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Relationships Between Measured and Calculated Energy Demand in the Norwegian Dwelling Stock

Trondheim, 12 2015

Project work

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Preface

This thesis is part of the specializing project in the 5-year Master of Science degree at the Norwegian University of Science and Technology, Department of Energy and Process Engineering.

Several people have been involved in the project and supported my work. I am grateful for the excellent supervision provided by my supervisor Helge Brattebø during the semester. Special thanks to my co-supervisor Magnus I. Vestrum, as well as Nina Holt Sandberg for helpful discussions and encouragement along the way. SINTEF Buildings and Infrastructure, through Judith Thomsen and Steinar Grynning, were helpful with providing data on new passive house projects. Kristian Stensrud at Heimdal Bolig AS, supplied the dataset for passive houses at Granåsen, Trondheim which yielded very useful results. Thanks as well to the Norwegian Water Resources and Energy Directorate (NVE) by Knut E. Bøhagen for supplying the dataset on energy performance certificates. I also wish to thank Anne Sigrid Nordby and Christian Solli for interesting input and discussions around the topic, and Thomas Haaland and Jakob Boye Hansen for proofreading and adding valuable comments.

The picture on the cover is a row of passive houses built at Stenbråtlia, Mortensrud in Oslo. Photography: H. Kicker, JKU Linz.

Summary

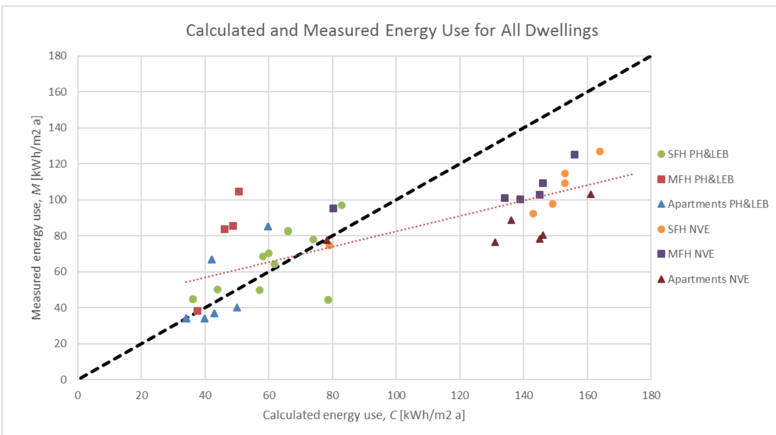
The main topic of this thesis has been to study relationships between measured and calculated energy use in the Norwegian dwelling stock, between different dwelling types and construction periods. The objective of the study was to close a knowledge gap on the actual ratio between measured and calculated energy demand in Norwegian dwellings. The background for the study is the decrease in specific energy consumption in the newer segments of the dwelling stock, and a need for a more precise modelling of energy use in the dwelling stock as the composition becomes more diverse.

A literature study on international literature revealed that measured energy consumption is expected to be more than the calculated value for dwellings with a low expected energy demand, and less than the calculated value for dwellings with a high expected consumption. To examine these findings in the Norwegian case, literature data on expected and measured energy use in Norwegian and Swedish passive houses has been gathered. A case study on passive houses in Trondheim is also evaluated with respect to calculated and measured energy consumption. Additionally, a dataset of about 22 000 Energy Performance Certificates (EPC) has been supplied by the Norwegian Water Resources and Energy Directorate, representing the remainder of the dwelling stock.

The data was divided into dwelling groups of single-family houses (SFH), multi-family houses (MFH) and apartments as well as age cohorts. Mean values for the ratio between calculated and measured energy consumption for space heating and domestic hot water were calculated. For the analysis of the EPCs, standard deviations within the age cohorts are calculated.

Although there are possible flaws in the data, like excessive removal of outliers or overestimation of energy use for lighting and electrical appliances, results show that energy consumption generally is below the calculated value for older dwellings, while it is above the calculated value for passive houses and low energy buildings as shown in the accompanying figure.

These results will have implications for future research in terms of scenario analysis of the dwelling stock, and implies that passive houses cannot optimally decrease specific energy consumption without willingness or knowledge from users. Policy makers must take this into consideration when assessing the viability of passive houses as a national standard before 2020.



Sammendrag

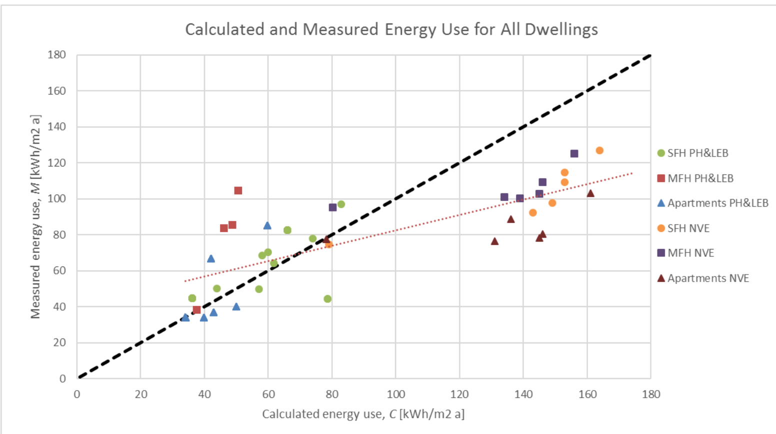
Denne oppgaven studerer forholdet mellom målt og beregnet energibruk i den norske boligmassen, mellom forskjellige boligtyper og alderssegmenter. Målet ved oppgaven er å forbedre kunnskap om det faktiske forholdet mellom målt og beregnet energibruk i Norske boliger. Bakgrunnen for oppgaven er nedgangen i spesifikk energibruk i nyere segmenter av boligmassen, og et behov for en mer presis modellering av energibruk i boligmassen, som følge av at komposisjonen blir mer og mer kompleks.

Et litteraturstudie på internasjonal litteratur avdekket at målt energibruk er forventet å være høyere enn den beregnede verdien for boliger med lav beregnet energibruk, og mindre enn den beregnede verdien for boliger med høy beregnet energibruk. For å undersøke dette i norske boliger, ble litteraturdata på målt og beregnet energibruk i norske og svenske passivhus samlet inn. I tillegg, ble målt og beregnet data på et passivhusprosjekt i Trondheim evaluert. Et datasett av energimerkede boliger fra Norges Vassdrags- og Energidepartement (NVE) på 22 000 boliger ble analysert for å representere resten av boligmassen.

Målingene ble delt opp etter boligtyper: eneboliger (SFH), flermannsboliger (MFH) og leiligheter. I tillegg ble boligtypene delt opp etter alderskohorter. Gjennomsnittsverdier for forholdet mellom målt og beregnet energibruk til oppvarming og varmtvann ble beregnet. For å analysere data fra Energimerkeordningen ble også standardavviket for aldersgruppene beregnet.

Selv om det er mulige feilkilder ved datasettene, som fjerning av data som egentlig er korrekt, og overestimering av energibruk til elektriske apparater og belysning, viser resultatene tydelig at faktisk energibruk generelt ligger under den beregnede verdien for gamle hus, mens den generelt ligger over for passivhus og lavenergibygg som vist i den vedlagte figuren.

Disse resultatene vil ha betydning for fremtidig forskning i forbindelse med scenarioanalyse av boligmassen, og de impliserer at passivhus ikke kan senke spesifikk energibruk optimalt uten kunnskap eller villighet fra brukersiden. Politikere må ta dette i betraktning når de vurderer mulighetene for å ha passivhus som nasjonal standard før 2020.



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Abbreviations

DD degree-day

DHW domestic hot water

EBLE Evaluation of Buildings with a Low Energy Demand

EPBD the Energy Performance of Buildings Directive

EPC Energy Performance Certificate

EPR Energy Performance Rating

ESP energy saving potential

GHG greenhouse gas

MFH multi-family houses

NVE the Norwegian Water Resources and Energy Directorate

SFH Single-family houses

1 Introduction

The residential building stock is responsible for a large percentage of total energy use in Norway. In 2012, 20% of the total energy consumption on the Norwegian mainland, originated from residential buildings, which represents 47.3 TWh of total consumed energy [1]. This large share of the national energy demand, is subject to policies on energy efficiency and subsequently, as the building stock ages [2], measures to increase energy efficiency become increasingly important. Furthermore, there is a significant potential of greenhouse gas (GHG) mitigation connected to energy efficiency and shifts toward less carbon-intensive energy carriers.

With an ageing building stock follows an increased need for refurbishment. In addition, new buildings are being added to the stock with better energy performance. As there is an increased number of houses with a low-energy profile (TEK10, Passive houses, Zero energy buildings), the building stock becomes more diverse, and energy use will differ among different segments. Consequently, the energy saving potential (ESP) will depend on dwelling age, dwelling type and standard, and geographical location among other factors. A more complex dwelling composition will require a detailed modelling of the dwelling stock.

To improve the precision of modelling, and verify the energy saving potential for buildings with a higher standard, this study examines the relationship between measured and calculated energy use in the Norwegian Dwelling stock. This is not a new topic, and several similar studies have been conducted across Europe [3] [4] [5] [6]. Nevertheless, few such studies have been conducted in Norway and therefore, this study aims to aggregate data already done on this topic and analyse different parts of the dwelling stock for relationships between measured and calculated energy use.

This paper focuses on exploring the following research questions:

- What is the relationship between measured and calculated energy use in the Norwegian dwelling stock, when segmented into age cohorts and building types?
- What are the phenomena and causes of the ratio between measured and calculated energy use for space heating, and how does it differ for varying building type and age segments of the stock?
- What are the implications of these findings for policy recommendations and future analysis of national energy demand in the Norwegian dwelling stock?

To answer these questions an extensive literature search has been conducted, both in international and domestic literature on measured and calculated energy use in passive houses and low energy buildings. Specifically, energy use for space heating and domestic hot water (DHW) is assessed. Measurements and calculations done on passive houses by Heimdal Bolig AS are analysed in a separate case study. Additionally, a dataset supplied by the Norwegian Water Resources and Energy Directorate (NVE) on measured energy use in dwellings gives a holistic understanding on trends in energy use in the entire dwelling stock, when compared to calculated values of energy use in stereotypical dwellings from different construction periods.

2 Background

This section shows the energy use in Norwegian dwellings during the last 40 years. The dwelling stock is categorized into building types and age cohorts, and the calculated energy use for these segments is presented. Furthermore, the drivers and policies leading towards a lower specific energy demand for dwellings are outlined, illustrating how important it is to validate energy efficiency measures, especially when doing calculations on a macro scale like energy use in Norwegian dwellings.

2.1 Historical Development of Energy Use in Households

Household energy consumption has been estimated at around 44-46 TWh/yr for the last ten years. As seen in figure 1, energy consumption has been steadily on the rise from 1976 until the early 1990s. In recent decades, the growth rate has slowed down and after the turn of the millennium the consumption has stayed more or less constant. The exceptionally high consumption in 2010 can partially be explained by the low outside temperatures that occurred this year. While electricity consumption has increased during this time, oil consumption for household use has decreased. The decrease in fossil fuel consumption is mainly driven by a phase-out of oil-fired boilers and a gradual switch to non-fossil heat sources, like electric heaters and heat pumps, as a result of the 1970s oil crisis and rising oil prices in general.

[7] presents three main causes for the flattening of total energy consumption in Norwegian households:

- As more and more people live in cities, relatively more apartments than single-family houses or multi-family houses are built. This has led to the growth in floor area per person being reduced in recent years. It is important to note that the floor area per person is still increasing, but the growth rate has slowed. As the growth in floor area per person slows, the growth in energy consumption per person slows as well.
- A continuous implementation of energy efficiency measures has lead to a gradual decrease in energy consumption per floor area per year (kWh/m^{2}a).
- With global temperatures rising as a result of climate change, heating requirements have decreased, leading to lower energy consumption per square meter.

Energy consumption per square meter has decreased by 14% since the early 1990s (from 210 to 180 kWh/m^{2}a) [8]. The decrease in energy consumption per floor area has a number of drivers, one of the most important being refurbishment in the existing building stock. In addition, new buildings with better standards like TEK87, TEK97 and TEK10 are being added to the building stock, while old, energy intensive buildings are being demolished. Improvements in technology like heat pumps and more efficient heating systems also contribute to the reduction in energy consumption.

Conversely, demographic drivers work to increase the energy consumption per square meter. The population of Norway has increased, and the area (m^2) per person and per household is still

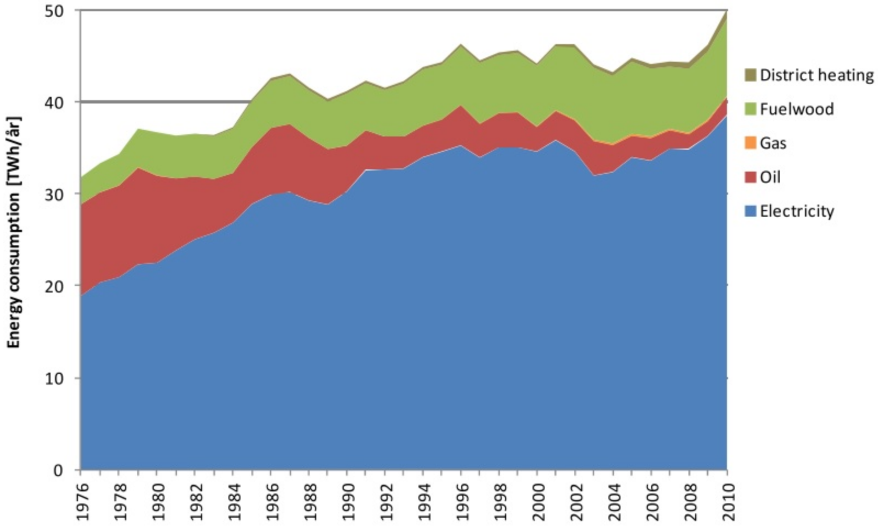


Figure 1: Household energy consumption, 1976 to 2010. [8]

increasing, although at a slower rate than in the 1990s. The number of persons per household is decreasing, requiring additional buildings to the stock. All in all the demographic drivers contribute to a net increase in total energy use.

Additionally, energy consumption for appliances, lighting and electrical equipment, hereby referred to as el. specific energy consumption, has steadily increased throughout the 20th century. Using data from the Swedish Energy Agency [9], electricity consumption for appliances and equipment has increased from 2900 kWh per dwelling (kWh/dw) in 1970 to around 4500 kWh/dw in 2013. All drivers that influence energy consumption are summarized in table 1. Thus, taking all these factors into consideration one can explain the growth of Norwegian energy consumption in recent decades.

Driver	Trend	Effect of driver on energy consumption
Population	Increased a lot since the 1990s	Positive
Number of households	Increased a lot since the 1990s	Positive
m^2/household	Increased, but slowed growth throughout the 2000s	Positive
m^2/person	Increased steadily	Positive
Persons/household	Decreased since the 1990s	Positive
El. specific consumption	Increased since the 1970s	Positive
Outside temperature	Increased	Negative
Technological improvements	Increased	Negative
Renewal of dwelling stock		Negative

Table 1: Drivers that influence energy consumption in dwellings (kWh). A positive effect leads to an increase in energy consumption, while a negative effect leads to a decrease.

2.2 Segmented Energy Use in the Dwelling Stock

This section presents an estimation of the energy use in the different parts of the dwelling stock. Some accuracy for total energy use in the dwelling stock is sacrificed to show the relative contributions to energy use from different building types and age cohorts. In [10] the Norwegian dwelling stock from 2005 is split into types of buildings and their energy performance. From this, a total estimated energy use in the dwelling stock is presented. The Norwegian dwelling stock of 2005 consists of about 2.2 million dwellings. In 2014, this number was at 2 446 363 dwellings [11]. These dwellings can be categorized into three main groups:

- Single-family houses (SFH)
- Divided small houses, also called multi-family houses (MFH)
- Apartments

Single-family houses, or detached houses are free-standing residential buildings usually occupied by one household or family. Also included in this definition are free-standing residential buildings with an additional basement suite or a similar dwelling, and holiday homes e.g. cabins. Around 57% of the dwelling stock is included in this category.

Multi-family houses are houses with multiple housing units contained within one residential complex. These are around 21% of the total dwelling stock. Included are vertically and horizontally divided houses, or more specifically:

- Chain detached houses
- Semi-detached houses
- Quad homes
- Townhomes

Apartments are often included in the multi-family housing definition, but are evaluated separately in this analysis due to the different characteristics of the dwelling type. Apartments are single dwellings which are part of a bigger dwelling complex like detached blocks of flats and combined buildings. This constitutes around 22% of the dwelling stock.

The dwellings are further divided into six age cohorts, according to year of construction, as shown in table 2.

Figure 2 gives additional explanation to the composition of the building stock. The secondary axis denotes the average U-value of the building façade, with lower U-values providing higher thermal

Cohort number	1	2	3	4	5
Construction period	before 1945	1946-1970	1971-1980	1981-1990	1991-2005

Table 2: Age cohorts by construction period, for calculation of energy use in dwelling stock.

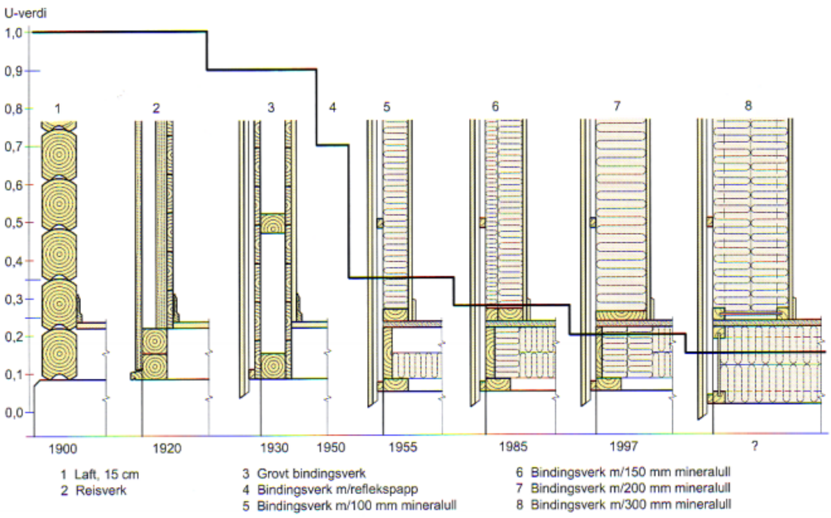
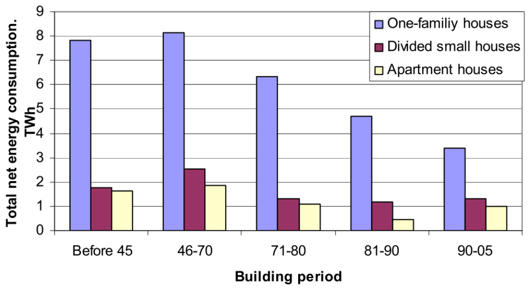


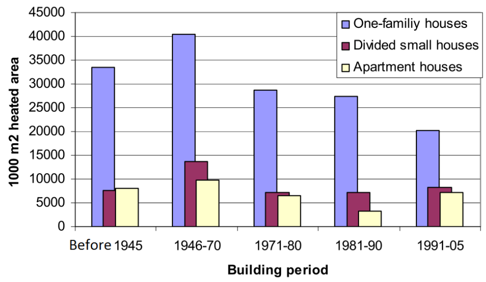
Figure 2: Advancement in insulation in Norwegian dwellings throughout the 20th century.[12]

insulation. General thermal insulation levels are similar for the age cohorts, with an especially large decrease in U-value occurring in the 1950s. Figure 3 shows the relative contributions for all dwelling types and age cohorts.

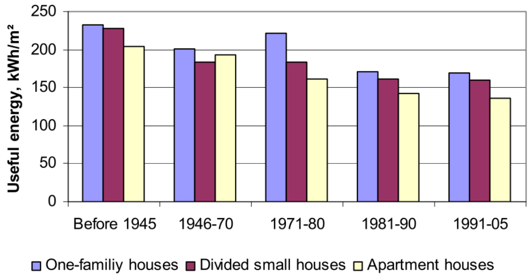
With the composition as given in table 3 and specific energy demands and heated area as shown in figure 3, total energy use is estimated to be 49 TWh. This is approximately 8% higher than the stationary energy consumption based on official Norwegian statistics (see figure 1). Even though specific energy consumption varies more with age cohorts than building types, single-family houses have by far the largest contribution to energy use because of the large total area of the stock. The cohort with the largest contribution to energy use is single-family houses from 1946-1970. This is because of the large amount of homes built in the period after World War 2, and the poor insulation levels of constructions at the time.



(a) Total net energy consumption



(b) Heated area



(c) Specific energy consumption

Figure 3: Total net energy consumption, specific energy consumption and heated area for all dwelling types and age cohorts as defined by [10]. Purple bars represent single-family houses, red bars are multi-family houses and the yellow bars are apartments.

	Before 1945	1945-1970	1971-1980	1981-1990	1991-2005
Single-family houses					
Number of dwellings in the group	277 249	342 225	214 572	206 920	159 850
Number of dwellings per house	1	1	1	1	1
Dwelling area per house	121	118	133	133	144
Number of stories	2	2	2	1.5	1.5
Percentage of total dwelling type	23%	29%	18%	17%	13%
Multi-family houses					
Number of dwellings in the group	83 436	136 153	72 105	71 460	90 154
Number of dwellings per house	2	4	4	4	2
Dwelling area per house	92	101	100	101	124
Number of stories	2	2	2	1.5	2
Percentage of total dwelling type	18%	30%	16%	16%	20%
Apartments					
Number of dwellings in the group	106 869	142 764	83 245	41 380	88 914
Number of dwellings per house	8	24	24	24	20
Dwelling area per house	75	68	79	78	81
Number of stories	4	4	4	4	4
Percentage of total dwelling type	23%	31%	18%	9%	19%

Table 3: Composition of the dwelling stock as defined by [10], with supplementary information about the different dwelling types and construction periods.

2.3 A Shift Towards Lower Specific Energy Consumption

One of the main driving forces towards stricter building standards is the Energy Performance of Buildings Directive (EPBD). This directive was set by the EU and aims to improve energy efficiency in the building stock. In 2003, the EPBD was implemented in Norway. It requires that countries set a minimum standard for energy performance, establish a scheme for building's energy performance, as well as a scheme for the energy validation of some technical installations in buildings. These requirements are represented through the TEK10 building standard, which is regulated by the Norwegian Building Authority, and the energy labelling regulations which are administrated by NVE.

In 2010 the EU introduced more stringent energy performance regulations represented by the New Energy Performance of Buildings Directive. This states that new buildings must be so-called nearly zero energy buildings by the end of 2020. The standard has not yet been implemented in Norway, since the country is not part of the European Economic Area (EEA) agreement.

As a consequence of the EPBD, the energy labelling scheme was implemented in July 1, 2010. Anyone selling or renting out houses and all commercial buildings larger than 1000 m^2 must have a valid energy certificate. It consists of an energy label that shows the buildings energy performance under normal use. In this way, the energy certificate is independent of how the owner actually uses the building.

2.4 Passive Houses and Low Energy Buildings

The passive house standard is a natural extension of the already outlined trends in energy use in the Norwegian dwelling stock, that is the gradual decrease in energy use per area and the shift towards alternative energy sources. With the EU moving towards more stringent building regulations, the passive house concept was developed in Germany in the 1990s by the Passivhaus-institute in Damstadt. It is characterized by constructions with high insulation levels, mechanical ventilation systems with heat recovery to reduce heat losses, and an expected low energy demand for space heating and DHW.

In Norway, the standard is implemented through NS3700 'Criteria for passive houses and low energy buildings'. The standard separates between passive houses and low energy buildings of class 1 and class 2, with passive houses having the strictest requirements for U-values of the construction and energy consumption for space heating. Additionally, dwellings are required to utilize another heat source than electricity or fossil fuels for a considerable amount of the total heating demand. Examples of other heat sources are heat pumps, district heating or solar heating systems. As a reference value, specific energy use for space heating and DHW for passive houses is expected to be around 40-50 kWh/m^2a. As there are diminishing returns to energy efficiency with a higher resource input, there is an increasing need for verification of energy efficiency measures in order to holistically weigh both the costs and benefits of such measures against each other. This is one of the main drivers behind this report.

2.5 Energy Simulation Models

To accurately model energy use in the dwelling stock it is important to have simulated values that reflect the actual energy use in the dwellings. The standard 'NS 3031: Calculation of energy performance of buildings - Method and data', creates a common basis for simulations of energy use in dwellings. This is done both to verify that the building follows the given building standard, and in order to issue and Energy Performance Rating (EPR) for the given dwelling. To make it easier for construction engineers and architects to optimize the energy performance of buildings the simulation program SIMIEN [13] was created. This program takes in technical specifications of a building, like U-values and use patterns, and returns relevant data, like the expected total and use specific energy consumption and the expected energy performance of the building. The calculations are done in compliance with NS 3031. A Swedish equivalent to SIMIEN is DEROB-LTH, orginially developed at Austin School of Architecture, and further developed at Lund Institute of Technology [14].

However, these calculations use standard parameters to assess the influence of user behaviour on energy use. This can be an advantage when assessing the EPR of a dwelling independent of the type of user who will inhabit it, but can lead to considerable errors when doing simulations on a macro scale, like energy use in the whole Norwegian dwelling stock. The recent EU project TABULA, followed by the EPISCOPE project[15], oversees trends in the Norwegian dwelling stock for scenario analysis to forecast the demand for refurbishment of the dwelling stock, among other things. Specific energy demands that better reflect the effect of user behaviour within different segments of the stock, would give a more precise energy simulation for the entire stock. This is a knowledge gap that this report seeks to fill.

3 Literature Review

This section presents existing literature on measured and calculated energy use in the dwelling stock. To begin, a brief presentation of international studies in Western European countries is given. The scope is then narrowed down to Nordic studies, with Swedish literature thought to most closely represent the Norwegian situation. Norwegian literature on energy use in the dwelling stock is presented. Finally, a study on Danish low energy buildings is presented, giving an example of methodology for assessing case studies on measured and calculated energy use.

3.1 International Studies

[5] conducted an extensive study on calculated energy consumption (Energy Performance Rating) as well as the measured values for 3400 German homes, given in kWh/m^{2}a. The data was analysed with respect to the EPR Space and water heating, and concluded on four major trends in the data, that can be applied to several other West-European countries.

- There is a large gap range between measured energy consumption (kWh/m^{2}a) for dwellings with an identical EPR.
- On average, measured consumption tends to fall 30% below the calculated EPR.
- As the measured EPR (kWh/m^{2}a) increases, the gap between the measured and calculated values increases, ranging from about 17% for dwellings with an EPR of 150 kWh/m^{2}a to about 60% for dwellings with an EPR of 500 kWh/m^{2}a. This is defined as 'the prebound effect'.
- For dwellings with an EPR lower than 100 kWh/m^{2}a, the dwellers tend to consume more energy than calculated. This is referred to as the rebound effect.

The analysis concludes that, in general, the higher energy consumption per unit of area in a dwelling, the more economical the occupants tend to behave with respect to their space heating. Other studies in several European countries give weight to this theory.

[16] found an identical effect in their analysis of data from 4700 households in the Netherlands. The average measured heating demand was found to be around 70% of the calculated value. This ratio was lower for dwellings with a high energy consumption and increasing to more than 100% of the measured energy for dwellings with a higher energy efficiency.

In a British study, [17] applied a Structural Equation Model (SEM) to find a correlation between a dwelling's energy demand and its energy efficiency. The energy efficiency is expressed as an EPR, Standard Assessment Procedure (SAP) with a rating from 1-100, with 100 being the most energy efficient. The study used data from the English House Condition Survey of 2531 dwellings, and found that homes with a high SAP have a 'propensity to consume more energy' compared to the expected energy consumption. Kelly also suggests that due to the law of diminishing returns, the cost of further increasing the efficiency of homes with a high SAP will be high. Furthermore, retrofitting of homes with a low SAP rating may lead to an increase in internal temperature

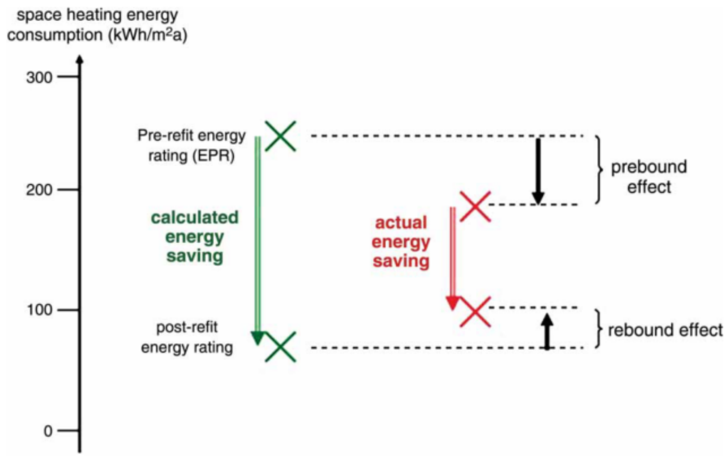


Figure 4: Schematic showing how the rebound and prebound effects might limit energy saving to be reduced from its theoretical amount.[5]

rather than a decrease in energy consumption.

[18] compared measured space heating energy consumption with the Energy Performance Certificate (EPC) of french households. The EPC contains data on a MWh per dwelling/year (MWh/dw.y) basis, revealing information about expenditure against the dwelling's total energy rating. The study defines the energy intensity factor, I, so that:

$$I = \frac{C_{obs}}{C_{EPC}} \tag{1}$$

Where:

C_{obs} : the observed space heating energy consumption.

C_{EPC} : the theoretical space heating energy consumption based on conventional engineering calculations such as an EPC.

Results indicate that French households spend 2-5% of their income on space heating and achieve an energy intensity of around 0.6. Households in better buildings, or who have higher incomes, have an energy intensity of 0.8-1.1, while spending less than 2% of their income on space heating. Again, this study confirms that the energy intensity factor tends to be higher for dwellings with a better standard.

As a conclusion, [5] suggests that variations in actual energy consumption compared with the EPR, (including both the prebound and rebound effect) may nullify a significant portion of the gains in energy savings as illustrated in figure 4.

3.2 Nordic Studies

3.2.1 Janson et al.(2010)

In a doctorate thesis [19], four passive house projects are thoroughly evaluated with respect to energy use, ventilation performance and satisfaction both from a client and customer perspective. Three of the projects are apartment buildings, while one is a single-family house. In two of the projects the measured energy use lies above the calculated energy use, while the measurements for the other two studies lie below the calculated value. Some of the inhabitants that had exceptionally low energy consumption for space heating, were explicitly asked why they did not heat their dwellings. Many people reported that they did not feel the need for additional heating, and the author cites the number of inhabitants and the location of the apartments in the building as influencing factors, among others. Dwellings with a relatively high number of people will tend to have a lower requirement for space heating as more body heat is given to the surroundings. The calculations and measurements found in the thesis have been used in this study and the individual projects are further described in Section 4.3.

3.2.2 Dokka et al. (2011)

SINTEF Building and Infrastructure conducted interviews on consultants in companies and organisations related to calculations and measurements for energy use in buildings [20]. To gain knowledge about the gap between measured and calculated energy use, the study interviewed consultants in Skanska, Rambøll, Norconsult, Multiconsult and the Norwegian Home Builders' Association. The following relations and experiences are mentioned as relevant for deviations between the actual and measured energy use in buildings:

- Standardized input data in the calculation model do not correspond with real user behaviour.
- Assumptions used in calculations may not follow through to the actual construction of the building.
- Consultants have poor experience in the assessment of actual energy consumption.
- Calculations of actual energy use are not prioritized.

Furthermore, the report sets guidelines for establishing a database on the measured and calculated energy use in the dwellings stock. The report states the importance of such a database to be able to thoroughly evaluate energy use, but it is clear that work on such a database has not yet been completed in Norway.

3.2.3 Langseth (2011)

A report done for Xrgia by [21], compares measured and calculated energy use of low energy and passive houses in 64 dwellings built in Norway, Sweden, Germany, Austria and Switzerland. The results are shown in figure 5. 29 dwellings report a higher energy use for space heating than the calculated value, and 17 dwellings report a lower value.

In addition to systematic errors in the measurements, the authors mention several suspected causes for the discrepancy between the measured and calculated values:

- Errors in the construction and engineering errors.
- Errors in in the technical installations, wrong adjustment of thermostat and ventilation systems, compared to design conditions.
- Higher internal temperatures than the calculations.
- Erroneous design of the building, failure to consider user behaviour.
- The use phase of the dwelling not following design specifications, including higher DHW consumption than assumed.

The authors make the conclusions that the measured energy use in passive houses and low energy dwellings generally lie above the calculated value. This is true both for energy for space heating and total delivered energy. While this study finds general relationships between the measured and calculated energy use in dwellings, one of its main flaws is that it only incorporates 4 measurements from Norwegian dwellings. Additionally, this study only covers passive houses and low energy buildings. There is clearly a need for more data on this topic, as no Norwegian studies are to be found on the dwelling stock as a whole. This project thesis aims at closing this knowledge gap.

3.2.4 Energy Use in Danish dwellings

To show how an evaluation on measured and calculated energy use in dwellings usually is conducted, a study on 65 social housing units by [6] is presented. The dwellings are located in Stenløse Syd in Denmark, and are defined as 2-3 storey low-rise, high-density housing settlements. Consisting of eight long detached blocks of varying lengths, the buildings are constructed according to Danish low-energy standard class 1 or better [22], classifying them as ultra-low-energy housing units.

The monitoring results compare measured energy use for space heating and DHW consumption with calculated values. Energy consumption was calculated using the Danish computer program Be06, the official program for verifying that specifications comply with building regulations. Space heating consumption was recorded during the winters of 2008-2009 and 2009-2010. As shown in figure 6, results show an average energy consumption for space heating of buildings of 26 kWh/m^{2}a. This corresponds to a 73% increase in the measured values compared to the initial

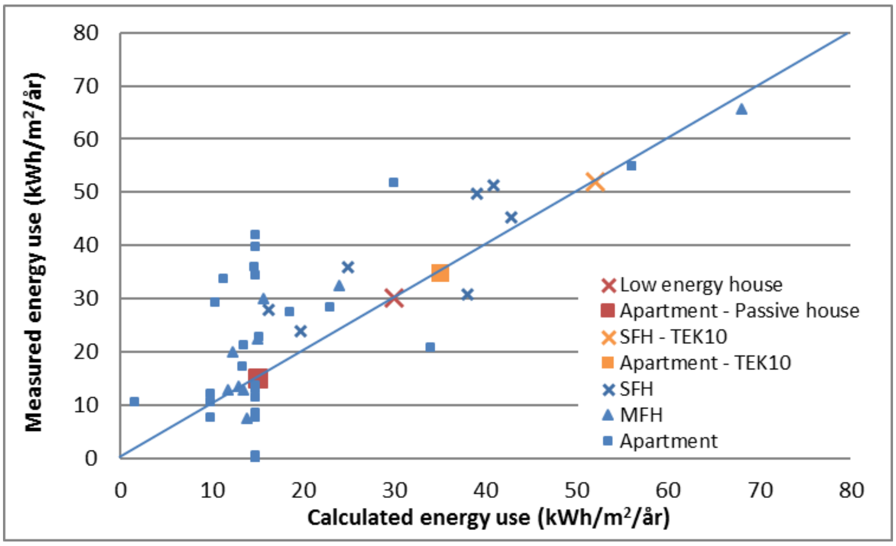


Figure 5: Measured and calculated energy use for space heating in passive houses. Red markers are reference values to buildings standards. Figure translated from Norwegian from [21]

calculated value of 15 kWh/m^{2}a, or an energy intensity factor, I of 1.73. The two major factors contributing to the discrepancy between the expected and measured values, are higher infiltration losses and higher operating temperatures in the dwellings. When each of these parameters was accounted for, the calculated heating energy use was given as 19.5 kWh/m^{2}a for calculations with a higher air change rate, and 25.2 kWh/m^{2}a for calculations with a higher indoor temperature. It is unclear if the study corrected the measured values with respect to outside temperature or not.

There seems to be an overwhelmingly large gap for DHW consumption with a total energy use given at 278 MWh/yeah. The authors suspect a circulation loss of 75% when comparing this value to the actual measured consumption at approximately 20.5 kWh/m^{2}a. The calculated energy consumption for DHW was 11.3 kWh/m^{2}a, giving an I of 1.81.

The same study also did a comparison of measured and calculated energy consumption of a detached single-family house in the same location. Although the measurements were found to be erroneous for parts of the year, table 4 shows measured and calculated values for the months with correct measurements. Calculated values were corrected for different factors, i.e. small errors in the input concerning heat recovery efficiency, internal heat loads and temperature factors for constructions. Both the original and corrected values are listed in table 4. As many factors influence the actual energy use in dwellings, in order to preserve transparency, it is important to thoroughly present specifics of the studies. This study is not used further in this report since the scope only includes dwellings in Norway and Sweden, but the other the studies assessed in section 4.3, are presented in a similar way to the Danish study.

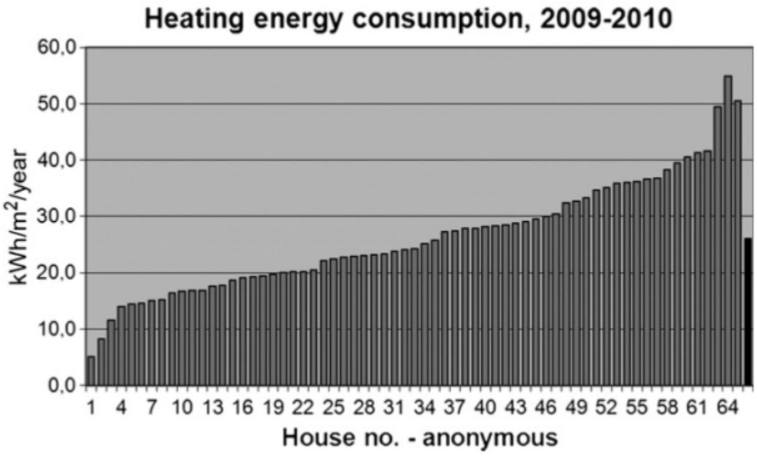


Figure 6: Energy consumption for space heating in 65 Danish housing units, kWh/m^{2}a. The dark bar denotes average.[6]

Month (-)	Measured (kWh)	Calculated (kWh)	
		Original	Adjusted
2010-01	1088	537	545
2010-02	964	433	440
2010-03	778	307	312
2010-04	363	138	141
2010-05	345	98	97
2010-06	198	89	88
Total	3736	1602	1623

Table 4: Electricity consumption for heating in a Danish detached single-family house - measured and calculated values. [6]

4 Methodology

Many different sources were used in this report to find empirical data for measured and calculated energy use in the Norwegian dwelling stock. Norwegian and Swedish literature was used to cover passive houses and dwellings with a low energy demand. In addition, several public and private instances were contacted to gain additional data on these building types. SINTEF Building and Infrastructure are conducting a project on Evaluation of Buildings with a Low Energy Demand (EBLE), and provided some data on specific projects. Heimdal Bolig AS, one of the major home builders in the Trondheim region, provided measurements and simulations of their Passive house project at Granåsen in Trondheim. A dataset on EPCs was also given from correspondences with NVE. A set of almost 22 000 EPCs, conducted by NVE, was analysed with respect to measured and calculated energy use for space heating and DHW. All evaluations are done in Excel.

4.1 The Energy Intensity Factor and the Measured Deviation from Calculations

Several important concepts are mentioned in literature when discussing the measured and calculated energy use in buildings. [3] discusses a phenomenon called the "rebound effect", which describes increases in the consumption of energy services that often follow energy efficiency improvement. A literature survey revealed several meanings of the term and defines the "classic" rebound effect, the "energy savings deficit" and the "energy performance gap", depending on the calculation method used to compute the metric. The study reveals confusion within the scientific community regarding definitions and a large discrepancy in the 'rebound effect' depending on the actual metric used. Thus, it is important to define a relevant metric when comparing the energy performance of, and the gap between measured and calculated energy use in buildings.

To evaluate the relationship between measured and calculated energy use in the dwelling stock, two parameters were calculated, the energy intensity factor I, and the difference between measured and calculated energy use ΔE. The energy intensity factor is given in a similar manner as [18]. Two values are defined,

M : Measured energy use for a dwelling (kWh/m^{2}a)

C : Calculated energy use for a dwelling (kWh/m^{2}a)

The energy intensity factor I then becomes similar to (1) (pp. 10),

$$I = \frac{M}{C} \tag{2}$$

In this way, if the measured value is higher than the calculated value, I will be higher than 1, and in the opposite case it will be lower than 1. To find the magnitude of the deviation (kWh/m^{2}a),

$$\Delta E = M - C \tag{3}$$

If measured energy use is larger than the calculated value, ΔE is positive. In the opposite case ΔE will be negative. Unless stated otherwise, energy use for space heating and DHW is assessed.

4.2 Typologies of the Dwelling Stock

In order to analyse and compare different parts of the dwelling stock, one must first classify and divide it into useful parts. Thus, all the data collected is segmented into different building types and age cohorts. Energy use will vary depending on these parameters. The dwelling stock is divided into three subsets as given by [10] and described in section 2.2, namely single-family houses, multi-family houses and apartments. Furthermore, dwellings from the EPCs are segmented into age cohorts as shown in table 5, depending on construction period as given in [23]. The age cohorts differ from [10], as buildings built after 2005 are also included.

Cohort number	1	2	3	4	5	6	6.1	6.2
Construction period	1850-1955	1956-1970	1971-1980	1981-1990	1991-2000	2001-2015	2001-2010	2011-2015

Table 5: Age cohorts by construction period, used when analysing the NVE dataset.

Cohort 6 contains relatively few measurements, therefore it was retained as a whole for consistency. However, it was also advantageous to further divide it into two sub-cohorts (6.1 and 6.2), to better reflect the change in building standard after the implementation of TEK10. This cohort is evaluated both as a whole and with the two sub-cohorts in mind.

4.3 Literature Data

Data from Norwegian and Swedish literature on passive houses and low energy buildings was gathered to calculate I and ΔE for this dwelling group. To find an average I and ΔE for passive houses and low energy buildings, a weighted average of all the studies with respect to the number of measurements for each study was calculated. What follows is a description of all the studies used in the assessment of the energy intensity factor for passive houses and low energy buildings. For specific data on measured and calculated energy consumption for the studies, see Appendix A.

4.3.1 Swedish Studies

[24] analysed 20 terrace houses in Lindås outside of Göteborg built after the passive house standard, finished in 2001. Each house is equipped with a mechanical ventilation system with heat recovery. The exhaust air in a counter flow heat exchanger heats the supply air, with a heat recovery of approximately 80%. Solar collectors are installed in each unit to provide energy for approximately 40% of the hot water demand. The remainder of the demand is covered by electricity. The energy simulation program DEROB-LTH v1.0 was used in the simulations [14].

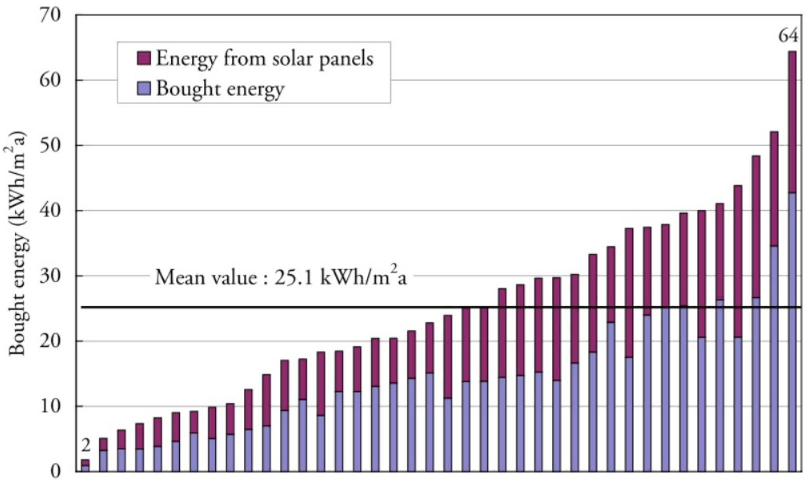


Figure 7: Total energy use for DHW in apartments in Värnamo, Sweden. [19]

From the simulations, numbers for DHW, space heating and total energy demand are found. Monitored demand in all 20 houses show some deviations from the calculated values. All the results are corrected to a standard year.

From the values, one can see that the deviations in el. specific energy demand and energy demand for space heating are the main reasons that the calculations do not add up to the measurements. Simulations show that energy demand for space heating increases three-fold if the indoor temperature increases from 20°C to 26°C.

[19] presents 4 demonstration projects for passive houses in Sweden and discusses correlations between measured and calculated figures. An apartment complex in the town of Värnamo consisting of 40 rental apartments in five separate buildings has been analysed with respect to energy performance. Energy demand for space heating in one of the five buildings in the project was simulated in DEROB-LTH v1.0 [14]. Measured values were total energy use, energy use for space heating and energy use for DHW. Each apartment is equipped with its own mechanical ventilation system with air-to-air heat recovery. This system, equipped with an additional heating battery covers the heating requirement for the dwelling. Space heating was calculated with an indoor temperature of 20°C and 22°C. Even though the construction was designed to avoid thermal bridges , small thermal bridges might have occurred in the construction which were not accounted for in the calculations. Results show a simulated heating energy requirement of 9.1 kWh/m^{2}a with an indoor temperature of 20°C, and 12.8 kWh/m^{2}a for 22°C.

The measurements for annual space heating were done during the period 01.02.2007 - 01.02.2008 and corrected with respect to degree-days. Since the year of measurement was warmer than a standard year, the annual energy use for space heating for a normalized year were higher than the measured values. For DHW heating, the apartments were equipped with solar panels, in addition to electrical heating in centres for DHW preparation in each building. A mean value of 25 kWh/m^{2}a was measured for DHW, with solar panels supplying an average of 42% of the energy demand, as shown in figure 7. The measurements for total energy use in the five buildings vary from 44 kWh/m^{2}a to 133 kWh/m^{2}a with a mean value of total bought energy of 70 kWh/m^{2}a.

[19] compared measured and calculated energy use for 12 apartments in Frillesås south of Gothenburg. The apartments are built as Passive Houses and, in line with the standard, the energy for space heating is supplied by district heating, as well as DHW being supplied by heat from solar panels and district heating. All apartments are supplied with a small mechanical ventilation unit with an air-to-air heat exchanger. Calculated results show an energy demand for space heating at 14.8 kWh/m^{2}a for an indoor temperature of 20°C, and 18.9 kWh/m^{2}a for a temperature of 22°C. In retrospect, an erroneous assumption was found in the calculations, by placing the heating coil after the heat exchanger. In reality, the heating coil was placed before the heat exchanger, which underestimated the energy demand for heating.

The measured results show bought energy demand for space heating for the period 01.02.2007-01.02.2008. However, there proved to be a fault in the ventilation units in some of the apartments leading to some measurements to be incorrect compared to energy use during standard operation. When energy needed for space heating during 10.11.2007-10.11.2008 is examined, the bought energy for space heating is seen to be lower. This difference could also somewhat be explained by differences in outdoor climate. Space heating is revised to a normal year, increasing the measured value. The mean value of energy use for space heating, DHW and common electricity during the period 01.02.2007-01.02.2008 was 50 kWh/m^{2}a, and should be compared to the energy limit of 110 kWh/m^{2}a in the Swedish building code.

[19] also performed an analysis of a single-family house in Lidköping called Villa Malmborg. This Passive house is built specifically for the family living there, with expectations of low maintenance and energy demand costs. The building is heated by air, with a mechanical ventilation unit installed on the ground floor with an air-to-air heat exchanger. Approximately 85% of the heat is recovered through the heat exchanger. The DHW is heated by district heating. Simulations calculated the energy demand for space heating at 24.9 kWh/m^{2}a for an indoor temperature of 20°C, and 31 kWh/m^{2}a for 22°C. Some thermal bridges were not included in the simulations.

Several measured results were conducted for energy use for space heating. Based on measurements on domestic hot water use, and energy bills for bought district heating, a revised space heating demand was found.

Another study by [19] analysed the energy use in an apartment complex in Alingsås outside of Göteborg which was refurbished in 2010. The homes were originally built in 1971, consisting of 16 buildings with a total of 299 apartments. Most of the heating demand to the apartments is supplied by ventilation with heat recovery, as well as district heating. The building was built to comply with the Swedish Passive House Standard. Simulations done in DEROB-LTH v1.0 indicate an energy use for space heating at 23 kWh/m^{2}a with an indoor temperature of 20°C, 25 kWh/m^{2}a for DHW and a total energy use of 76 kWh/m^{2}a.

Measurements were done on 16 apartments yielding a mean energy use for space heating at 26.6 kWh/m^{2}a revised for a normal year. From measurements of bought volume of DHW, the energy use was set to 16.1 kWh/m^{2}a. The mean value of annual household electricity was measured during the measuring period 01.04.2008-01.04.2010.

[25] compare measured and calculated energy use for 16 refurbished apartments in Backa Röd in Göteborg. The refurbishment was finished in 2009 and the apartments were built as passive houses and utilize district heating to cover the heating and DHW demand. A balanced mechanical ventilation was installed with a rotary heat exchanger, having a heat recovery of 85%. The actual measured total energy demand is 52 kWh/m^{2}a, revised to a standard year. The total

consumption can be compared to the pre-refurbishment energy consumption which was measured to be 170 kWh/m^{2}a.

4.3.2 Norwegian Studies

Several studies have been conducted to determine the energy performance of Løvåshagen in Bergen, consisting of 4 residential buildings from 3-5 stories high. Two of the buildings are built as low energy houses while two are built after the Passive house standard. The buildings were finished in 2008. Conclusive measurements are made for both the Passive houses which consist of 19 apartments, and the low energy houses which consist of 19 apartments.

[26] conducted several measurements of energy use for space heating and total energy use. Unfortunately, there were difficulties with several of the measurements and they were only conducted over a period of a few months. The authors make an attempt at extrapolating the data to prove representative of a normal year, but several assumptions must be made to achieve a conclusion. Thus, these results seem to be unreliable and will not be used in this study.

However, other studies have revealed calculated energy demand for the Passive and low energy houses. The heat source is solar collectors and electricity in addition to a mechanically balanced ventilation system with heat recovery (efficiency 83%). Space heating and DHW was calculated, and the solar collector is estimated to provide 22.6 kWh/m^{2}a or 47% of the total energy demand [27]. Based on measurements from 2009, [28] found measured, temperature-corrected, delivered energy to be approximately 90 kWh/m^{2}a. The author comments that these values might be an underestimate assuming source errors like uninhabited flats or errors in measurements. Indeed, [27] found considerably higher energy demand based on similar measurements of energy delivered from the grid. These findings were temperature-corrected measurements from 2011 and 2012, and total delivered energy from the grid is found to be 126.5 kWh/m^{2}a for the low energy buildings, and 126 kWh/m^{2}a for the Passive houses. It is interesting to note that delivered energy does not seem to vary considerably from the low energy buildings to the Passive houses, which have a much lower expected energy demand. Both calculations underestimate the total energy use for the dwellings.

[29] performed an evaluation of energy use in Passive houses for students in Berg, Trondheim. The complex consists of 38 student homes with a maximum occupancy of 8 persons. The dwellings are classified as multi-family homes with a balanced ventilation system with heat exchangers and district heating to supply space heating. The measurements were taken in the period 2011-2012, and the mean value of the total delivered temperature corrected energy is measured at 146 kWh/m^{2}a.

As part of the independent research organisation SINTEF's project 'Evaluation of Dwellings with a Low Energy Demand' (EBLE), [30] preformed an evaluation of 9 single-family homes built after the Passive house standard. The two-storey dwellings are located at Rossåsen in Sandnes on the western coast of Norway. Following the Passive house standard, the buildings are built with a low U-value for the external walls and roof. Thus, there is a low leakage to the surroundings. Each household is equipped with a 6 kW air-to-water heat pump supplying heat for DHW, floor heating of the bathroom, and for one radiator on each floor. A balanced ventilation unit with a rotary heat exchanger with 82% recovery, can be adjusted according to air-flow and temperature.

In addition, heat recovery is automatically turned off in the summer.

The calculations were performed in the simulation program SIMIEN v. 5.015 [13]. Total delivered energy was estimated and corrected for temperature and climate. Primarily, measurements are presented as total delivered energy, with no direct results for energy use for space heating and DHW. Total average delivered energy for the 9 dwellings is measured to 86 kWh/m^{2}a. Two dwellings had a lower measured than calculated energy demand. One of these buildings was uninhabited during the period where space heating is utilized, but it was still included in the mean value. This will give a lower mean than the value for the inhabited houses.

[31] conducted an evaluation of two Low energy buildings in the northern part of Norway. During the simulations, the dwellings were placed in a northern climate zone, and total delivered energy use was calculated for the two apartments as well as energy use for space heating and DHW. The measured values give a higher result than the calculated values and are shown in Appendix A.

In the aforementioned report [21] an analysis of four single-family homes built in 2007 is included. The homes are built in Grimstad as low energy houses, meaning they have a much lower expected energy use than the standard at the time (TEK97). Not many specifications about the houses are included in the report, but calculated energy use for DHW and space heating is around 40 kWh/m^{2}a for each dwelling. In three out of four dwellings the measured energy use is above the calculated value, around 45-50 kWh/m^{2}a. See Appendix A for individual values for the four houses.

4.4 Case Study

To expand on the available data, a passive house project at Gransåsen in Trondheim built by Heimdal Bolig AS has been assessed as a case study. The case consists of 12 single-family houses, and 10 multi-family houses, all built in 2012. A representative model of the dwellings is shown in figure 8. Calculations were preformed by SINTEF and the dwellings were designed to follow the Norwegian passive house standard, NS3700. Therefore, energy for space heating is supplied partly by district heating as well as electricity. Additionally, mechanical ventilation systems with heat exchangers are installed to minimize heat losses. All simulations were done in SIMIEN. In the case of the single-family houses, calculations for energy use were done for individual houses, while for the multi-family houses the calculations were done for the entire section of row-houses consisting of 5-7 dwellings. Total delivered energy for electricity and district heating was measured by the inhabitants and reported to Heimdal Bolig. Not all inhabitants reported energy use for a whole year, so the usable data were only measurements for a whole year or, in the case of the multi-family houses, measurements for a whole section. For the multi-family houses, this was measurements of 10 dwellings, or two sections, out of more than 30 dwellings. For the single-family houses this was 12 out of 17 dwellings. Average energy intensities and deviations from the measured values were found for the single-family houses and for the two sections of multi-family houses separately, and are presented in Appendix A, together with the data gathered from literature.

Figure 8: A representative model of the single-family houses and multi-family houses included in the analysis. The multi-family houses are in the front, with the single family-houses in the background. [32]

4.4.1 Temperature Corrected Energy Use

When assessing the measured energy use for the dwellings constructed by Heimdal Bolig AS, the measured values were corrected for temperature in the given time period they were measured. To achieve this, the degree-day (DD) method for temperature correction was used. The temperature corrected energy consumption is given as in [33]:

$$E_c = E_m(k\frac{DD_n}{DD_m} + (1-k)) \tag{4}$$

Where

E_c : temperature-corrected energy consumption [kWh]

E_m : measured energy consumption [kWh]

k : share of temperature-dependent energy consumption

DD_n : number of degree-days in a normalized year [K days]

DD_m : number of degree-days in the given year [K days]

Although only measurements over a whole year are included in the analysis, the measurements are taken over different time periods. Therefore, the degree-day number is taken for the specific month the measurement was taken. The degree-day number for the specific years, and normalized values are taken from Enova [34]. The following guidelines set by Enova and NVE, were used when assessing the temperature-corrected energy consumption. A general temperature-dependent share for Norwegian dwellings is given as 55% of total energy consumption. In addition, all energy supplied by district heating is considered temperature dependent. Thus, the temperature-corrected energy use was either a general share of 55% of total energy use, or all district heating in the cases where energy consumption from district heating exceeded 55% of total energy use.

4.5 Dataset from NVE

In connection with the Norwegian Energy Agency's documentation of energy performance in dwellings, a dataset of nearly 22 000 measured and calculated energy consumption in Norwegian dwellings has been collected. From July 1, 2010, all Norwegian dwellings that are rented or sold must have an EPC. An internet registration tool collects data which are provided by the home owner for older houses, or by a certified expert for dwellings built after 2010. The minimal data requirement is building type, construction year, area of use and heating source. Based on this, and other information supplied by the user, an EPR with expected delivered energy is given, calculated according to the procedure given in NS:3031. In addition, the dataset only includes the EPCs with the measured energy use given. Given the low verification potential of the data given, especially in the older EPCs, the data has some limitations of use. However, the substantial pool of measurements provided, and certain assumptions can give useful insight to the energy performance of Norwegian dwellings.

The data was divided into age cohorts and building types as described in section 4.2. Furthermore, energy intensity factors, I, and the deviation of calculated values, ΔE, were calculated. Both the mean and standard deviation of the calculations is given in section 5.2 of the results. In the EPCs, only total delivered energy is given. However, as previously mentioned, it is favourable to compare only the energy needed for heating, since this relationship will better reflect energy performance compared to calculations. An el. specific energy use of 41.28 kWh/m^{2}a was subtracted from both the measured and calculated values in order to achieve an approximation of energy use for space heating and DHW.

Upon inspection of the raw data, the estimated values for specific energy demand seem unrealistically high. For instance, the average expected specific energy use set by the EPC for multi-family houses built between 1801-1955, is 341 kWh/m^{2}a. This is more than twice the value estimated by other studies [10]. Indeed, NVE has a tendency to overestimate energy consumption in order to avoid a too good EPC to be registered. For instance, the coefficient of heat leakage is set at a standard of 8 for homes built between 1969 and 1986 if the home has not been tested for leakage. Other sources indicate a large variation of leakage coefficients for homes built around 1970 [36]. It was therefore necessary to use different values for the estimated energy use for each age cohort and building type.

The values used for the calculated energy use are given in table 6. Weighted average energy intensities for space heating and DHW from TABULA were used to estimate the average energy intensity for each age cohort and building type [35]. The energy intensity is weighted with respect to differences in standards in each cohort, mainly due to renovation work. This is why energy intensity is not necessarily decreasing with younger age cohorts, as especially many dwellings from 1981-1990 have been renovated. Even though there are large variations in energy use within cohort, this approximation is deemed acceptable since there is a large amount of data available.

4.5.1 Removal of Outliers

Since many of the EPCs are conducted without professional guidance, it lies in the nature of the method used to construct the dataset that there will be gross errors in the parameters. Examples of expected errors can be decimal errors, input of specific energy consumption (kWh/m^{2}a) instead of total delivered energy, or input of measurements for energy use or area for an entire apartment block instead of one apartment. Upon inspection of the dataset these erroneous data are found in all age cohorts. These data points must be eliminated in order to find the real expected relationship between the measured and calculated values.

Generally, scientists believe that data should never be rejected without external evidence that the measurement in question is incorrect. However, because an individual data point deviating grossly from the mean will have a substantial effect on the total mean and standard deviation of the building cohorts this is deemed necessary to achieve realistic results. Chauvenet's criterion was applied to the individual cohorts to find which data points should be rejected. A detailed description of Chauvenet's criterion can be found in Appendix B. First we must assume that the measurements are distributed similarly to a normal distribution. This is reasonable, due the

Dwelling type	Construction period	Weighted average delivered energy (heating+DHW) (kWh/m^{2}a)
Single-family houses		
	1801-1955	164
	1956-1970	153
	1971-1980	153
	1981-1990	143
	1991-2000	149
	2001-2010	87
	2011-2020	82
Multi-family houses		
	1801-1955	156
	1956-1970	146
	1971-1980	145
	1981-1990	134
	1991-2000	139
	2001-2010	84
	2011-2020	60
Apartments		
	1801-1955	161
	1956-1970	146
	1971-1980	145
	1981-1990	131
	1991-2000	136
	2001-2010	82
	2011-2020	59

Table 6: Calculated values representing stereotypes in the dwelling stock for different dwelling types and construction periods. [35].

large number of measurements, and the law of large numbers.

We wish to find a probability band, centred around the mean of a normal distribution that should contain all n samples of the dataset. Any data point that lie outside of this probability band can be considered an outlier, removed from the dataset, and a new mean and standard deviation can be calculated.

Because of the unreliability of the original dataset it is necessary to apply Chauvenet's criterion more than once for each age cohort. However, the more times one applies the method, the less reliable it becomes. Therefore, one must find a balance between removing the obvoiusly erroneous data, and 'trimming' the dataset for realistically high I values, even if the data point lies slightly outside the allowed probability band. The discarded values are preserved separately to conserve transparency and the possibility for error correction. This method does not account for errors that fall within the expected distribution, but this is deemed acceptable due to the large number of data points contained in the dataset.

4.6 Assumptions

An assumption had to be made for el. specific energy use as mentioned in section 4.5, in order to find an approximation for energy use for space heating and DHW. Many studies in Norway and Sweden have tried to find the el. specific energy use in the dwelling stock. Data from the Swedish Energy Agency [9] gives an average of 4736 kWh/a for all dwelling types. [38] conducted

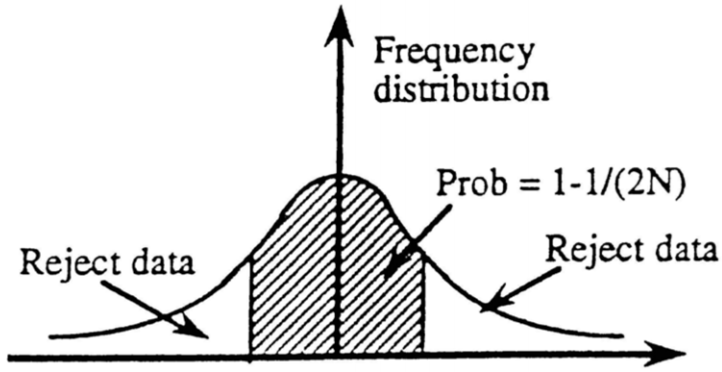


Figure 9: The probability band P centered around the Gaussian distribution with mean μ, and standard deviation σ. The band will vary in size in relation to sample size N [37].

a survey in Norwegian households and found a value of around 4000 kWh/a for el. specific energy use for single-family houses and multi-family houses. For apartments this value was as low as 3000 kWh/a. However, [8] analysed the results of the survey and concluded that the authors had underestimated the energy use. Here a value of 4500 kWh/a is given.

Given these variations, it was necessary to find a value that best represents the different building types. To account for variations, an el. specific energy use per area (kWh/m^{2}a) was found. Although the el. specific energy use does not directly correlate with building area, this is seen as an acceptable approximation. Calculations from TABULA and NVE give an el. specific energy use of 41.28 kWh/m^{2}a. With a dwelling of 75 m^2, roughly the average floor area for apartments given by the Norwegian Statistical Bureau, this yields an el. specific energy use of 3096 kWh/a, which seems reasonable when compared to the value given in [38].

4.6.1 Assumptions to Literature Data and Case studies

Studies use different parameters to compare the measured and calculated energy use. Some studies only provide measurements of total delivered energy, while others have separated energy use into areas of use, like space heating, DHW etc. To account for this, and make the studies comparable to a larger degree, some assumptions and calculations were made to fill the data gaps. In the cases where only energy use for space heating was stated with no value for energy use for DHW assumed values were added for DHW in accordance with the TABULA model. This value is 25 kWh/m^{2}a for apartment buildings and 19 kWh/m^{2}a for single-family houses. No values for DHW were added for multi-family houses. Where no more precise data was available, the previously described value of 41.28 kWh/m^{2}a was used to differentiate between total energy use and energy use for DHW and space heating. In some cases, where total delivered energy cannot be compared, only the electricity demand is taken into account. This is however acceptable, since in most cases the alternative energy source will cover the base load, and the electricity use is expected to vary to a greater degree.

When assessing the case study from Granåsen, specific values for el. specific energy use were applied based on the calculations for the actual buildings. For the single-family houses el. specific energy use was 5058 kWh. For the multi-family houses 21 425 kWh was used as a total for an entire section of houses.

4.6.2 Assumptions to Dataset From NVE

The main assumption when doing calculations on the dataset from NVE is that all the dwelling types are close to normally distributed with a mean value and standard deviation around the different construction periods, indicating that energy use in these dwellings will not vary greatly within these age cohorts. This is necessary in order to calculate the mean and standard deviation of the dwellings, and required to apply Chauvenet's criterion. Histograms for all the dwelling types and age cohorts can be found in Appendix C. An el. specific energy consumption of 41.28 kWh/m^{2}a was used to calculate the measured energy use for space heating and DHW.

5 Results

In this section, results from the study are presented. All parameters concern energy use for space heating and DHW unless otherwise stated. First, energy intensity factors, I, and the measured deviation from calculated results, ΔE, for data gathered in literature and the case study is presented. Secondly, measured energy use for space heating for all age cohorts and dwelling types for the NVE dataset is given, following I and ΔE for the same data. Finally, mean values of energy intensities for the NVE dataset as well as literature and case study data are put together in context, and an estimate of the under-reporting of energy use in passive houses and low energy buildings is given. All results are discussed in section 6.

5.1 Literature and Case Study

Table 7 presents all collected results from literature on passive houses and low energy buildings, as well as results from the case study on passive houses in Granåsen, Trondheim. Both total energy consumption and energy use for space heating and DHW is assessed and subscripted accordingly in the table. The parameters concerning space heating and DHW are presented graphically in the remainder of this section. A more detailed table on measured, calculated and assumed values for all studies can be found in Appendix A. These results are discussed in section 6.1.

5.1.1 Energy Intensity Factor

The energy intensity factor I for all passive houses and low energy buildings assessed in literature and the case study is presented in figure 10. The energy intensity factor is for energy use for space heating and DHW. The results show that the energy intensity factor generally is above 1 for passive houses and low energy buildings. Because the average energy use for all measurements is given in many cases there are fewer data points than there are measurements. Multiple measurements will overlap and the number of measurements in each study can be found in table 7. These results are discussed in section 6.1.

5.1.2 Measured Deviation from Calculated Values

The measured deviation from calculated energy use for space heating and DHW looks similar to the energy intensity factor for the same data. Nevertheless, dwellings that have an energy intensity factor that deviates substantially from 1, will have a relatively larger ΔE in absolute value. This is reflected in figure 11. Also, for this metric multiple data points will overlap, depending on the number of measurements each study is based on. The implications of ΔE are discussed in section 6.5.

	Study	Location	Building type	Standard	Year of construction	No. of measurements	Energy Intensity I_{tot}	Energy Intensity $I_{heating}$	Deviation (kWh/m^{2}a) ΔE_{tot}	Deviation (kWh/m^{2}a) $\Delta E_{heating}$	Corrected for DD
Swedish											
	[19]	Värnamo	Apartments	Passive house	2006	8	0.93	1.00	-5.38	-0.10	Yes
		Frillesås	Apartments	Passive house	2006	12	1.15	0.85	11.82	-6.00	Yes
		Lidköping	SFH	Passive house	2007	1	1.01	1.14	6.10	6.10	Yes
	[25]	Allingsäs	Apartments	Passive house	2010	16	0.83	0.86	-16.00	-6.00	No
		Backa Rød	Apartments	Passive house	2009	5	0.89	0.80	-10.00	-10.00	No
	[24]	Gothenburg	MFH	Passive house	2001	20	0.86	1.02	-10.88	0.80	Yes
Norwegian											
	[27]	Løvåshagen	Apartments	Passive house	2008	19	1.59	1.43	34.00	24.72	Yes
			Apartments	Low Energy building	2008	19	1.25	1.43	25.50	25.50	Yes
	[29]	Berg Studentby	MFH	Passive house	2011	37	1.59	2.06	54.00	54.00	Yes
	[30]	Rossåsen	SFH	Passive house	2012	9	1.26	1.23	18.00	8.42	No
	[31]	Jektholtet-Harstad	Apartments	Low Energy building	2006	1	1.01	1.05	1.00	4.00	Yes
			Apartments	Low Energy building	2006	1	1.21	1.17	28.00	14.00	Yes
	[39]	Snåsa	SFH	Low Energy building	2013	2	0.71	0.56	-34.50	-34.50	Yes
	[38]	Grimstad	SFH	Low Energy building	2007	1	1.36	1.17	29.40	10.40	N.A.
			SFH	Low Energy building	2007	1	1.26	1.04	21.50	2.50	N.A.
			SFH	Low Energy building	2007	1	1.37	1.18	29.60	10.40	N.A.
			SFH	Low Energy building	2007	1	1.15	0.87	11.60	-7.40	N.A
	Case study	Granåsen	SFH	Passive house	2012	12	1.34	1.25	32.64	16.50	Yes
			MFH	Passive house	2012	5	1.47	1.75	36.71	36.73	Yes
			MFH	Passive house	2012	5	1.50	1.81	37.36	37.36	Yes
						Weighted average	1.24	1.38	20.94	19.12	

Table 7: Energy Intensity factor, I, and deviation from measured values ΔE, for dwellings analysed in Norwegian and Swedish studies. I_{tot} and ΔE_{tot} represent parameters for total energy use, while subscript heating is with respect to energy use for space heating and DHW.

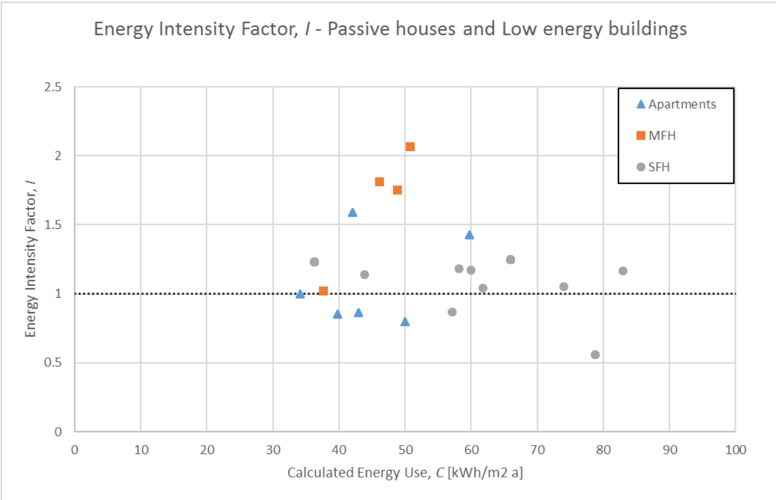


Figure 10: Energy intensity, I for all data gathered in literature and case study. MFH are multi-family houses and SFH are single-family houses. The dotted line represents where measured energy use is equal to calculated energy use.

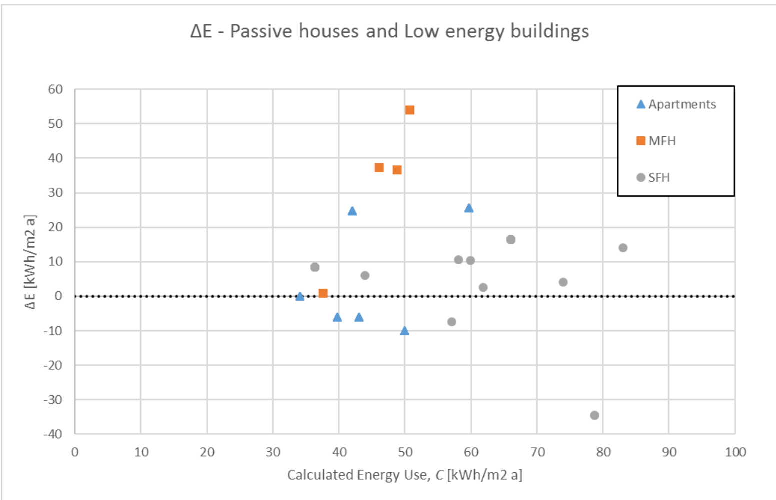


Figure 11: Measured deviation from calculated values for all data gathered in literature and case study. MFH are multi-family houses and SFH are single-family houses. The dotted line represents where measured energy use is equal to calculated energy use.

5.2 Dataset from NVE

Table 8 shows the mean and standard deviation for all parameters assessed in the NVE dataset. Measured and calculated energy use for space heating and DHW is evaluated, as well as the energy intensity factor, I, and the measured deviation from the calculated values ΔE. All the analysed parameters are presented graphically in the rest of section 5.2.

5.2.1 Measured Energy Use for Space Heating and DHW

The average value and standard deviation of measured specific energy use for space heating and DHW for all dwelling types and age cohorts is presented in figure 12. The figure shows that specific energy use generally increases with older age cohorts with some exceptions. The variance for the age cohorts increases in magnitude with older age cohorts. Since the newest age cohorts are not evenly distributed around the mean value, the error bars based on the standard deviation will not fully represent the real variance. Nevertheless the figure gives a good representation of the uncertainty of the results. The results are discussed in section 6.2.

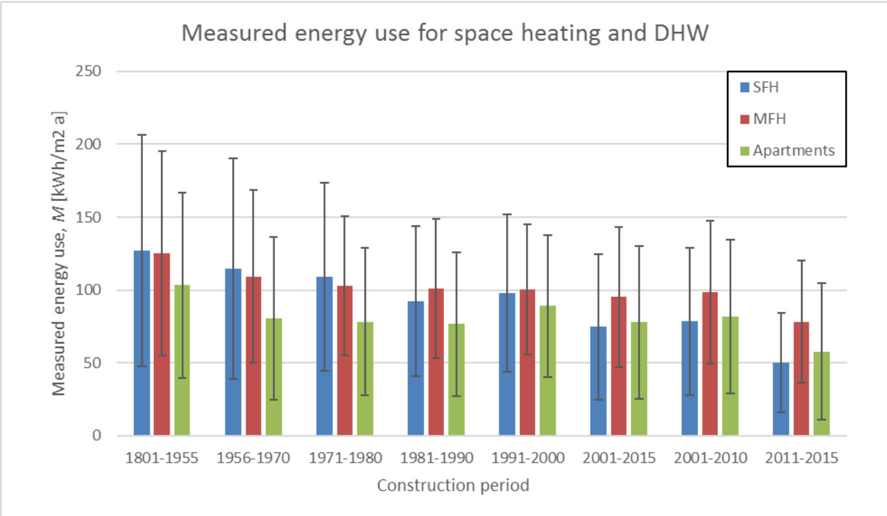


Figure 12: Measured energy use for DHW and space heating for all age cohorts and dwelling types in the NVE dataset. Error bars indicate one standard deviation.

Building type	Age cohort	M [kWh/m^2a]	C [kWh/m^2a]	$I_{heating}$	ΔE [kWh/m^2a]
Single-family Houses					
	1801-1955	127.07 ± 79.17	164	0.77 ± 0.44	-36.98 ± 71.70
	1956-1970	114.56 ± 75.49	153	0.75 ± 0.49	-38.44 ± 75.49
	1971-1980	109.16 ± 64.43	153	0.71 ± 0.42	-43.84 ± 64.43
	1981-1990	92.35 ± 51.33	143	0.65 ± 0.36	-50.65 ± 51.33
	1991-2000	97.69 ± 53.94	149	0.66 ± 0.36	-51.30 ± 53.94
	2001-2015	74.66 ± 49.71	79	0.89 ± 0.58	-9.07 ± 48.82
	2001-2010	78.33 ± 50.66	87	0.90 ± 0.58	-8.66 ± 50.66
	2011-2015	50.27 ± 34.07	62	0.81 ± 0.55	-11.73 ± 34.07
Multi-family Houses					
	1801-1955	125.20 ± 69.91	156	0.80 ± 0.44	-30.90 ± 69.66
	1956-1970	109.21 ± 59.32	146	0.75 ± 0.41	-36.86 ± 59.37
	1971-1980	101.99 ± 48.88	145	0.72 ± 0.32	-43.01 ± 48.88
	1981-1990	100.81 ± 47.83	134	0.75 ± 0.35	-33.19 ± 47.83
	1991-2000	100.40 ± 44.93	139	0.72 ± 0.32	-38.60 ± 44.92
	2001-2015	95.09 ± 29.71	80	1.19 ± 0.60	15.12 ± 47.69
	2001-2010	98.49 ± 48.79	84	1.17 ± 0.58	14.48 ± 48.79
	2011-2015	78.27 ± 41.85	60	1.30 ± 0.70	18.26 ± 41.85
Apartments					
	1801-1955	103.25 ± 63.49	161	0.64 ± 0.39	-57.75 ± 63.49
	1956-1970	80.29 ± 55.77	146	0.55 ± 0.38	-65.71 ± 55.77
	1971-1980	78.23 ± 50.40	145	0.54 ± 0.35	-66.77 ± 50.40
	1981-1990	76.61 ± 49.44	131	0.58 ± 0.38	-54.39 ± 49.44
	1991-2000	88.88 ± 48.84	136	0.65 ± 0.36	-47.12 ± 48.84
	2001-2015	77.70 ± 52.50	78	1.00 ± 0.69	-0.43 ± 51.73
	2001-2010	81.73 ± 52.68	82	1.00 ± 0.64	-0.27 ± 52.68
	2011-2015	57.75 ± 46.82	59	0.98 ± 0.79	-1.25 ± 46.82

Table 8: M, C, I and ΔE for all dwelling types and cohorts assessed in the EPC dataset from NVE. The mean for all cohorts is given, as well as the value after the plus-minus sign indicating one standard deviation.

5.2.2 Energy Intensity Factor, I, and Deviation ΔE

To verify that the energy intensities were normally distributed and centred around a mean and standard deviation, histograms for all dwelling types and cohorts are presented in Appendix C. For illustrative purposes, and to ease later discussion, six histograms are presented in figures 13, 14, and 15. The number of data points having a certain intensity factor within an age cohort, is depicted on the vertical axis with the distribution of intensity factors on the horizontal axis. The histograms show that energy intensity factors in general vary symmetrically around a mean value, especially for the older age cohorts. The age cohort 2001-2015 generally has more widespread values, with a histogram that is skewed towards higher intensity factors.

The mean and standard deviation of the energy intensity factors, and the measured deviation from the calculated values, for all the age cohorts and dwelling types are shown in figure 16. The figure shows a discrepancy between the energy intensity factor for old and new buildings. Additionally, even though measured energy use, M, has a lower variance for newer dwellings, the variance in I and ΔE increases with younger cohorts. This is reflected in the histograms for the age cohorts. The energy intensity factors are further discussed in section 6.1.

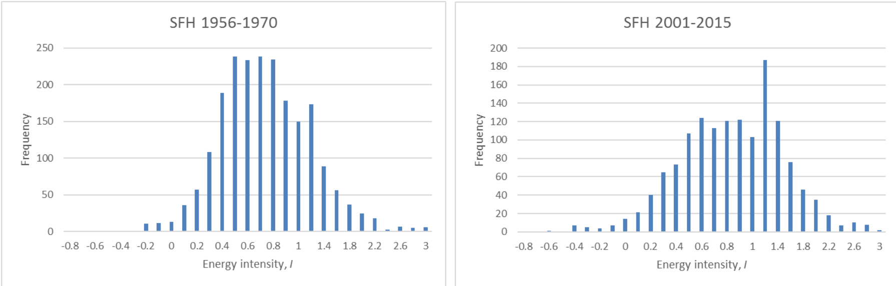


Figure 13: Histograms for two age cohorts for single-family houses.

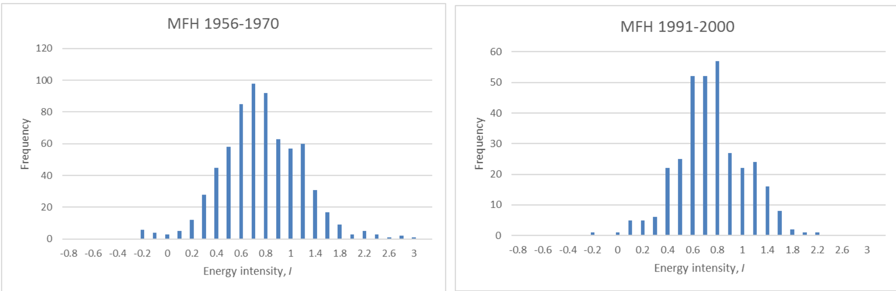


Figure 14: Histograms for two age cohorts for multi-family houses.

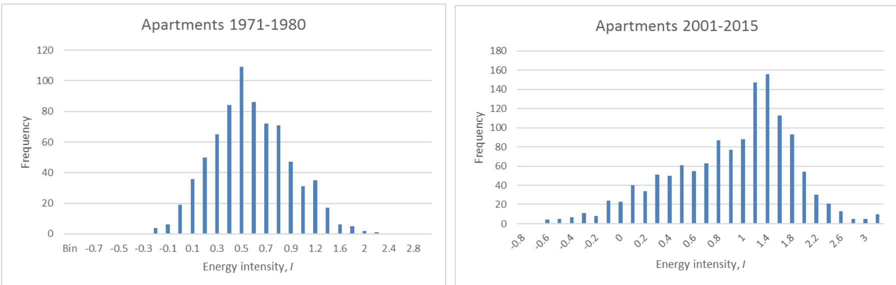
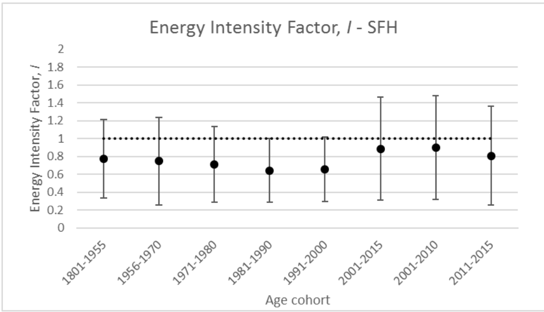
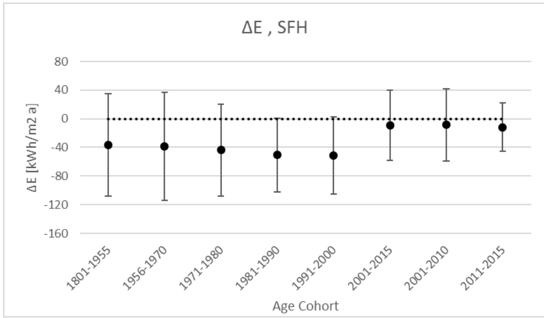


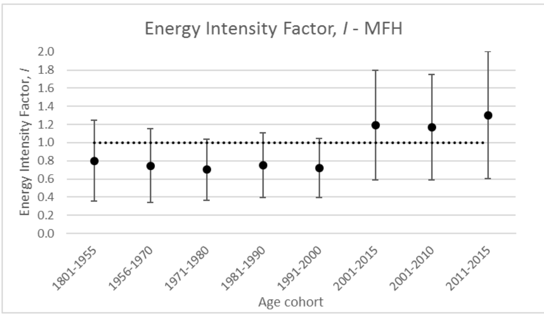
Figure 15: Histograms for two age cohorts for apartments.



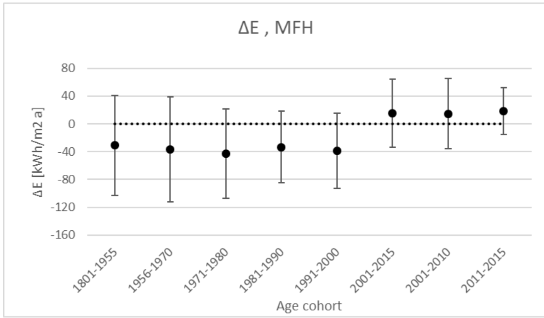
(a) I, single-family houses



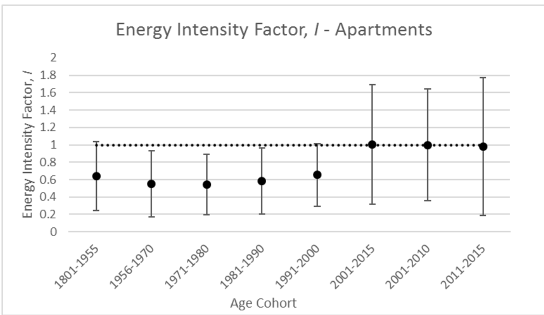
(b) ΔE, single-family houses



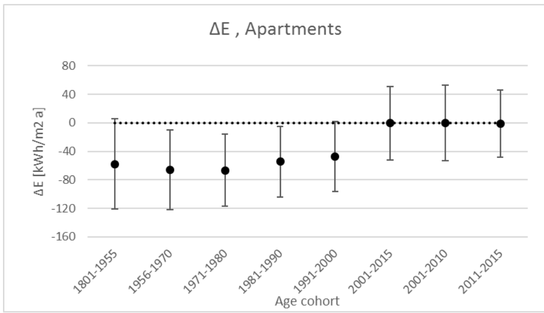
(c) I, multi-family houses



(d) ΔE, multi-family houses



(e) I, apartments



(f) ΔE, apartments

Figure 16: Energy intensity factors, I, and the deviation from the calculated value ΔE, for all age cohorts in the NVE dataset, for single-family houses (a-b), multi-family houses (c-d) and apartments (e-f). Age cohort 2001-2015 is partitioned into two subcohorts. The dashed line is where measured energy use equals calculated energy use ($I = 1$ or $\Delta E = 0$).

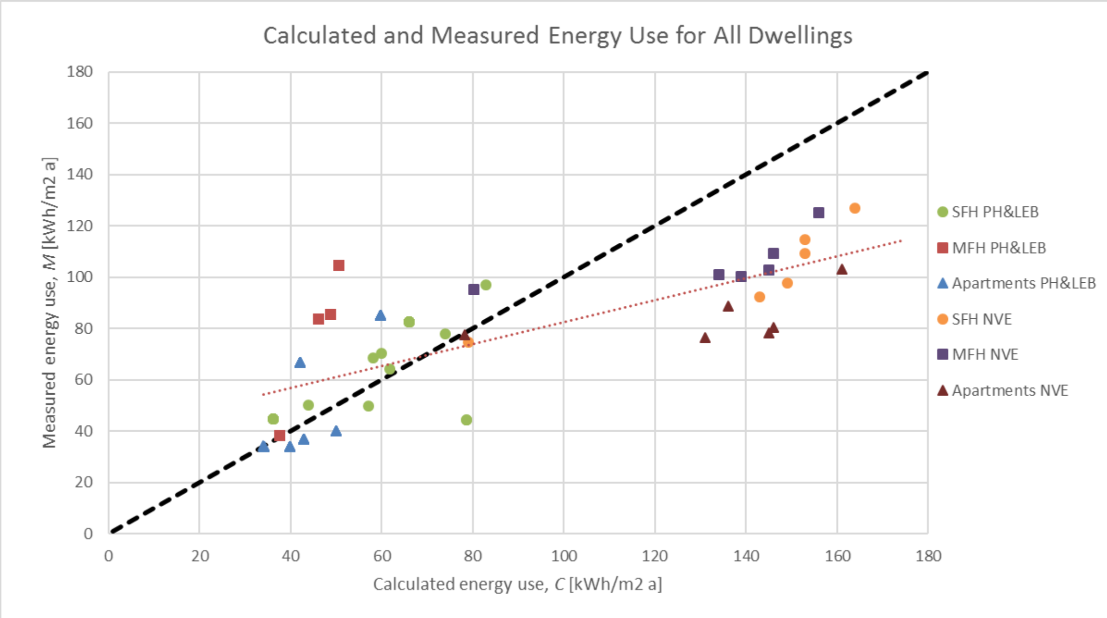


Figure 17: Measured and calculated energy use for space heating and DHW for all age cohorts and dwelling types from the EPC data, as well as data from literature and case study on passive houses and low energy buildings. The red dashed line is a linear regression line, the black dashed line shows $I = 1$.

5.3 Conclusive Results

Figure 17 compares the energy intensity of the different age cohorts from NVE data, with data from literature and the case study on passive houses and low energy buildings. To show the trend of how the energy intensity factor varies with buildings standard, a linear regression was fitted. The regression has an R^2-value of 0.60 which reflects how well the curve follows the data points. A curve with an R^2 of 1 will perfectly follow the data points. The results are further discussed in section 6.5.

5.3.1 Under-Reporting of Energy Use in Passive Houses and Low Energy Buildings

To give an indicator of the order of magnitude of the deviations in measured and calculated values for passive houses and low energy buildings, an estimate of the deviation from calculated energy use in Norwegian passive houses is performed. [40] states that around 1000 passive houses are planned or under construction in Norway at this time. With an average heated area of 109 m^2 per household [8], and an average ΔE of 19.12 kWh/m^2a, this gives an under-reported energy use for space heating and DHW of 2.08 GWh if the reporting is based on calculated values. This is further discussed in section 6.5.

6 Discussion

In this section the results from the study are discussed. First, the main findings from literature data, case study and the dataset on EPCs are presented. Secondly, the findings are compared to the consensus in literature as presented in section 3, followed by a review of the strengths as well as possible flaws and errors in the results. Finally, an analysis of implications for policy makers and for future research on energy use in dwellings is performed.

6.1 Main Findings

The literature results for passive houses and low energy buildings show a large variation in the energy intensity factor, although in general they are higher than 1. There are too few data points to conclude how I varies with building type, but single-family houses seem to have the least variation in the energy intensity factor. Calculations done for the literature data are more robust than the ones used for the NVE dataset. The literature data might be expected to have an energy intensity factor closer to 1, since the calculations are done on a case by case basis with the specific conditions of the project in mind. Therefore, it is difficult to compare the two directly. However, if the I ratio of passive houses and low energy buildings was calculated with the same methodology as the NVE dataset (standard expected energy use, large sample size), it would be expected to be higher than 1.37 (the current value),

Results from the NVE dataset show a clear trend for the energy intensity in the dwelling stock. In general, dwellings of the same building type with a high expected energy use for DHW and space heating will have a measured energy use that is lower than the expected value. However, calculations are more accurate in predicting energy use in the oldest age cohorts (1801-1955), than the immediate subsequent age cohorts. Since the dwellings are considered to be very poorly insulated, it might be difficult to conserve energy in the oldest age cohort. The I value does not change considerably until the youngest age cohorts, where dwellings with a calculated value similar to the standards for TEK10 will have an I close to 1. Apartments generally have a lower I than multi-family houses and single-family houses for the same age cohort. This indicates that apartments use even less energy than estimated by calculations. Reasons for this could be that apartments get a lot of heat from surrounding dwellings, as well as el. specific energy use being lower than the average for this dwelling type.

In single-family houses the decreasing trend with increasing energy use is harder to make out, as the youngest age cohorts, still have an I below 1. Nevertheless there is a noticeable difference between the dwellings of the older age cohorts and modern constructions with a standard higher than TEK97. The dwellings from the youngest age cohort have a lower I than the passive houses and low energy buildings even though they belong to the same construction period.

The histograms in Appendix C reveal that the newer age cohorts have a larger variation in measurements than the older cohorts. The histograms for 2001-2015 for all dwelling types, typically have a peak at a high I with a 'tail' with lower intensities in a more uniform distribution. This is especially true for apartments and multi-family houses indicating that user behaviour has a larger influence on energy use for these dwelling types than the single-family houses. However, it remains a fact that there are more measurements from single-family houses in the newest age cohorts than the two other dwelling types. This will have an implication for the distribution of the intensities in a cohort.

6.2 Agreement With Literature

It is clear that the results coincide with earlier findings from existing literature as presented in section 3. When comparing this study with results from [5], both show an increase in the energy intensity factor, for buildings with a low energy requirement, although the I is around 0.75-0.8 for dwellings around 150 kWh/m^{2}a, corresponding to a 'prebound effect' of 25-20% as defined by [5]. This is a larger but comparable negative deviation than the one of 17% as found by [5], which corresponds to an I equal to 0.83. The results from this study, generally show an energy intensity factor larger than 1 for dwellings below 100 kWh/m^{2}a, or what Sunikka-Blank and Galvin call the 'rebound effect'.

A main difference however, is that dwellings of a very poor building standard have a slightly higher I than dwellings from the 1970s-1990s. A possible reason for this might be that the cold climate in Norway limits the energy saving potential for 'the prebound effect', making it harder for old dwellings to spend less energy. Another explanation could be that old dwellings are inhabited by older people, less interested in energy conservation. This is however merely a speculation without any supporting evidence. When comparing when the energy intensity factor becomes larger than 1, the regression curve in table 17 indicates an $I = 1$ first at around 70 kWh/m^{2}a, indicating a shift to the left on the curve compared to European studies. There are however uncertainties with this regression curve as will be discussed in section 6.3.

The measured results generally follow the same trends as found by TABULA, with decreasing specific energy consumption (kWh/m^{2}a) with younger age cohorts. However for dwellings built between 1971-2000, the measured energy use flattens out, although the error bars still show a decreasing trend, indicating that as insulation levels marginally increase, user behaviour shift towards higher relative consumption. An exception from the decreasing trend is a general increase in specific energy consumption for dwellings built between 1991-2000 compared to the earlier and later age cohorts, though not for multi-family houses. This trend is identified by the TABULA model, although there it is also stated for multi-family houses.

The calculations done by [10] and presented in section 2.2, state specific energy consumption to be higher in the age cohort 1971-1980 (see figure 3). The energy use per dwelling in these calculations is for total energy use and not energy use for DHW and space heating. Nonetheless, no data to support this conclusion was found in the dataset provided by NVE.

6.3 Possible Errors and Biases in the Datasets

As the results coincide with conclusions drawn from earlier studies, they are deemed reliable. The large sample size of the NVE dataset, especially for dwellings with a high expected energy consumption, gives weight to the conclusions already outlined in the earlier sections. Additionally, the consistent statistical analysis gives little room for gross errors in the calculations. However, there are several other possible errors that could influence the results, causing the I value to deviate from the actual value for space heating. First of all, the quality of the dataset of EPCs is questionable. The fact that many of the EPCs are filled out on a voluntary basis might cause a certain bias in the sample population and give a possibility for gross errors.

An aspect of the voluntary participation in the EPR program is sample bias. The voluntary participants would be expected to be more interested in energy use in their homes than the general population, giving a lower measured energy use than the representative value, and thus a lower I, especially for the older dwellings. However, all dwellings that are bought or sold are required to have an EPR. Since the EPR is given based on building specifications, and not actual consumed energy there would be no apparent incentive to under-report energy use in the EPC. This would help to reduce the sample bias, and give a more realistic estimate of the measured values.

The results prove quite sensitive to differences in what value is used to account for the el. specific energy consumption. Some studies have found an average el. specific energy use in Norway of 4500kWh/dwelling [1]. This value gives a lower energy intensity for many categories, especially for apartments, which generally have a lower el. specific energy use due to variations in [21] Although it is impossible to completely separate energy for DHW and space heating, and el. specific energy use, the value of 41.28 kWh/m^{2}a is deemed acceptable and sufficiently accounts for variations in the different dwelling types.

The assumption that the dwellings are more or less normally distributed around age cohorts for the different dwelling types is important for the results, both when applying Chauvenet's criterion and when calculating the mean and standard deviation. This is valid for most of the age cohorts, but energy use in dwellings is also dependent on other parameters than building age and building type. Therefore, some age cohorts, especially age cohort 6.1 and 6.2, will deviate substantially from a standard deviation. Here, transparency is important, and the fact that the age cohort from 2001-2015 is retained helps to reach the same conclusion even though all age cohorts are not normally distributed.

Correction of the measured EPC data with respect to climate is not possible, since the period of measurements is not given in the EPC. It is known that the measured values are based on the most recent measurements. The last years have been somewhat warmer than a standard year, and energy use is therefore expected to be lower than a standard year. Since the data points are distributed geographically across the country, this is not expected to have a substantial effect on the results. Additionally, if all measurements are adjusted upwards, the younger age cohorts will have an increased I and the conclusions will be the same. The results could be corrected for the general climate in their specific location, since the location is given in the EPC, but this falls outside the scope of this study.

The process of removing outliers is a controversial aspect of statistical analysis. Some outliers are easily identified, while others lie close to the maximum allowed deviation according to Chauvenet's criterion. However, the outliers that lie close to the maximum allowed deviation do not have a large effect on the mean energy intensity, and the gross errors are quite distinguishable from the representative values. Nevertheless, there is a possibility that important data are removed from the dataset, giving results that deviate from the real relationships. Additionally, Chauvenet's criterion only accounts for the gross errors that lie outside the expected normal distribution of the population. For the different age cohorts, there could be errors that still lie within the expected distribution. The main problem with these data samples is that there is no way to distinguish these errors from the correct measurements. Also, the amount of small errors is difficult to predict. However, the amount of errors that lie within the normal distribution is considered to be small, given the relatively small amount of gross errors, and the results are not very sensitive to errors that do not deviate considerably from the mean.

The main problem when assessing the results from literature and case study is the low number of measurements the study is based on. The Norwegian building sector has a weak tradition of verifying energy calculations with actual measurements [20]. This yields considerable uncertainty when comparing the results from literature with the dataset from NVE as done in table 17 in the results section, especially with regards to the regression curve. The regression curve does not weight the passive houses to number of measurements, that is each mean value for the measured value is only given once. Since each data point in the NVE dataset is based on hundreds of measurements, the curve must be viewed as an approximation. Given the low number of passive houses and low energy buildings built in Norway and the large plans for future expansion it is expected that this uncertainty will decrease as more studies on the subject become available.

6.4 Phenomena and Causes to the Difference in the Energy Intensity Factor

The results clearly show that user behaviour influences energy use in buildings to a large extent. The building standard sets a precedent for the expected energy use in a dwelling, but the variation in measured energy use is large, indicating that how people value energy conservation versus comfort in their home has a large impact on energy use. The increased variance of energy intensity factors for dwellings with a low expected energy demand indicates that user behaviour varies to larger extent for this dwelling group. The simple conclusion drawn by [18] can be applied here. A household that spends a large amount of their income on space heating will be less wasteful with their energy use than a household that spends a small amount on heating e.g a dwelling with a low expected energy demand. Nonetheless, if a building is used according to its design, an I close to 1 could be achieved.

In many cases the histograms show a peak in I value somewhat above the mean in a seemingly evenly distributed cohort. This indicates that a subset of the population uses more energy than the average and could depend on many parameters. For instance, the number of persons in a dwelling, or whether the family living there has younger children or not. People that own an electric car could also be a subset of the population using more electricity than the rest. Assuming an electric car uses about 4500 kWh per year, even if all this energy would not be charged at home, this would add a considerable amount to yearly energy use for a dwelling. Other parameters influencing energy use in a dwelling could be the choice of indoor air temperature, window opening time, use and maintenance of the ventilation system, purchase and use of electrical equipment and lightning, use of hot water and the choice and use of solar shading. A multi-variable regression analysis on a more detailed dataset would be required to identify and rank all parameters that influence energy use in a dwelling.

6.5 Implications for Research and Policy Makers

The estimations of deviations from calculated energy use for passive houses and low energy buildings based on ΔE, show an over-reporting of savings when energy use is based on calculated values. Although the magnitude of the estimated deviation might not seem substantial right now, future expansion must be considered. Following the new EPBD set by EU, there is an incentive to raise building energy use requirements to a passive house level or lower by 2020. In this context, the rebound effect must be taken into consideration when assessing the energy saving potential of such measures. The diminishing returns for energy efficiency improvements might show that passive houses are not the optimal solution from a either a cost-benefit, or life cycle perspective, especially when looking at total GHG emissions from cradle-to-grave. However, if the energy intensity factor can be estimated, it will be possible to give a better assessment of space heating consumption in comparison with normative engineering calculations in forecasting studies supporting energy policies. This shows that policy makers must closely follow changes in research on this topic, in order to make policies that optimises energy conservation.

A recent report published by the Norwegian national audit, criticises the energy efficiency measures implemented by Enova, by stating that they are only 20% as effective as initially claimed [41]. This is mainly because energy savings are reported on basis of calculated values. The results from this study give weight to the conclusion by the national audit, and question the decision that the viability of the measures should be based on calculated energy use alone.

The inherent flaws in the NVE dataset, and the low amount of data available for low energy buildings and passive house dwellings indicate a knowledge gap on the actual energy savings provided by technical improvements. As requested by [20], there is a need for an expanded database on the relationship between measured and calculated energy use in the dwelling stock. In the coming years more data on measured and calculated energy use in passive houses and low energy buildings should be gathered, allowing for the establishment of a database based on the actual energy savings from passive houses and low energy buildings. This study could be seen as a beginning of this work.

A more accurate energy modelling can be performed using the energy intensity factors I. This will have implications for scenario analysis of the dwelling stock like the EPISCOPE project. Additionally, work must be done to decrease the gap between measured and calculated energy use now that it has been identified. If the energy intensity factor is taken into consideration when performing calculations in the future, the calculations would better reflect reality, consequently moving the energy intensity factor closer to 1.

7 Conclusion

The prebound and rebound effect has been identified in the Norwegian dwelling stock. However, the prebound effect seems to be slightly limited in the oldest subset of the dwelling stock, although it would require a more detailed analysis to identify the reasons for this limitation.

There is no doubt that better building standards decrease energy consumption for heating and DHW, but one must question to what extent the current trend for constantly improving building standards is the optimal measure to decrease specific energy use in the dwelling stock. The results show user behaviour having a large impact on energy use in dwellings. The energy intensity factor can be as low as 0.55 for older parts of the dwelling stock, increasing to 1.37 for passive houses and low energy buildings. Therefore, dweller awareness and willingness to adhere to building design must follow technical improvements. Passive houses can be an effective way to decrease specific energy use in dwellings, but without additional measures the design goals will fall short of reality. As this study contains relatively few measurements, there is clearly a need for a more robust and expanded evaluation of energy use in passive and low energy dwellings.

There are inherent errors in the NVE dataset because of the lack of quality assurance when preforming the EPCs. It should be in everyone's best interest to have as precise assessments of actual energy use as possible, both for evaluating the current use in the dwelling stock and for analysis of future scenarios. The mandatory, professional, assessment of EPCs for all new buildings is a step in the right direction and if an energy intensity factor close to 1 for all subsets of the dwelling stock is achieved, this would be a great boon for policy makers and future energy conservation measures.

8 Future Work

There are many ways that the precision of these results could be improved upon. A sensitivity analysis of parameters would identify possible systematic errors, like more detailed values for el. specific energy use in the different segments of the dwelling stock. A more reliable data source could be investigated in a similar manner, for instance based on survey results with a large sample size. In this way, the data available could easier be tailored for the purpose of the study, like information about actual energy consumption for different areas of use, and detailed parameters on users and user behaviour. To identify which parameters have the largest influence on energy use, a multi-variable regression analysis could be applied on the expanded dataset.

As more and more passive houses are built, it is expected that a big enough sample size will become available to be able to reach a more robust conclusion on the energy intensity factor for buildings with a low energy demand. If a database on these studies is established, it could greatly benefit knowledge of actual use of passive houses, and the concept could be improved to better reflect actual use by inhabitants.

As the discrepancy between measured and calculated energy use has been identified, its implications should be studied more thoroughly. Calculations on energy use in the dwelling stock, and the energy saving potential in low energy buildings should be preformed to evaluate current and future energy policies.

It would also be interesting to evaluate passive houses from a life cycle perspective, from the perspective that they generally consume more energy than the calculated value. Greenhouse gas emissions over the lifetime of the building could be compared with a TEK10 building to see if the decreased energy savings still would outweigh the increased material costs following larger insulation levels and mechanical ventilation systems.

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Appendix A Calculated and Measured Eenergy Consumption for Passive Houses and Low Energy Buildings

	Study	Location	Building type	Calculated energy use (kWh/m^{2}a)				Measured energy use (kWh/m^{2}a)				Corrected for DD
				Total	Heat+DHW	Heating	DHW	Total	Heat+DHW	Heating	DHW	
Swedish												
	Janson (2010)[19]	Värnamo	Apartments	75.4	34.1	9.1	25.0	70.0	34.0	9.0	25.0	Yes
		Frillesås	Apartments	81.1	39.8	14.8	25.0	92.9	33.8	18.8	15.0	Yes
		Lidköping	SFH	85.2	43.9	24.9	19.0	91.3	50.0	33.0	17.0	Yes
	Andresen and Haase (2013) [25]	Allingsäs	Apartments	92.0	43.0	18.0	25.0	76.0	37.0	19.0	18.0	No
		Backa Rød	Apartments	91.3	50.0	25.0	25.0	81.3	40.0	19.0	21.0	No
	M.Wall (2006)[24]	Gothenburg	MFH	78.9	37.6	12.9	24.7	68.0	38.4	14.3	24.1	Yes
Norwegian												
	Berge(2013)[27]	Løvåshagen	Apartments	74.0	42.0	12.8	29.2	108.0	66.7	-	-	Yes
			Apartments	101.0	59.7	-	-	126.5	85.2	-	-	Yes
	Erstaas(2013)[29]	Berg Studentby	MFH	92.0	50.7	-	-	146.0	104.7	-	-	Yes
	Thomsen et al.(2015)[30]	Rossåsen	SFH	68.0	36.3	17.3	19.0	86.0	44.7	-	-	No
	Wigenstad(2007)[31]	Jektholtet-Harstad	Apartments	122.0	74.0	58.0	16.0	123.0	78.0	53.0	25.0	Yes
			Apartments	132.0	83.2	67.0	16.0	160.0	97.0	72.0	25.0	Yes
	Gullbrekken et al. (2015)[39]	Snåsa	SFH	120.0	78.7	-	-	85.5	44.2	-	-	Yes
	Langseth et al.(2011) [38]	Grimstad	SFH	82.2	59.9	40.9	19.0	111.6	70.3	51.3	19.0	N.A.
			SFH	84.1	61.8	42.8	19.0	105.6	64.3	45.3	19.0	N.A.
			SFH	80.4	58.1	39.1	19.0	110.0	68.7	49.7	19.0	N.A.
			SFH	79.4	57.1	38.1	19.0	91.0	49.7	30.7	19.0	N.A
	Own case study	Granåsen	SFH	96.0	66.0	-	-	128.6	82.5	-	-	Yes
			MFH	78.1	48.9	-	-	114.8	85.6	-	-	Yes
			MFH	75.4	46.1	-	-	112.73	83.5	-	-	Yes

Table 9: Measured and calculated energy use for dwellings analysed in Norwegian and Swedish studies on passive houses and low energy buildings. Black values are taken directly from literature. Blue values are sums of energy use for heating and DHW taken from literature. Red values in the columns for total and heat+DHW, are values based on either assumed el. specific energy use or DHW consumption. Red values in the DHW column are the assumed values for DHW.

Appendix B Chauvenet's Criterion

To identify the outliers contained in a normal distribution find the number of standard deviations that correspond to the bounds of the probability band around the mean (D_{max}). This reference maximum deviation is compared to the relative deviation between the difference of the suspected outlier and the mean as a fraction of the standard deviation. [37] Mathematically this is

$$D_{max} \geq \frac{|x - \mu|}{\sigma} \tag{5}$$

Where,

D_{max} : maximum allowable deviation

x : value of the suspected outlier

μ : sample mean

σ : sample deviation

The probability band P is related to the Gaussian distribution, will vary according to sample size n.

$$P = 1 - \frac{1}{2n} \tag{6}$$

Where:

P : probability band centred on the sample mean

n : sample size

In order to find the standard deviation level associated with P, one only needs to analyse one of the tails of the distribution, due to the symmetry of the Gaussian distribution. The probability band is therefore given as

$$P_z = 1 - \frac{1}{4n} \tag{7}$$

Where,

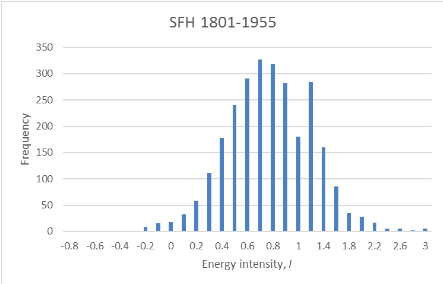
P_z : probability represented by one tail of the normal distribution

n : sample size

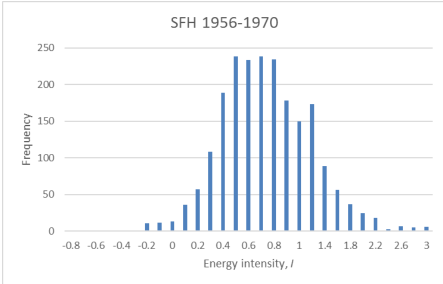
This probability band is related to the Gaussian distribution, and its relation to D_{max} from Equation 5 can be found either using a P-score table or in excel, using the formula =ABS(NORM.S.INV($1/4n$)).

Appendix C Histograms From the NVE Dataset

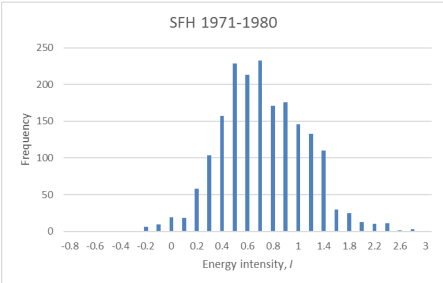
Figure 18: Histograms from the NVE dataset for all age cohorts, single-family houses.



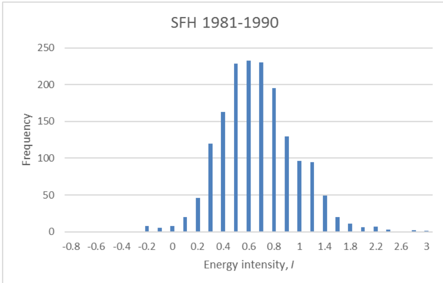
(a) 1801-1955



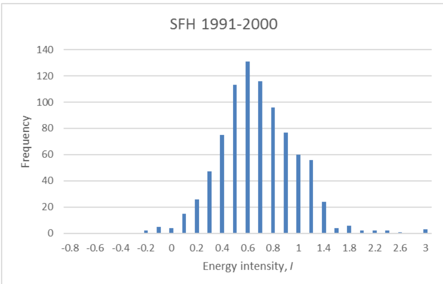
(b) 1956-1970



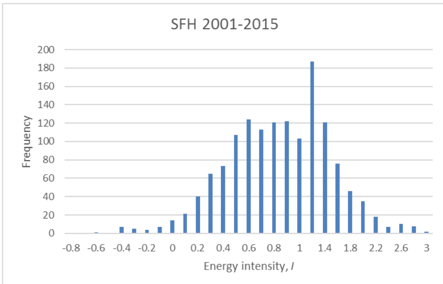
(c) 1971-1980



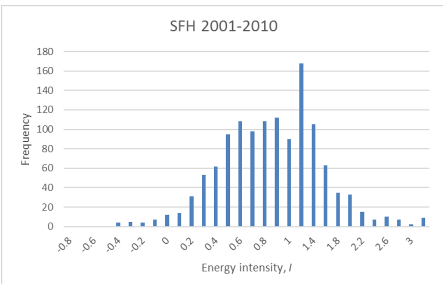
(d) 1981-1990



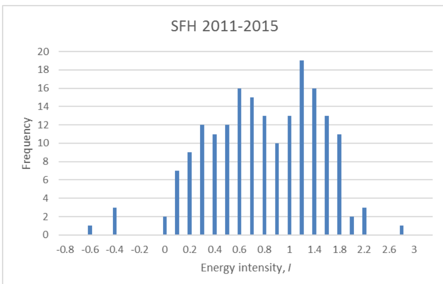
(e) 1991-2000



(f) 2001-2015

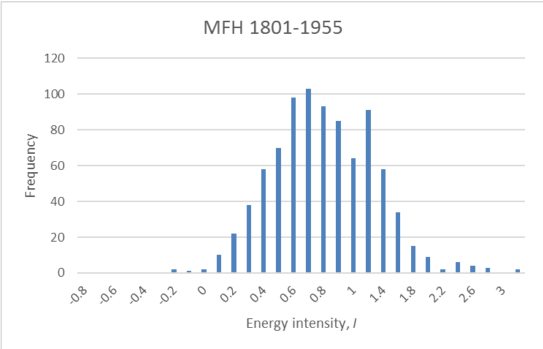


(g) 2001-2010

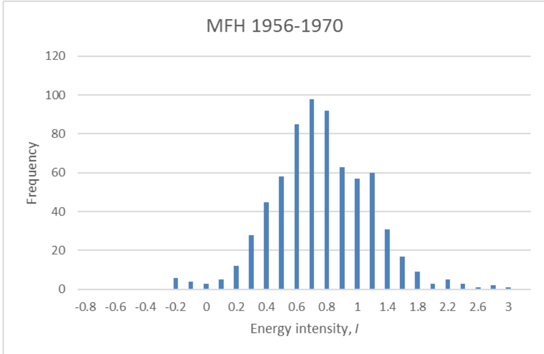


(h) 2011-2015

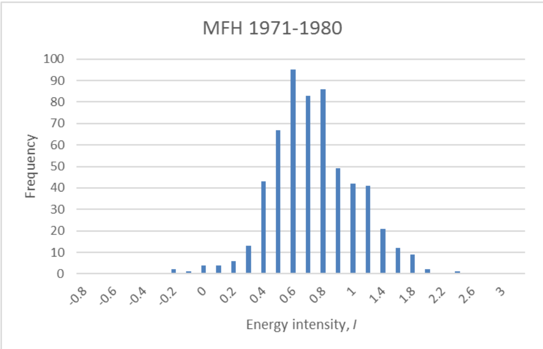
Figure 19: Histograms from the NVE dataset for all age cohorts, multi-family houses.



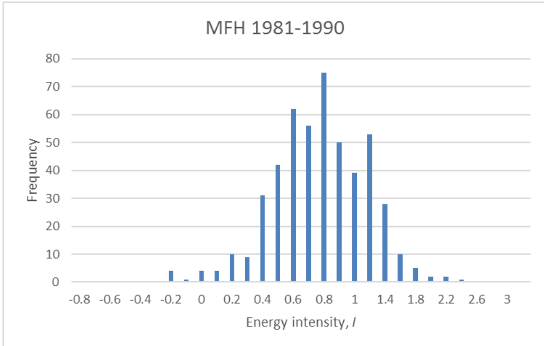
(a) 1801-1955



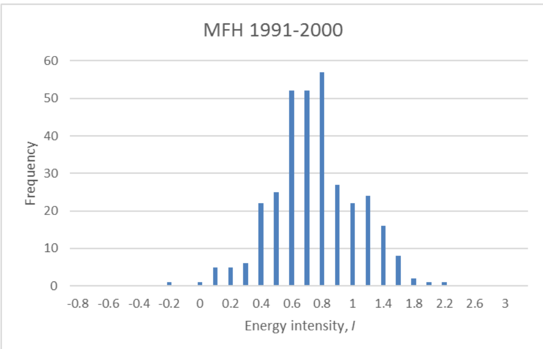
(b) 1956-1970



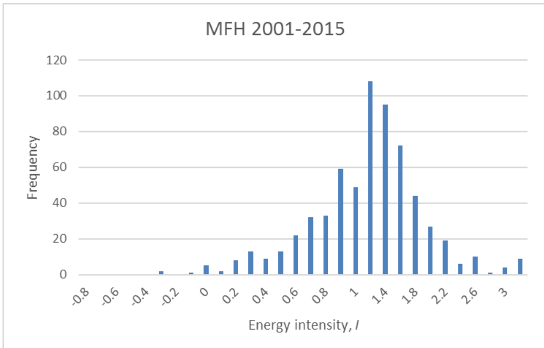
(c) 1971-1980



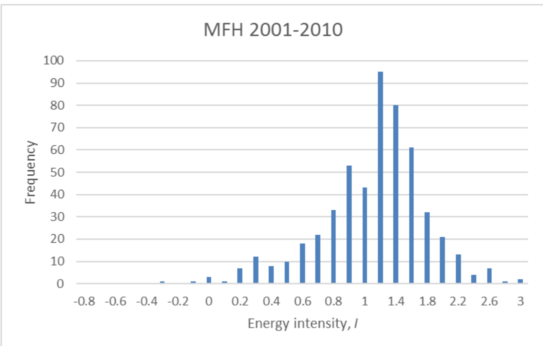
(d) 1981-1990



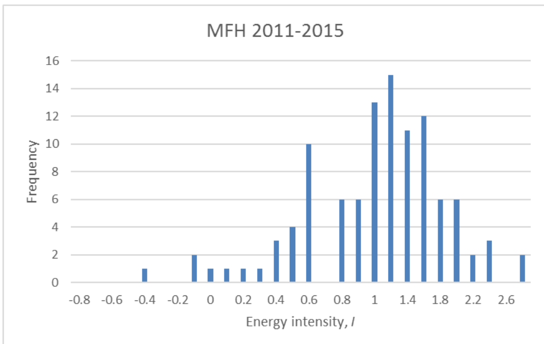
(e) 1991-2000



(f) 2001-2015

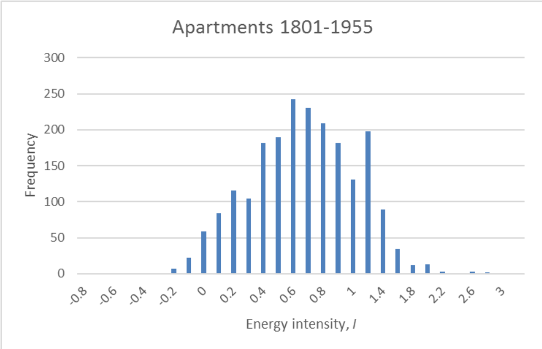


(g) 2001-2010

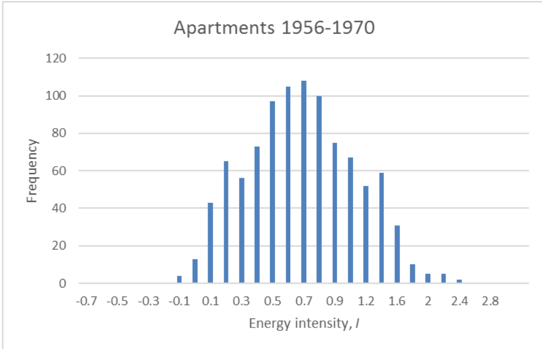


(h) 2011-2015

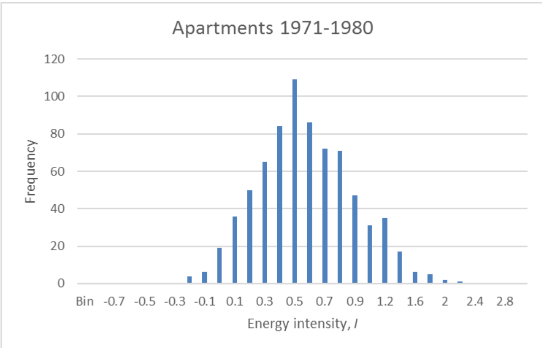
Figure 20: Histograms from the NVE dataset for all age cohorts, apartments.



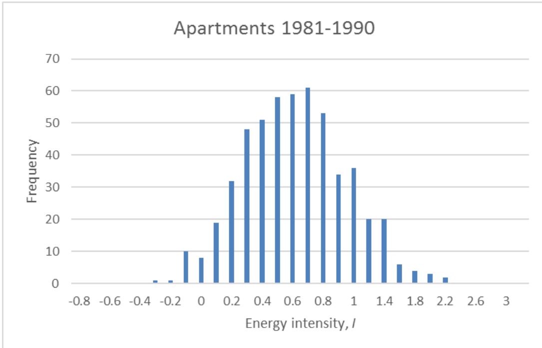
(a) 1801-1955



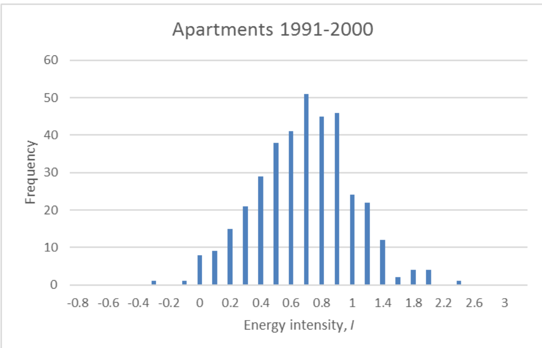
(b) 1956-1970



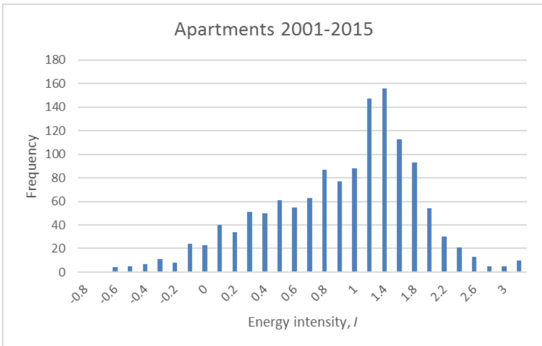
(c) 1971-1980



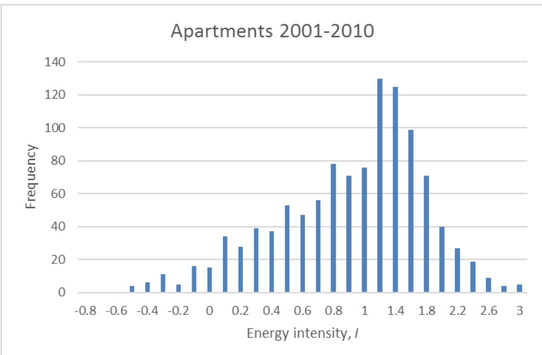
(d) 1981-1990



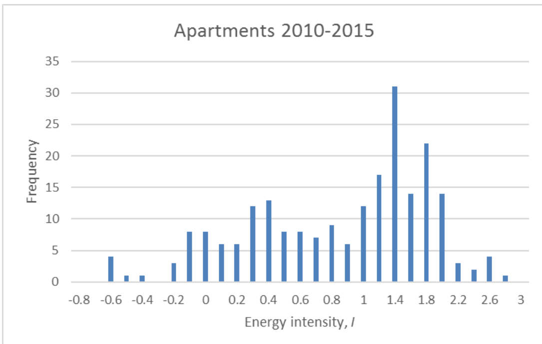
(e) 1991-2000



(f) 2001-2015



(g) 2001-2010



(h) 2011-2015

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