detached dwellings in Rudersdal have an energy label of A, 1% A2020, 2% A2015, and 2% A2010. It can also be seen that 1% of detached dwellings in Rudersdal have a B energy label.

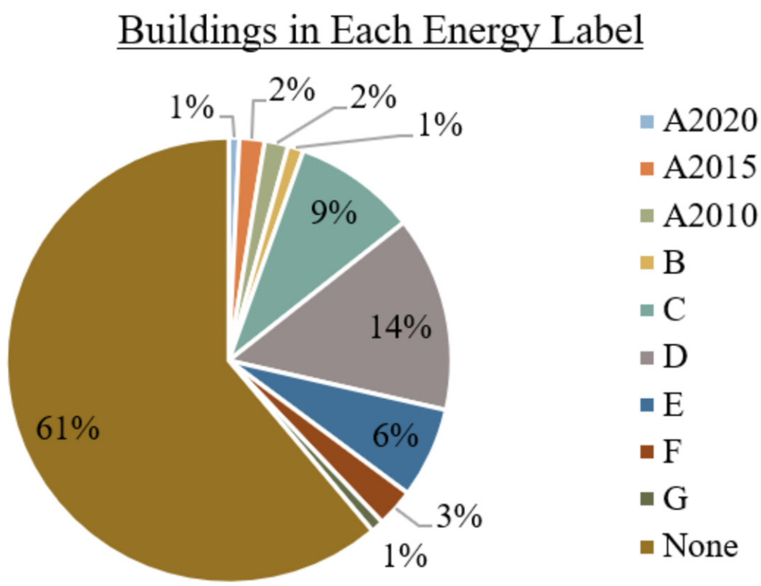
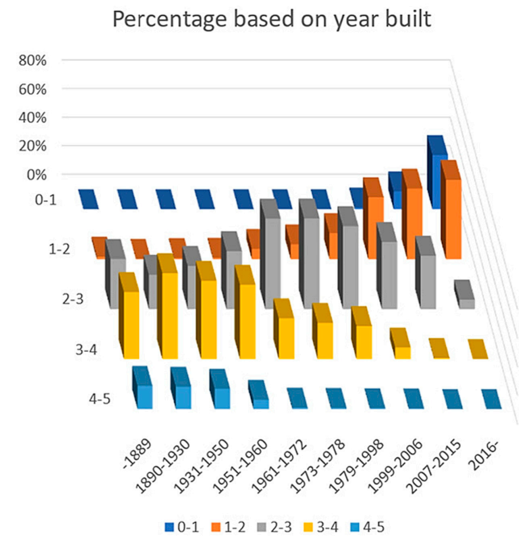



**Figure 5.** Percentage of detached dwellings in Rudersdal municipality for each energy label according to data from *Boliganalysen*.

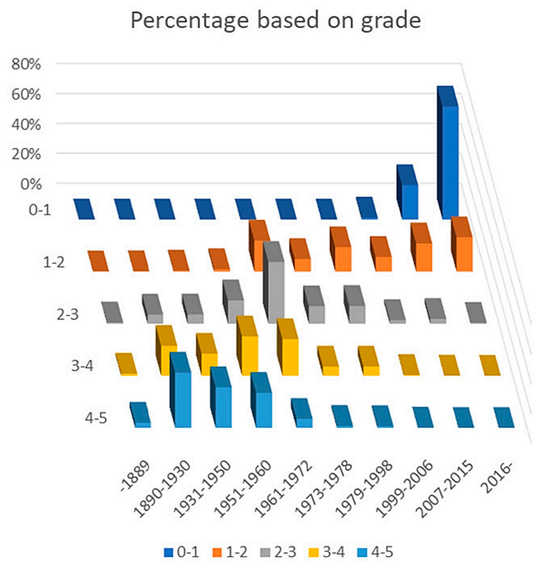
From Table 11 and Figure 6 the grade ranges, the number of detached dwellings in each grade and the percentage of each detached dwelling in each grade can be seen. The grade ranges from one to five, with A2020 getting a grade of one and both G and none getting a grade of five. Both G and none would therefore have the most potential to renovate because they have the worst energy label or have no energy label at all, meaning they either have a lot to improve during a renovation, or they know less about which improvements need to be made compared with buildings with an energy label. It can be seen in Table 11 that most of the detached dwellings in Rudersdal, 6350 buildings, have a grade of five. This can also be seen in Figure 6, where 62% of detached dwellings in Rudersdal have received a grade of five. Therefore, most buildings in the energy label indicator would have a high potential to renovate.

**Table 11.** Grade ranges for the indicator energy label, and the number of buildings in each grade. Note that G and buildings with no energy label are in grade 5, which shows the highest renovation potential.

| **Grade** | **1** | **1.5** | **2** | **2.5** | **3** | **3.5** | **4** | **4.5** | **5** |
|---|---|---|---|---|---|---|---|---|---|
| Energy label | A2020 | A2015 | A2010 | B | C | D | E | F | G and none |
| Number of buildings in each grade | 78 | 188 | 175 | 116 | 913 | 1452 | 674 | 282 | 6350 |

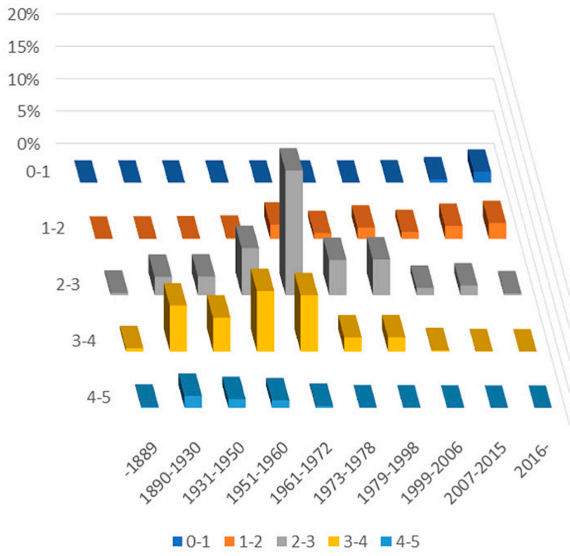



(**a**)




(**b**)

**Figure 6.** *Cont.*




(**c**)

**Figure 6.** (**a**) Detached dwellings in Rudersdal municipality shown as a percentage based on year of construction. (**b**) Detached dwellings in Rudersdal municipality shown as a percentage based on grade. (**c**) Detached dwellings in Rudersdal municipality shown as percentage based on total buildings.

### *5.5. Results: Final Grading of Detached Dwellings in Rudersdal Municipality*

The analysis carried out covers 10,228 dwellings in Rudersdal municipality and is hence difficult to illustrate. In Table 12 we have listed the number of houses in each grade category and their age class. The results are illustrated in Figure 6a–c. In Figure 6a the results are shown as the percentage based on the year built. This shows, for instance, that the largest share of buildings from 1961 to 1972 achieves a grade 3. Figure 6b shows the percentage of each grade and that the largest proportion of the grade 3 buildings date from 1961 to 1972. Figure 6c shows that the largest proportion of buildings date from 1961 to 1972 and that they achieve a grade 3.

**Table 12.** The numbers of detached dwellings in Rudersdal municipality shown for each grade and year built.

| Year | 0–1 | 1–2 | 2–3 | 3–4 | 4–5 | Total |
|---|---|---|---|---|---|---|
| –1889 | 0 | 2 | 39 | 52 | 18 | 111 |
| 1890–1930 | 0 | 3 | 292 | 727 | 189 | 1211 |
| 1931–1950 | 0 | 8 | 296 | 535 | 139 | 978 |
| 1951–1960 | 0 | 18 | 746 | 957 | 120 | 1841 |
| 1961–1972 | 0 | 226 | 1973 | 889 | 31 | 3119 |
| 1973–1978 | 0 | 92 | 558 | 223 | 7 | 880 |
| 1979–1998 | 0 | 178 | 566 | 225 | 6 | 975 |
| 1999–2006 | 3 | 107 | 116 | 20 | 1 | 247 |
| 2007–2015 | 52 | 205 | 155 | 3 | 0 | 415 |
| 2016– | 171 | 250 | 30 | 0 | 0 | 451 |
| Total | 226 | 1089 | 4771 | 3631 | 511 | 10,228 |

## 6. Discussion

The DH data on $CO_2$ and cost, used in the indicator analyses, are based on averages for all of Denmark. There can be a big difference in both $CO_2$ and cost when it comes to assessing the different DH networks in the country. According to *Forsyningstilsynet*, the cost depends on the choice of heating supplier, the network itself, whether heat loss is included in the wiring, the location in relation to customers, the size, and the ownership [31,32]. Table 7 shows that there is a big difference in kg $CO_2$ depending on the heating supplier, which can differ within the different DH networks. Additionally, heat loss in the wiring and the $CO_2$ emissions emitted in DH can differ considerably. All of this means that detached dwellings with DH in Rudersdal can have a greater or smaller renovation potential than is seen for the average Danish detached dwelling. According to Rudersdal's heating plan, there are two DH networks in Rudersdal, Holte Fjernvarme and Norfors. It would be interesting to follow up this study by determining the specific fuel mix used in these DH networks.

When using the results of these indicators, one should bear in mind that [25] uses detailed data from The Danish Energy Label Scheme on everything that is included when obtaining an energy label for all detached dwellings that had one in October 2020. Though 61% of Rudersdal's detached dwellings do not have an energy label, it would have been useful to have obtained these detailed data on the detached dwellings that do have one.

All of the indicators have a grade of zero, representing no renovation potential, except the energy label. One could argue that a detached dwelling that has the best energy label, A2020, has no renovation potential and should therefore have been assigned a zero. By changing A2020 to zero, all other energy labels might also have been assigned a lower grade, except for those buildings without any energy labels, which would still receive a grade of five. On the other hand, the requirement for the new EPBD initiative is that buildings with an energy label of G must be energy renovated before 2030, which would argue for G keeping the grade five. Using the same argument, F should also receive a grade five, whereas buildings with an energy label of F must be energy renovated before 2033. If G and F should both receive a grade of five, and grade A2020 a grade of zero, how would the other grades be assigned? There would be six remaining, which would need to be distributed between four grades (one to four). This might not be a problem if the grading system for the new initiative were different from the one we have today. One cannot be sure if the buildings that have a grade F today will receive an F after implementing the initiative. The best way of preparing for the new initiative would be to include everything that is included when an energy consultant calculates the energy label today (if the data had been available), use this to assign an energy label to all the detached dwellings, and from this find the bottom 15% and assign it a grade G, as the new labelling system will if implemented. If this is done correctly, one would need to assess all of the residences in Denmark to find the bottom 15%, and one would still not be sure that what is included when calculating the energy label today will be exactly the same after implementation.

Regarding the energy consumption, $CO_2$ emissions and price of heating indicators, it can be seen that, generally, the scenario describing the period after switching a heating supplier and improving the building's envelope is the one that represents the highest renovation potential because most detached dwellings receive a grade of five when this scenario is applied.

Switching the heating supplier to DH or HPs generally reduces the potential to save money. This is because the heat is supplied by gas in most of the detached dwellings in Rudersdal, which is one of the cheapest heating options today. The only way a gas-supplied detached dwelling might have the potential to save money would be to switch to a HP or to improve the building's envelope, as the consumption would be lower and would therefore cost less. However, gas, when switched to DH or heat pumps, has one of the biggest potentials in $CO_2$ emissions. In terms of gas heat supply and biomass heat supply and switching to DH or HPs, there will be some give and take. While biomass is better for the environment but costs more, as seen by biomass receiving a grade of zero for $CO_2$

emissions but mainly receiving a grade of five for cost, gas costs less but is worse for the environment, as seen by the way in which it mainly receives a grade of zero or one for cost but five for $CO_2$ emissions. This means that detached dwellings with gas or biomass as their heat supply received a high grade in either one of the indicators $CO_2$ emissions or cost of heating, but a low grade in the other. Electric heating and heating oil suppliers are more straightforward because the potential to switch is relatively high. For $CO_2$ emissions the detached dwellings with these heat suppliers mainly received a grade of three, and because of the cost they mainly received a grade of five.

To truly help the municipality and its residents to prepare for the new EPBD initiative, more raw detailed data on detached dwellings are needed, as well as information on renovation processes. In addition, the social pillar of sustainability needs to be measured to truly call it a domain-based framework.

## 7. Conclusions

Europe has, in general, an old building stock, and this old building stock is not energy efficient. The EU is therefore introducing new legislation to increase the rate of energy renovations in Europe. It is a significant challenge to find out which houses should be renovated, because that also depends on the heating supply. This paper reports on an indicator framework with four indicators that was created to investigate the energy efficient renovation potential of detached dwellings in Rudersdal municipality, Denmark. These were (i) energy consumption, (ii) $CO_2$ emissions, (iii) heating costs and (iv) energy labels. These indicators were developed based on the sustainability factors that were found in the literature review and are listed above. Three different scenarios were created to investigate which energy efficient renovation methods was the best option for residents in Rudersdal, these being as follows: (a) improving the building's envelope, (b) switching the heating supplier, and (c) both.

From the results, it can be concluded that the scenario with the highest renovation potential was the scenario involving switching the heating supplier and improving the building's envelope, in that most detached dwellings in this scenario received a grade of five. For the indicator $CO_2$ emissions, 60% of the detached dwellings that had received a grade of five were in the scenario involving switching the heating supplier and improving the building's envelope. From this indicator, it can be seen that switching the heating supplier had a big effect on the detached dwellings in that almost all of those (99.75%) that received a grade of five were in the two scenarios where the heating supplier was changed. In terms of $CO_2$ emissions, it can be seen that switching from a biomass heating supplier to DH or a heat pump resulted in no renovation potential, but that switching from gas, oil or electric heating would reduce $CO_2$ emissions substantially. For the indicator cost of heating, it could be seen that 44% of detached dwellings that received a grade of five were in the scenario involving switching the heating supplier and improving the building's envelope. For this indicator, it can be seen that switching from gas heating to DH or a heat pump was the least beneficial, whereas for biomass, electric heating and heating oil, it was very beneficial to switch to DH or a heat pump.

For the energy label indicator, it can be seen that 39% of the detached dwellings in Rudersdal have a valid energy label, leaving 61% without. The indicator results show that most buildings in Rudersdal would receive a grade of five with a high energy renovation potential. This is because so many detached dwellings in Rudersdal do not have a valid energy label and 1% of the detached dwellings in Rudersdal have an energy label of G, resulting in 62% of the detached dwellings receiving a grade of five.

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**Data Availability Statement:** Data are available on request. The data are not publicly available due to [GDPR].

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