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DOI
10.1016/j.enbuild.2018.10.025

Publication date
2019

Document Version
Final published version

Published in
Energy and Buildings

Energy & Buildings 182 (2019) 251–263

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Actual energy saving effects of thermal renovations in dwellings—longitudinal data analysis including building and occupant characteristics

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A R T I C L E I N F O

Article history:
Received 1 June 2018
Revised 22 September 2018
Accepted 14 October 2018
Available online 23 October 2018

Keywords:
Thermal renovations
Dwellings
Longitudinal data
Energy saving gap
Occupant and building characteristics

A B S T R A C T

Energy renovations often result in lower energy savings than expected. Therefore, in this study we investigate nearly 90,000 renovated dwellings in the Netherlands with pre and post renovation data of actual and calculated energy consumption. One of the main additions of this paper, compared to previous studies on thermal renovation, is that it only takes dwellings into account with the same occupants before and after renovation, using a large longitudinal dataset. Overall this paper shows new insights towards the influence of the energy efficiency state of a building prior to energy renovation, the type of building, the number of occupants, the income level of the occupants and the occupancy time on the actual energy savings, the energy saving gap and on the probability of lower energy savings than expected. We also investigate if the influence is different per type of thermal renovation measure. Some of the findings are: it is impossible to conclude which single thermal renovation measure is the most effective because this is dependent on the energy efficiency of the building prior to the energy renovation, type of building, income level and occupancy; occupants with a high income save more energy than occupants with low income; dwellings with employed occupants benefit more from improved building installations than dwellings occupied by unemployed occupants; The prebound and rebound effects are only part of the explanations for lower than expected energy savings; Deep renovations result more often in lower than expected energy savings than single renovation measures but nevertheless they result in the highest average energy saving compared to other thermal renovation measures. The results could be used for more realistic expectations of the energy reduction achieved by thermal renovations, which is important for (amongst others) policy makers, clients and contractors who make use of energy performance contracting, home owners, landlords and (social) housing associations and as a starting point to improve the energy calculation method.

1. Introduction

Several studies demonstrate evidence of the energy performance gap [1–3]. This gap indicates that, on average, energy-efficient dwellings consume more energy than expected, and energy-inefficient dwellings consume less energy than expected. The consequence of this gap is that another gap arises, the gap between actual and predicted energy savings after energy renovations [4]. In this paper, this new gap is referred to as the energy saving gap (ESG). The ESG is also demonstrated in other studies [5–9]. All indicate that on average, the majority of energy renovations result in lower energy savings than expected.

Many researchers, policy makers and practitioners assume the occupant to be primarily responsible for overestimated energy saving effects [10,11]. The rebound and prebound effects should explain the discrepancy between expected and achieved savings [4,12]. The rebound effect can be explained as follows: "Since energy-efficiency improvements reduce the marginal cost of energy services, the consumption of those services may be expected to increase. This increased consumption of energy services may be expected to offset some or all of the predicted reduction in energy consumption" [13]. In practice this means that instead of reducing energy for space heating by improving the thermal characteristics of a house, a renovation might instead lead to increased comfort demand [14,15]. This would imply that occupants behave less energy efficient in efficient dwellings (rebound effect) and vice versa (the prebound effect) [4]. However, other factors could also explain (part of) the energy saving gap. For example: incorrect

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https://doi.org/10.1016/j.enbuild.2018.10.025
0378-7788/

assumptions of building characteristics, especially of older buildings [16–18]. The building characteristics of older buildings are not always well documented; therefore, the insulation levels of those buildings are often estimated and might not reflect reality (measuring is time consuming and relatively difficult) [17,19]. Also mistakes in the construction process could cause (part of) the gap. Another reason for the gap could be the calculation method. A building energy simulation is always a simplification of reality; if the method is oversimplified, then this could result in under- and/or overestimations of building energy consumption.

The energy saving gap has become a concern by several parties, some of the reasons why a better insight in lower than expected savings are desired are: firstly, policy makers often use expected energy savings as a basis to design new energy saving policies, the ESG makes that the policies do not match the intended goals [20]. An evaluation of the EED [21] mentions that energy renovation plans or guidelines are still lacking in identifying the most effective measures for each climate, country (according to its national energy regulations), type of dwelling, size, age, operation, and maintenance, dwelling envelope, and more. Secondly, clients and contractors who make use of energy performance contracting would benefit from accurate energy saving predictions: "energy performance contracting is a particular form of service contract in which the contractor must ensure, through a binding commitment, that a specified amount of energy will be saved through the project" [22,23]. Third, home owners, landlords and (social) housing associations might be more willing to renovate if they have a high certainty on the payback time of their thermal renovation measures [24].

Therefore we aim in this study to obtain a better insight into the actual energy savings after thermal renovations, the energy saving gap and the probability of lower energy saving effects than expected. Contrary to most previous studies on thermal renovation, we use longitudinal data instead of cross-sectional data [8,25–28], including pre- and post-renovation energy consumption data (measured and calculated), as well as building and occupant characteristics data. This longitudinal character prevents possible bias, as changes of occupants are followed in time. The possible bias is also reduced by taking the occupant into account, which is seldom done before in studies towards actual energy savings after thermal renovations [5]. Furthermore, post-renovation studies are often based on relatively small samples because pre- and post-thermal renovation data are scarce, but in this paper we have the availability of a relatively large dataset, including nearly 100,000 renovated dwellings. The research is divided into four parts. In the first part we investigate if building and occupant characteristics (the energy efficiency of the building prior to a thermal renovation, type of building, number of occupants, income level of occupant and the occupancy time) have an effect on the energy savings of different types of thermal renovation measures. We also investigate if the effect is different per renovation measure. This analysis is followed by a similar analysis of the energy saving gap. Then we determine how frequent the prebound and rebound effects occur in the renovated buildings. Finally, we conclude with a detailed logistic regression in which we investigate which factors influence the probability on lower than expected energy savings after a thermal renovation.

The research is structured as follows: In Section 2, we provide the state of the art of the research, which includes the calculation method for residential energy consumption. Then, we describe the database and the research method. After this we give a description of how we define thermal renovations in this paper. The results section presents the results of the four different analyses described above. In the discussion section, we explain the advantages and disadvantages of the method and data that we used and how this influences the results, and finally we draw general conclusions.

2. State of the art—actual and theoretical energy consumption and the energy saving gap

In this section we explain the calculation method of theoretical energy consumption used in this paper, the expected/actual energy savings and the energy saving gap.

Since heating is the main energy consumer of dwellings in the Netherlands and because energy consumption for heating has the highest unexplained energy performance gap [26], only the energy use for heating and domestic hot water (dhw) is studied. Because approximately 90% of the Dutch households use gas as a heating source we can, by studying only gas consumption distinguish the energy used for heating and dhw versus the energy used for household appliances. This means that houses that do not use gas as a heating source are removed from the analysis. Energy saving in this paper can therefore be read as gas savings/energy saving for heating. Cooling systems are not common in Dutch households and are therefore not included in the analysis. The expected energy consumption (energy demand) for heating used in this paper is based on the method that the Dutch government uses to define the Energy Performance Certificate. The method is based on a quasi-steady-state calculation (the entire calculation method is described in ISSO 82.3 [29]). To calculate the energy demand for heating the following parameters are taken into accounts: air tightness, insulation levels, ventilation rates, efficiency of the heating system. A normalised number of occupants per m^2 determine together with the efficiency of the dhw system how much energy is required for hot water.

The amount of expected energy saved after a renovation is the difference of the estimated energy consumption before renovation and after renovation (Eq. (1)). We correct for building size by using the energy consumption per square meter of floor area, because building-related energy is highly dependent on the floor area of the building [30]. Since we do not know the specific moment of the year the renovation took place, we decided to compare the first year of our database (2010) with the last year of our database (2014) (Eq. (1)). This means that energy saving is determined as the gas consumption of year 2010 minus that of year 2014. To make the years comparable a correction for degree days is applied. The amount of actual saving is the amount of energy consumed before the renovation minus the amount of energy consumed after the renovation (Eq. (2)). These data are obtained at an address level from Statistics Netherlands (CBS). The energy saving gap is equal to the expected savings minus the actual savings (Eq. (3)).

$$fQ_{saving} = fQ_{pre} - fQ_{post} \tag{1}$$

fQ_{saving} = expected energy savings after renovation [MJ/m2]
fQ_{pre} = expected gas consumption before renovation (year 2010)[MJ/m2]
fQ_{post} = expected gas consumption after renovation (year 2014) [MJ/m2]

$$Q_{saving} = Q_{pre} - Q_{post} \tag{2}$$

Q_{saving} = actual energy saving after renovation [MJ/m2]
Q_{pre} = actual gas consumption before renovation (year 2010) [MJ/m2]
Q_{post} = actual gas consumption after renovation (year 2014) [MJ/m2]

$$ESG = fQ_{saving} - Q_{saving} \tag{3}$$

ESG = energy saving gap [MJ/m2]
fQ_{saving} = expected energy saving after renovation [MJ/m2]
Q_{saving} = actual energy saving after renovation [MJ/m2]

3. Data

Two different data sources are used in this study. The first one is the SHAERE database, which is from the umbrella organisation of the Dutch social housing companies in the Netherlands (AEDES). The main aim of this database is to monitor the energy efficiency of the social housing stock in the Netherlands. It contains 60% of the social housing stock in the Netherlands, which, comprising 30% of the total housing stock, is relatively large, compared to other countries. This means that the database contains a significant share of all dwellings in the Netherlands. It also contains most of the input variables that are used to calculate the energy performance of dwellings, and these data are present for five consecutive years (2010–2014). The second source is data from Statistics Netherlands (2010–2014) and contains actual annual energy consumption data and occupant characteristics data on a household level. Because of privacy protection we are only allowed to publish the results on an aggregated level (a minimum of 10 cases).

Approximately 90% of the Dutch households use gas as a heating source for their homes [31]. Most households use a combined gas boiler that provides both heating and dhw. Since heating is the main energy consumer of the dwellings and because energy consumption for heating has the highest unexplained energy performance gap [26], we studied only dwellings that use gas as a heating source and electricity consumption is not taken into account (127,183 cases). This means that energy saving in this paper can be read as gas savings.

Dwellings with collective heating systems were deleted from the database because the Statistics Netherlands expressed doubts about the quality of those data. Furthermore, cases with a floor space of over 1000 m^2 and dwellings with gas consumptions higher than 500,000 MJ were discarded from the analysis (150 cases and 10 cases). Statistics Netherlands obtains its actual energy consumption data from energy supply companies, and it is officially only required to collect these data once every three years. Since it is important to have the correct energy consumption in the correct year for this analysis, we deleted the dwellings with the exact same energy consumptions as the previous year (307,975 cases) because it is highly unlikely that a dwelling consumes exactly the same amount of energy every year. To make the actual energy saving data comparable to the predicted energy saving, the energy consumption data were normalized to 2262° days per year which is used as standard in the theoretical calculations. Almost 95% of the occupants, stayed in their dwelling after renovations. To prevent possible bias from change in occupant behaviour as much as possible we excluded all cases where the occupant before renovation was different compared to after renovation (221,165 cases). One could expect that dwellings that are deeply renovated would undergo a change of occupants more often than those in which only one thermal renovation measure is applied, because for deep renovations it is more often necessary that the house is uninhabited. However, from our data, there was no difference in the percentage of changed occupants between the single renovation measures and the deep renovations. Also dwellings in which other renovation measures than mentioned in Section 5 or administrative corrections were found are excluded from the analysis (41,597 cases). Finally there were 228,991 cases that didn't have information to identify if a renovation was or was not executed; therefore also those cases are excluded from the analysis, leaving with a total of 235,753 cases. From which 87,513 houses are renovated between 2010 and 2014.

4. Methods

First, we used descriptive statistics in which we determine how frequent the thermal renovation measures occur in the database and how frequent this results in lower and higher than expected energy savings. These descriptive analyses should indicate whether thermal renovations indeed result more often in lower savings than expected.

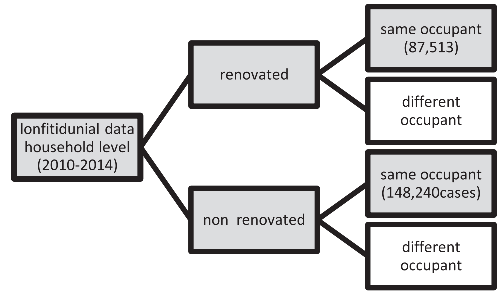

Fig. 1. Analysed data.

To test whether the savings per renovation measure differ significantly from dwellings that were not renovated, a Kruskal–Wallis test (which is a one-way ANOVA on ranks) with a follow-up pairwise comparison was executed. The Kruskal–Wallis test was chosen instead of a traditional ANOVA because the energy saving data are not normally but leptokurtic distributed. The leptokurtic distribution could make the Type I error rate too low, and consequently the power too high, if a traditional ANOVA was used [32]. Fig. 1

When the average energy savings per renovation measure are known, we investigate, as shown in Fig. 2, whether specific building and occupant characteristics influence the amount of energy saved and if they are different per renovation measure. For these analyses, we execute also the Kruskal–Wallis test. If there are only two groups compared, then the Whitney *U* test is used which is the non-parametric equivalent of the independent samples *t*-test. In the second part of the analysis, similar analyses were conducted for the energy saving gap (Fig. 2).

The following building and occupant characteristics are investigated: the energy efficiency of the building prior to the thermal renovation, the building type, household income, the number of employed occupants and the number of household members. These specific occupant characteristics were chosen for two reasons, namely availability and because previous research or existing theories expect a correlation between those aspects and energy consumption and/or the energy saving gap [1,33]. For example, from a previous study, we know that ventilation with heat recovery reduces energy more in dwellings that are well insulated and have a high airtightness than in those that are poorly insulated and have low airtightness [34]. This would mean that the energy efficiency state of the building prior to the thermal renovation influences the amount of energy saved. Regarding building type, we expect that insulation measures would be more profitable for single-family dwellings than for multifamily dwellings because the former generally have a relatively larger building envelope area. This means that heat loss because of poor insulation has a larger impact on single-family dwellings than on multifamily dwellings. The level of employment is assumed to be correlated with the occupancy time of a building. Previous research found strong correlations between the number of occupancy hours and residential energy consumption [35–37]. The number of household members was found to correlate with residential energy consumption [37–40]. Finally, income was also often mentioned as being influential on residential energy consumption [30,41].

Because the rebound and prebound effect are expected by several researchers to be a main cause of lower energy savings than expected, we apply in the third part of this research descriptive statistics in which we define if the rebound and/or prebound effect occur. The prebound effect is assumed to occur if the energy

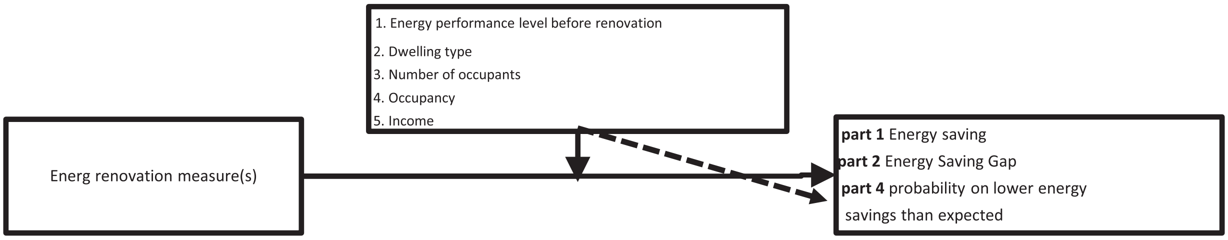

Fig. 2. Research method parts 1, 2 and 4 *(dashed line are direct effects in part 4).*

consumption before renovation is more than 10% lower than expected. The rebound effect is assumed to occur if energy consumption after renovation is more than 10% higher than expected. And finally we conclude this paper with a logistic regression in which we investigate the influence of the above-mentioned occupant and building characteristics on the probability that thermal renovations result in lower-than-expected energy savings (Fig. 2). Since we expect that the occupant and building characteristics do not only have a direct effect (continuous lines in Fig. 2) on the probability of overestimated saving effects but also an interaction effect (dashed lines in Fig. 2) we also add interaction terms of the building and occupant characteristics in the regression.

5. Description of thermal renovation in this paper

To prevent confusion and because the terms 'maintenance' and 'renovation' are often used interchangeably, this section defines what we (in this paper) understand by thermal renovations. We define in this paper thermal renovation as renovation measures that are taken to reduce energy consumption used for thermal comfort. We identify four different types of thermal renovations. The first is the single thermal renovation measure, which is defined as a significant improvement (going from at least one category to another (Table 1)) of only one building component. The building components that are considered are: roof insulation, floor insulation, façade insulation, window improvements, heating system, domestic hot water system (dhw system) and ventilation system. If dhw system and heating system are replaced at the same time, then this is identified as one measure, because most buildings in the Netherlands use a combined heating and dhw system. The second type of thermal renovation is a significant improvement in the insulation level of the entire building envelope. This means that at least two components are significantly improved in terms of insulation. The third type of thermal renovation is a significant improvement in all building installations (heating, dhw and ventilation). The fourth type of thermal renovation is deep renovation, which refers to a significant improvement in at least three building components that bring them to a level equal to or higher than the current building regulation standards. To determine whether the improvement is significant, we categorised the thermal renovations. The change from one "higher" category (see Table 1 for categories) to another is assumed to be a significant improvement. Additionally, the improvements of the building installations must meet at least the current renovation standards (Table 1). For example, in this paper, the replacement of a boiler is only considered to be a thermal renovation if the new boiler has an efficiency of 0.95 (HR107 boiler). The categories are based on the Dutch ISSO publication 82.3 [29] (Table 1). We choose to use those categories because also the theoretical energy consumption is based on those. The change from natural ventilation to mechanical exhaust ventilation is also considered to be an improvement, despite the fact that this change is not per se expected to result in a theoretical energy reduction.

The categorization of renovation measures makes that we can identify if a renovation took place. For this study we do not distinguish the different levels of renovation e.g. we don't take into account if a facade is renovated category 1 to 2 or from 1 to 5. Although this could also be an interesting topic for research in this study we assume that the renovation and the level of renovation is a choice that is taken carefully considering available budget on the moment of renovation, available techniques and practical aspects. The research of Majcen et al. [5] gives more insights on this topic.

6. Results

In this result section we start with an in depth analysis of the energy savings followed by in depth analysis of the energy saving gap and descriptive statistics of the rebound and prebound effect finally we conclude with a detailed logistic regression.

The descriptive statistics in Table 2 show the number renovated houses that resulted in higher savings than expected, lower savings than expected and savings that are almost similar to what was expected. The table also demonstrates that almost 90,000 dwellings underwent a renovation within the renovation categories mentioned in Section 5 (single measures; insulation of entire building envelope; improvement of building installations and deep renovations). As written in the method section all energy savings are corrected for degree days to make them comparable with theoretical energy consumption. Table 2 shows that on average, 40% of the cases have higher energy savings than expected, while 57% have savings that were lower than expected and only 3% of the renovations have well predicted results (10% higher or lower than the expected savings). We choose for 10% because previous comparisons of actual and theoretical energy consumption have shown that a prediction within a 10% range is very good. Further Table 2 indicates that deep renovations most often result in lower energy savings than expected (81%). The same holds true for thermal renovations where two or more insulation measures are applied. In 35% of the cases the improvement of building installations results in higher than expected energy consumption. Regarding the single measures, we observe that the improvement in the combined heating and dhw system and in façade insulation most often result in lower-than-expected energy savings.

6.1. Average actual savings per thermal renovation measure

Fig. 3 shows the average gas consumption per renovation measure. The results of the Kruskal–Wallis test, comparing the savings per renovation type, demonstrate that the actual energy savings per renovation measures differ significantly from each other ($H(11) = 3{,}526.84$, $p < 0.05$), although the difference between non-renovation and especially domestic hot water (dhw) and ventilation are only small compared to no renovation measure.

Fig. 3 demonstrates (as expected) that most gas is saved when deep renovations are executed. The results also indicate that the energy consumption of non-renovated dwellings also decreased. This phenomenon is also found in previous studies [5,42] that

Table 1
Categories of building characteristics based on ISSO 82.1 2011.

Catg.	Window (frame + glazing)[W/m2K]*	Floor insulation[Km²/W]	Façade insulation[Km²/W]	Roof insulation[Km²/W]	Heating system	dhw	Ventilation
1	Single glass(U ≥ 4.2)	No-insulation(Rc ≤ 0.32)	No-insulation(Rc ≤ 0.36)	No-insulation(Rc ≤ 0.39)	Local gas heater	Tankless gas water heater	Natural ventilation
2	Double glass(2.85 ≤ U < 4.2)	Insulated cavity 32 < Rc ≤ 0.82	Insulated cavity 0.36 < Rc ≤ 0.86	Insulated cavity 0.39 < Rc ≤ 0.89	Conventional boiler (η < 0.80)	Electric boiler	Mechanical exhaust ventilation
3	HR + glass(1.95 ≤ U < 2.85)	Up to 40 mm insulation 0.82 ≤ 1.15	Up to 40 mm insulation 0.86 ≤ 1.36	Up to 40 mm insulation 0.89 ≤ 1.22	Improved non-condensing boiler (η = 0.8–0.90)	Conventional combi boiler (η = 0.80)	Demand based mechanical exhaust ventilation**
4	HR + + glass(1.75 ≤ U < 1.95)	40–80 mm insulation 1.15 < Rc ≤ 2.15	40–80 mm insulation 1.36 < Rc ≤ 2.36	40–80 mm insulation 1.22 < Rc ≤ 2.22	Condensing boiler(η = 0.925–0.95)	Improved non-condensing combi boiler(η = 0.80–0.9)	Balanced ventilation with heat recovery***
5	Triple insulation glass (U < 1.75)	80–120 mm insulation 2.15 < Rc ≤ 3.15	80–120 mm insulation 2.36 < Rc ≤ 3.36	80–120 mm insulation 2.22 < Rc ≤ 3.22	Condensing boiler(η = 0.90–0.925)	Condensing combi boiler(η = 0.90–0.95)	
6		120–160 mm insulation 3.15 < Rc ≤ 4.15	120–160 mm insulation 3.36 < Rc ≤ 4.36	120–160 mm insulation 3.22 < Rc ≤ 4.22	Condensing boiler(η > 0.95)		
7		160–200 mm insulation 4.15 < Rc ≤ 5.15	160–200 mm insulation 4.36 < Rc ≤ 5.36	160–200 mm insulation 4.22 < Rc ≤ 5.22			
8		More than 200 mm insulatin Rc > 5.15	More than 200 mm insulatin Rc > 5.36	More than 200 mm insulatin Rc > 5.22			

* Wooden/plastic window frames are assumed
** Mechanical exhaust ventilation, rate is determined by CO_2 level in the house
*** Mechanical ventilation system (inlet and exhaust) that uses a heat recovery system to minimize heat loss due to ventilation

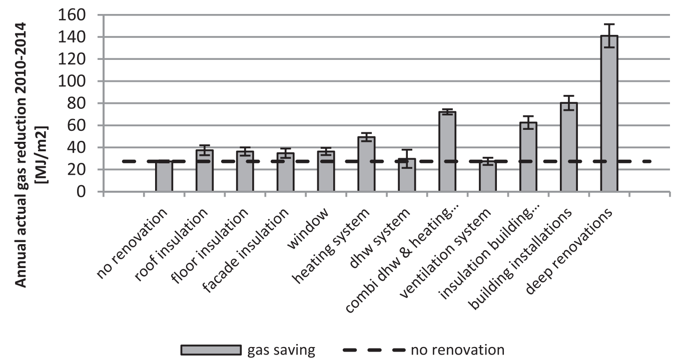

Fig. 3. Average energy saving (corrected for degree days) per thermal renovation measure (including confidence interval 0.05) *dashed line is actual difference in gas reduction between 2010–2014 for non-renovated houses.*

used data from the same source. There are several reasons that explain why non-renovated dwellings have a decrease in heating consumption between the years 2010 and 2014, such as a change in occupant behaviour (perhaps occupants used lower thermostat settings, or they might have reduced the number of hours that heat their dwelling). Another explanation could be mistakes in the monitoring system; e.g. renovation measures not registered in SHAERE. We made the years comparable by correcting the energy consumption by degree days, although this is a common method the method has also drawbacks that possible cause the found energy saving of non-renovated houses [43]. Because the exact reason of this autonomous reduction is unclear we represented the energy reduction of non-renovated buildings with a dashed line in Fig. 3 and the following figures. Taking this dashed line into account, Fig. 3 suggests that an improvement of dhw system or ventilation system might not result in or only limited energy reduction. This could be true because the main aim of improving a dhw system or ventilation system is often to increase the comfort level and not to save energy. For ventilation this is especially the case in this dataset because most of the ventilation systems are renovated from a natural system to a mechanical exhaust system.

The average energy saving per renovation measures is known. However, we expect that occupant and building characteristics influence energy savings. We also expect that this influence is different per energy saving measure. Therefore, in the following paragraphs we compare the average saving per building and occupant characteristics per thermal renovation measure.

6.1.1. Average actual energy savings—energy efficiency of the building prior to thermal renovation

The Dutch government uses the energy index and the energy label to identify the energy efficiency of buildings. This index is based on the simplified heat loss calculation (see Section 2), it is corrected for the floor area of the dwelling and the corresponding heat transmission areas [29]. The energy index is divided into several categories, which are the energy labels. Dwellings with an energy label A are supposed to be highly energy efficient, and dwellings with label G energy inefficient. In this section we investigate whether the energy label prior to the thermal renovation influences the average energy savings per renovation measure. Because almost no renovation measures are applied to dwellings with an energy label A, those dwellings are excluded from the analysis. The Kruskal–Wallis test in Table 3 shows that we found significant differences between the average energy savings per energy label for all renovation measures. Roof insulation, facade insulation and deep renovations yield the expected results: Energy savings are higher for non-energy-efficient dwellings than for energy efficient-dwellings. For the renovation measures 'improvements of the windows', 'insulation of building envelope' and 'building installations'

Table 2
Number of cases per thermal renovation type comparison number of over- under and well predicted cases.

Renovation measures 2010–2014	Frequencies	Frequencies -overestimated energy savings[a]	Frequencies - well estimated energy savings[b]	Frequencies - underestimated energy savings[c]
Single renovation measures	78583	43556(55%)	2466(3%)	32561(42%)
Insulation roof	*5164*	*3129(61%)*	*138(3%)*	*1897(37%)*
Insulation floor	*10095*	*4367(43%)*	*125(1%)*	*5603(56%)*
Insulation facade	*6504*	*4067(63%)*	*160(3%)*	*2277(35%)*
window	*10103*	*5293(52%)*	*291(3%)*	*4519(45%)*
Heating system	*7864*	*3790(48%)*	*217(3%)*	*3857(49%)*
dhw system	*1895*	*1021(54%)*	*13(1%)*	*861(45%)*
Combi dhw & heating	*27431*	*17158(63%)*	*1389(5%)*	*8884(32%)*
Ventilation system	*9527*	*4731(50%)*	*133(1%)*	*4663(49%)*
Building insulation	3552	2405(68%)	102(3%)	1045(29%)
Building installation	3848	2342(61%)	169(4%)	1337(35%)
Deep renovations	1530	1246(81%)	76(5%)	208(14%)
Total	87513	49549(57%)	2913(3%)	35151(40%)

[a] Overestimated energy savings in this paper means the energy saving is at least 10% lower than expected.
[b] Well estimated energy savings in this paper means the energy savings are not more than 10% higher than expected and 10% lower than expected
[c] Underestimated energy savings in this paper means that the energy saving is at least 10% higher than expected.

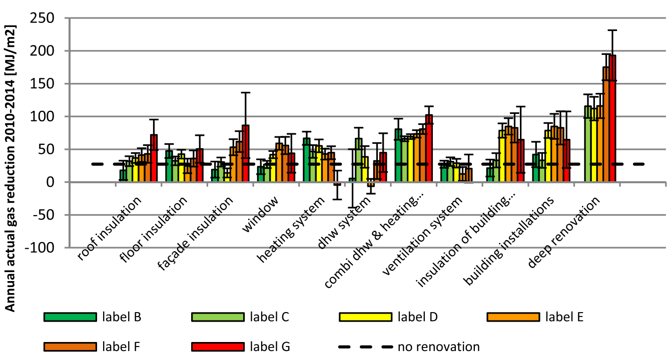

Fig. 4. Comparison between average energy saving (corrected for degree days) per renovation measure divided per energy label prior to thermal renovation and Kruskal–Wallis test.

we observe the same results, with the exception of dwellings with an energy label F or G. However, the confidence interval for those dwellings with an F and G label is relatively large. For the change in heating system and ventilation system we notice the opposite effect: energy-efficient-dwellings benefit more from an improved heating system than non-energy-efficient dwellings. In general, we found a relatively large confidence interval for the average energy reduction of dwellings with an energy label G, which indicates that the energy savings vary highly per case. Improvements in the dhw and floor insulation do not seem to be dependent on the energy label of the dwelling prior to thermal renovation.

As shown in Fig. 4 and Table 3 roof, façade insulation, window improvements and insulation of the building envelope applied on dwellings with an energy label B (and sometimes also C) save less energy than dwellings that are not renovated (dashed line), which could mean that there is no significant energy saving. A possible explanation for this could be that dwellings with an energy label B are maybe not renovated, but administrative corrections are applied in the database. Because houses with a B label are already relatively efficient and therefore the probability that they will be renovated by the housing associations is lower. For two cases we found negative savings. The one for heating can be explained that in the Dutch case G label houses often have local gas heaters that have a lower capacity than newly installed heating installations which could lead to a higher consumption for heating because of increased comfort. Also for the improvement of domestic hot water system an increased comfort level could be an explanation for a negative energy savings.

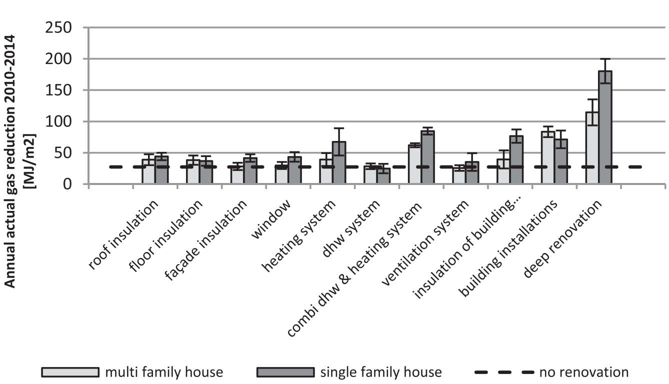

Fig. 5. Difference in actual energy saving (corrected for degree days) for single and multi-family dwellings.

Table 3
Kruskal–Wallis test: Energy label–saving.

Renovation measure	Kruskal–Wallis test
Roof	H(5) = 19.082, $p < 0.05$
Floor	H(5) = 18.717, $p < 0.05$
Façade	H(5) = 45.853, $p < 0.05$
Window	H(5) = 76.566, $p < 0.05$
Heating	H(5) = 55.054, $p < 0.05$
Dhw	H(5) = 28.242, $p < 0.05$
Combi dhw & heating	H(5) = 57.371, $p < 0.05$
Ventilation	H(5) = 34.820, $p < 0.05$
Insulation	H(5) = 122.957, $p < 0.05$
Installations	H(5) = 39.486, $p < 0.05$
Deep renovation	H(5)= 39.990, $p < 0.05$

6.1.2. Average actual energy savings—type of dwelling

Apart from the energy efficiency of the dwelling prior to the renovation we also compared the influence of the type of dwelling on the effectiveness of an energy renovation (Fig. 5 and Table 4).

Table 4
Man–Withney *U* test: Dwelling type–saving.

Renovation measure	Man–Withney *U* test
Roof	Z(1) = 2.036, $p = 0.154$
Floor	Z(1) = 1.316, $p = 0.251$
Façade	Z(1) = 8.092, $p < 0.05$
Window	Z(1) = 16.514, $p < 0.05$
Heating	Z(1) = 66.867, $p < 0.05$
Dhw	Z(1) = 2.148, $p = 0.143$
Combi dhw & heating	Z(1) = 68.555, $p < 0.05$
Ventilation	Z(1) = 18.997, $p < 0.05$
Insulation	Z(1) = 15.770, $p < 0.05$
Installations	Z(1) = 35.808, $p < 0.05$
Deep renovation	Z(1) = 2.036, $p = 0.154$

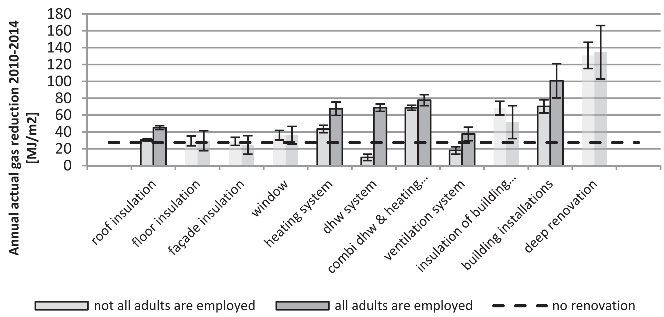

Fig. 6. Difference in energy saving (corrected for degree days) for households where all occupants have jobs and those in which not all occupants have jobs insignificant measures are shown transparent.

The results demonstrate that, on average, single-family dwellings always save more energy than multifamily dwellings (Fig. 5). The figure also shows that the differences between multi and single family houses are almost similar for all renovation measures, which could indicate that there is no interaction effect between the renovation measures and the type of dwellings. Differently stated: a single family house benefits in terms of actual energy savings more from a thermal renovation than a multi-family house independently of which thermal renovation measure is taken. The only exception is the improvement of a dhw system and the change of all building installations, which could be explained by the fact that the use of dhw is not dependent on the building characteristics, such as the energy consumption for heating. Possible explanation why energy renovation measures are often more effective on single family houses than on multifamily houses is that single family houses have often compared to multifamily houses a relatively large building envelop that has a high influence of the energy use for heating.

6.1.3. Average actual energy saving—occupancy

The third comparison compares occupancy time of a house and the actual energy saving effect per measure. Previous studies demonstrated that occupancy has a highly significant influence on residential energy consumption [33,36,37,44]. Since occupancy data was not available, we assumed that households with one unemployed adult member have a higher occupancy time than households in which all adults have jobs. As shown in

Fig. 6 and Table 5 renovation measures that improve building installations (heating, dhw system, ventilation, and all building installations) are all found to differ significantly for the group in which all (adult) household members work, compared to the group where at least one household member does not work. No significant differences are found for the other renovation measures.

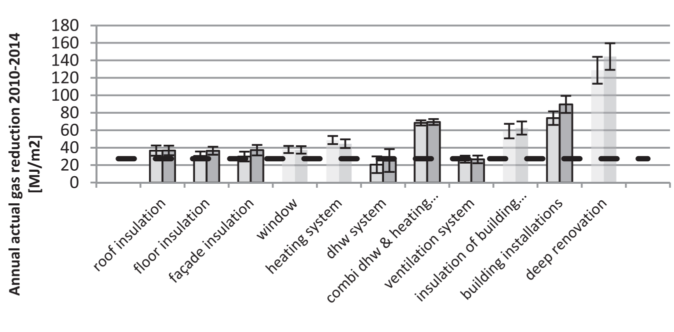

Fig. 7. Difference in energy saving (corrected for degree days) for households with below average incomes and those with above average incomes (insignificant measures are shown transparent).

Table 5
Man–Withney *U* test: Employment–saving.

Renovation measure	Man–Withney *U* test
Roof	$Z(1) = 11.782$, $p < 0.05$
Floor	$Z(1) = 2.110$, $p = 0.146$
Façade	$Z(1) = 0.009$, $p = 0.923$
Window	$Z(1) = 0.332$, $p = 0.564$
Heating	$Z(1) = 26.307$, $p < 0.05$
Dhw	$Z(1) = 24.686$, $p < 0.05$
Combi dhw & heating	$Z(1) = 6.952$, $p < 0.05$
Ventilation	$Z(1) = 28.042$, $p < 0.05$
Insulation	$Z(1) = 2.434$, $p = 0.119$
Installations	$Z(1) = 10.062$, $p < 0.05$
Deep renovation	$Z(1) = 0.451$, $p = 0.502$

A possible explanation for the energy savings being influenced if the building installations are improved but not when the insulation level is improved could be that employed occupants have a more predictive occupancy pattern; therefore, the automatic control systems (for example, automatic thermostats) that often come with new building installations function better. However, this does not explain why the savings from hot tap water differ significantly. More research is needed to explain this phenomenon.

6.1.4. Average actual energy saving—income

The fourth comparison we make for energy saving is if energy savings per thermal renovation measure differ for incomes above versus below modal income. Based on previous literature, we would expect the average energy savings to be higher for people with a high income level than for those with a low income level [13,45]. Fig. 7 and Table 6 shows that for all significant cases, occupants with a salary above the modal income save more energy than occupants below the modal income. These results could confirm previous findings that occupants are more willing to compromise on comfort to save energy and money if they have a relatively low income. After the renovation, they need less energy to achieve the same comfort level; therefore, they can afford a higher comfort level, which results in lower energy savings.

We also tested the influence of number of occupant but because we didn't find significant results we don't present them in the result section.

6.2. Average energy saving gap per thermal renovation measure

For the energy saving gap (expected saving minus actual saving) we executed similar analysis as we did for the actual energy saving. The aim of these analyses is to obtain a better insight into the aspects that are important for energy saving predictions. The results should give us some guidance for aspect that should be improved in the Dutch energy calculation method. In Fig. 8 we compare the ESG per renovation measure.

Table 6
Man–Withney *U* test: Income–saving.

Renovation measure	Man–Withney *U* test
Roof	$Z(1) = 5.246$, $p < 0.05$
Floor	$Z(1) = 13.466$, $p < 0.05$
Façade	$Z(1) = 5.265$, $p < 0.05$
Window	$Z(1) = 0.640$, $p = 0.424$
Heating	$Z(1) = 2.699$, $p = 0.100$
Dhw	$Z(1) = 5.506$, $p < 0.05$
Combi dhw & heating	$Z(1) = 7.198$, $p < 0.05$
Ventilation	$Z(1) = 6.781$, $p < 0.05$
Insulation	$Z(1) = 0.118$, $p = 0.731$
Installations	$Z(1) = 5.640$, $p < 0.05$
Deep renovation	$Z(1) = 1.380$, $p = 0.240$

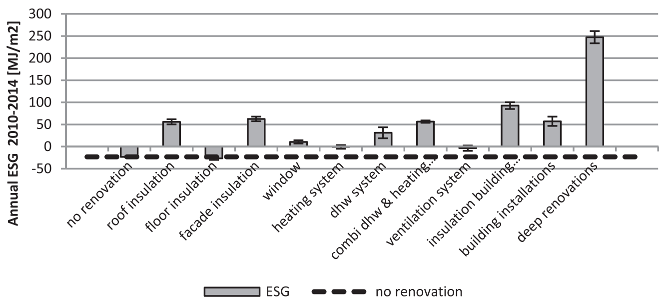

Fig. 8. Average energy saving gap per thermal renovation measure.

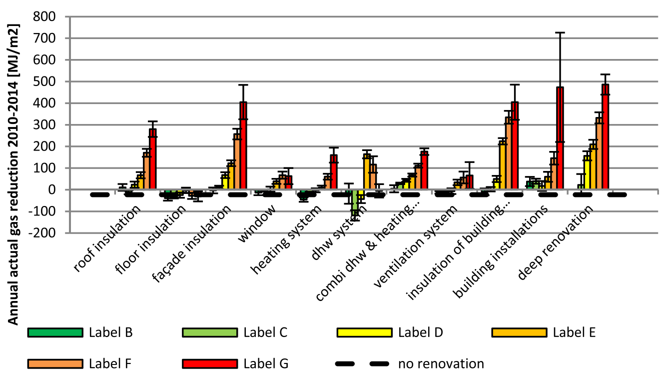

Fig. 9. Average energy saving gap per energy label of the building prior to renovation for every type of thermal renovation.

The Kruskal–Wallis test confirms that all renovation measures differ significantly (H(11) = 11,071.498, $p < 0.05$) compared to no renovation measures. Fig. 8 demonstrates that eight of the eleven renovation measures demonstrate a positive energy saving gap, meaning that the expected energy saving was higher than saved in reality. A negative energy saving gap implies that in reality, more energy is saved than expected. This means that floor insulation and improvements in the heating and ventilation system save more energy than expected, while the other measures save less energy than expected. However also when no renovation measures are applied we see a negative ESG (Fig. 8). If we take this into account all measures except floor insulation result in lower energy savings than expected.

6.2.1. Average energy saving gap—energy efficiency of the building prior to thermal renovation

Fig. 9 and Table 7 demonstrate that the ESG of all types differs significantly depending on the energy efficiency status of the building before renovation. The results show that for all types of thermal renovations the energy saving gap is larger if the energy label is lower. Which means that renovations of houses with a low energy efficiency before renovation result in a bigger gap between estimated and actual energy saving. Only a change in the dhw system and floor insulation show different patterns. For dhw this is as expected because energy consumption for dhw is more related to occupant behaviour than to building characteristics.

6.2.2. Average energy saving gap—type of dwelling

With regard to the type of dwelling, the average energy saving gap differs significantly for floor, façade insulation, improvements in heating, dhw and ventilation systems, the insulation of the entire building envelope, the improvements in all building installation systems and the deep renovations (Fig. 10 and Table 8). The results show that the ESG is different per renovation measure. For most significant renovation measures we found a positive ESG (energy saving results are overestimated) with an exception for the ventilation system and single family houses with an improved dhw system. However for ventilation the ESG is smaller than the ESG for non-renovated houses. A renovation of the dhw system in single family houses shows a bigger negative ESG than the houses that are not renovated, this implies that on average a change of the dhw system in single family houses result on in more energy savings than expected.

Table 7
Kruskal–Wallis test Energy label–ESG.

Renovation measure	Kruskal–Wallis test
Roof	H(5) = 622.256, $p < 0.05$
Floor	H(5) = 20.115, $p < 0.05$
Façade	H(5) = 669.096, $p < 0.05$
Window	H(5) = 190.020, $p < 0.05$
Heating	H(5) = 297.538, $p < 0.05$
Dhw	H(5) = 434.609, $p < 0.05$
Combi dhw & heating	H(5) = 902.413, $p < 0.05$
Ventilation	H(5) = 97.024, $p < 0.05$
Insulation	H(5) = 1034.098, $p < 0.05$
Installations	H(5) = 148.644, $p < 0.05$
Deep renovation	H(5)= 266.631, $p < 0.05$

6.2.3. Average energy saving gap—occupancy

Fig. 11 and Table 9 illustrates that there are only a few types of renovation that show a significant differences in ESG between houses where all adults work and houses where not all adults work. Most of those measures are building installations measures (heating system; dhw system; combi dhw & heating system and ventilation system). We have seen a similar effect in the actual energy savings in Section 5.2.3. The only exception is insulation of the building envelope, but although significant the differences for that measure are relatively small.

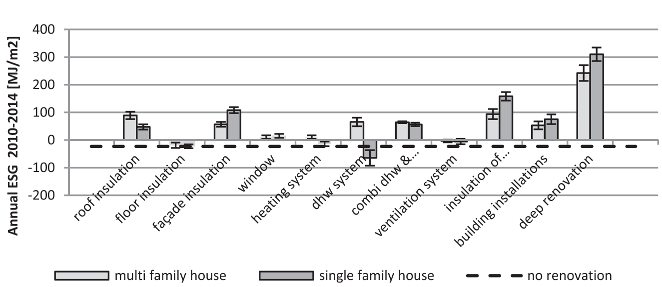

Fig. 10. Average energy saving gap, multifamily dwelling and single family dwellings compared per thermal renovation measure. Insignificant measures are shown transparent.

Table 8
Man–Withney U test: dwelling type–ESG.

Renovation measure	Man–Withney U test
Roof	Z(1) = 14.435, $p < 0.05$
Floor	Z(1) = 0.604, $p = 0.437$
Façade	Z(1) = 63.121, $p < 0.05$
Window	Z(1) = 0.006, $p = 0.937$
Heating	Z(1) = 20.219, $p = 0.100$
Dhw	Z(1) = 56.751, $p < 0.05$
Combi dhw & heating	Z(1) = 7.344, $p < 0.05$
Ventilation	Z(1) = 4.692, $p < 0.05$
Insulation	Z(1) = 57.014, $p < 0.05$
Installations	Z(1) = 5.555, $p < 0.05$
Deep renovation	Z(1) = 16.820, $p < 0.05$

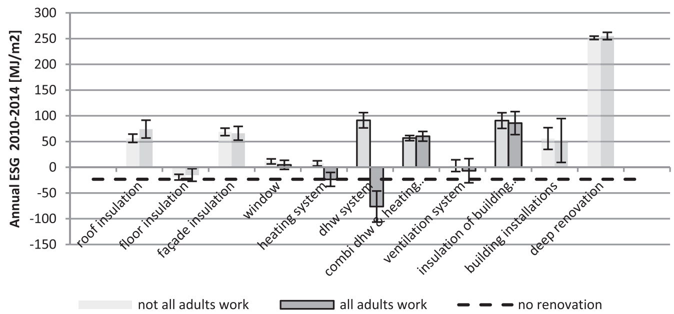

Fig. 11. Average energy saving gap, households in which not all adults work and those where all adults work are compared per thermal renovation measures. Insignificant measures are shown transparent.

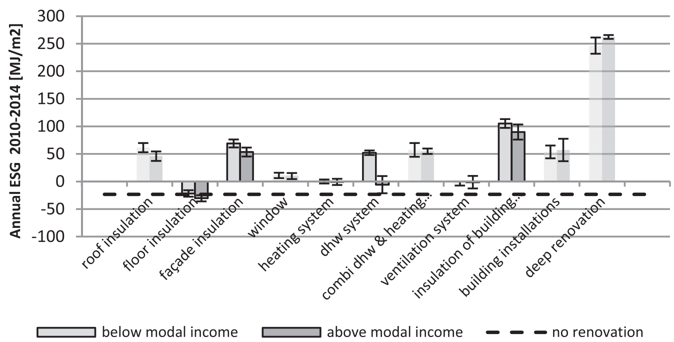

Fig. 12. Average energy saving gap, households with an income below and above the national average are compared per thermal renovation measures. Insignificant measures are shown transparent.

6.2.4. Average energy saving gap—income

A comparison of occupants' earnings below and above the national modal income reveals significant differences for the average energy saving gap of floor insulation, façade insulation, heating, ventilation and the insulation of the building envelope. In the cases with overestimated energy savings (positive energy saving gap), we notice that the households with an income below the national modal is larger than those with a higher income (Fig. 12 and Table 10), whereas the opposite holds true for the measures with a negative energy saving gap. This could indicate people with a low income living in energy-inefficient dwellings are more willing to reduce their comfort levels to save money than households with a high income. Tables 4–10,13

6.3. Occurrence of the prebound and rebound effect

Since previous studies assume that the rebound and prebound effects are the most important explanations for lower energy saving effects than expected, we take a closer look at those effects in this section. If the prebound and rebound effects are indeed the main cause of the energy performance gap, we would expect that the energy consumption before renovation is often lower than expected and the energy consumption after renovation is often higher than expected. If only the prebound effect occurs, we expect a lower energy consumption than expected before a thermal renovation and an energy consumption as expected after renovation. If only the rebound effect occurs, we would expect energy consumption as estimated before renovation and a lower energy consumption as expected after thermal renovations. In Table 11 we determined the number of buildings that have a higher, lower or similar as expected energy consumption. The table shows that both the rebound and/or prebound effects occurred only for a limited number of cases. Most households maintain their 'habit' by using more energy than expected before and after renovation or using less energy than expected before and after renovation. If we check

Table 9
Results Man–Withney *U* test: ESG–(un)employed.

Renovation measure	Man–Withney *U* test
Roof	$Z(1) = -1.893$, $p = 0.058$
Floor	$Z(1) = -0.687$, $p = 0.492$
Façade	$Z(1) = -1.464$, $p = 0.143$
Window	$Z(1) = -1.751$, $p = 0.080$
Heating	$Z(1) = -5.012$, $p < 0.05$
Dhw	$Z(1) = -10.151$, $p < 0.05$
Combi dhw & heating	$Z(1) = -2.111$, $p < 0.05$
Ventilation	$Z(1) = -2.432$, $p < 0.05$
Insulation	$Z(1) = -1.977$, $p < 0.05$
Installations	$Z(1) = -0.330$, $p = 0.741$
Deep renovation	$Z(1) = -0.323$, $p = 0.746$

Table 10
Results Man–Withney *U* test: ESG–income.

Renovation measure	Man–Withney *U* test
Roof	$Z(1) = -0.190$, $p = 0.850$
Floor	$Z(1) = -3.825$, $p = < 0.05$
Façade	$Z(1) = -2.599$, $p < 0.05$
Window	$Z(1) = -1.152$, $p = 0.249$
Heating	$Z(1) = -2.679$, $p < 0.05$
Dhw	$Z(1) = -7.228$, $p < 0.05$
Combi dhw & heating	$Z(1) = -1.188$, $p = 0.235$
Ventilation	$Z(1) = -0.330$, $p = 0.741$
Insulation	$Z(1) = -3.134$, $p < 0.05$
Installations	$Z(1) = -0.671$, $p = 0.502$
Deep renovation	$Z(1) = -0.686$, $p = 0.493$

per thermal renovation measure, we observe more or less the same 'pattern' for most renovation measures as listed in Table 11. However, for deep renovations, we note that the prebound and rebound effects together occur significantly more often (30%) than for the other renovation measures. This indicates that while those effects are responsible for some of the overestimated energy savings, they are not the only reason.

6.4. Probability of lower energy savings than expected

Because the previous section indicated that the rebound and prebound effect are not the only cause of lower energy savings than expected, we conduct a binary logistic regression analysis to identify which other parameters influence the probability on lower energy savings than expected. As mentioned before we consider the energy saving results to be lower than expected if the saving is more than 10% lower than calculated. The independent variables used in the logistic regression are the building and occupant characteristics that we discussed earlier as well as the energy saving measures and the energy performance gap of the building before the thermal renovation (Table 12). This parameter is added because previous studies state that next to the prebound and rebound effects, a probable explanation for the energy saving gap are an incorrect assumption in the energy calculation before renovation [1,17]. As a second step of the logistic regression, we include the interaction between the thermal renovation type and the building and occupant characteristics because the previous sections demonstrated that these characteristics influence the energy savings differently per type of thermal renovation.

The binary logistic regression without interaction effects (Table 13), demonstrates an insignificant result for the energy efficiency state of the building prior to thermal renovation, dwelling type and income. This is unexpected, since the previous analysis suggested that there is a relation between those parameters and the effectiveness of a renovation measure. We will examine the influence of the energy efficiency of a building when we look at the interaction effects. Most of the thermal renovation measures demonstrate a significant effect. A change in the dhw system in-

Table 11
Frequencies of over- and underpredicted energy consumption prior to and post thermal renovation.

Before renovation	After renovation			
		Underprediction	Well predicted	Overprediction
	Underprediction	16538(20%)	3598(4%)[b]	3904(5%)
	Well predicted	5639(7%)	4576(6%)	5339(6%)[c]
	Overprediction	6049(7%)[a]	6498(8%)	31749(38%)

[a] prebound & rebound effect
[b] prebound effect
[c] rebound effect

Table 12
Variables in logistic regression (DV = dependent variable, IV = Independent variable)[1].

Type of variable	Variable	Categories
DV	Lower energy savings than expected	Yes/no (1/0)
IV	Thermal renovations	No renovation, Roof*, floor, façade, window, heating, dhw, combi dhw & heating, insulation, installations, deep renovation
IV	Energy index	Continuous variable
IV	Building type	Single family dwellings*/ multi family dwellings
IV	Occupancy	All adults work/at least one adult does not work
IV	Income	Above national middle income/below national middle income
	Energy performance Gap	The energy saving gap prior to the thermal renovation (Energy performance gap < 0, actual energy consumption lower than estimated, energy performance gap > 0 actual energy consumption higher than estimated)
IV	Interaction	All building and occupant characteristics variables* thermal renovation measures
IV	Interactions	Energy performance gap of year 2010 Energy index

[1] Note: No multicollinearity was found between the independent variables (VIF is in all cases around 1).
* reference dummy variable

Table 13
Logistic regression results without interaction effects (Odds ratio above 1 higher chance on lower energy savings than expected, Odds ratio below 1 lower chance on lower energy savings than expected).

		95% CI for Odds Ratio		
	B(SE)	Lower	Odds ratio	upper
Energy Index	−0.047(0.28)	0.902	0.954	1.008
Renovation measures*	**			
Floor insulation	−0.352(0.067)**	0.617	0.703	0.802
Façade insulation	0.095(0.071)	0.958	1.100	1.263
Window	−0.350(0.062)**	0.621	0.705	0.800
Heating system	−0.573(0.065)**	0.496	0.564	0.640
dhw system	1.251(0.110)**	2.814	3.493	4.335
Combi dhw & heating system	−0.276(0.059)**	0.676	0.759	0.851
Ventilation	−0.353(0.065)**	0.619	0.702	0.797
Insulation	0.139(0.093)	0.959	1.150	1.378
Installations	0.098(0.076)	0.951	1.103	1.279
Deep renovations	0.588(0.138)**	1.374	1.801	2.359
Single family dwelling*	0.022(0.029)	0.676	0.759	1.036
Income*	−0.046(0.028)	0.924	0.978	1.105
Occupancy*	−0.182(0.028)**	0.991	1.047	0.880
Energy Performance Gap	0.073(0.002)**	0.790	1.076	1.080
Constant	0.865(0.076)**		2.375	

** Result is significant $p < 0.05$, $R2 = 0.064$ (Cox&Snell) 0.089 (Nagelkerke). Model $\chi 2(15) = 2754.971$, $p < 0.05$.

creases the chance on lower savings than expected the most (odds ratio of 3.799). The occupancy level based on all occupants working or at least one adult occupant not working demonstrates that a low occupancy results in lower energy saving effects than expected more often than a high occupancy level. Finally, a large energy performance gap (which means the expected energy consumption is higher than the actual energy consumption) in the year 2010, when thermal renovations are not yet applied, result in higher chances that the energy saving results would be overestimated.

The first binary logistic regression is followed up with a second logistic regression using interaction effects. The interactions are based on the results we found in the previous sections. Based on the increase of the Cox and Snell R^2 and the Nagelkerke R^2, we can conclude that some of the interactions that we found in the previous sections are indeed present, and they contributed significantly to predicting the probability of energy saving effects after renovations will be lower than expected (Table 14). The interactions between "income and renovations" and "occupancy and renovations" are insignificant; therefore, they are not included in the model. For the energy efficiency of the building prior to the renovation we only found interactions effects and no direct effects. For those interactions we found significant effects for most renovation measures. Most building installation renovation measures show a higher chance on lower than expected energy savings after renovation when the building has a high energy efficiency, while the opposite applies for the insulation measures. Except for floor insulation and improved windows, the chance on lower than expected

Table 14
Logistic regression results with interaction effects (Odds ratio above 1 higher chance on lower energy savings than expected, Odds ratio below 1 lower chance on lower energy savings than expected).

		95% CI for Odds Ratio		
	B(SE)	Lower	Odds ratio	upper
Renovation measures*	**			
Floor insulation	0.822(0.174)**	1.1618	2.275	3.200
Façade insulation	−0.931(0.239)	0.0247	0.394	0.629
Window	0.056(0.164)	0.767	1.058	1.458
Heating system	−1.477(0.157)**	0.168	0.228	0.310
dhw system	1.276(0.488)**	1.489	3.584	8.627
Combi dhw & heating system	−0.220(0.112)	0.645	0.803	1.000
Ventilation	−0.367(0.154)**	0.512	0.693	0.937
Insulation	−1.359(0.353)**	0.129	0.257	0.513
Installations	0.559(0.239)	1.094	1.749	2.796
Deep renovations	−1.012(0.646)	0.102	0.363	1.289
Single family dwelling*	−0.335(0.110)**	0.576	0.715	0.887
Occupancy*	−0.175(0.028)**	0.808	0.851	0.896
Energy Performance Gap	0.076(0.002)**	1.075	1.079	1.083
EI*ren. Measure	**			
EI * floor insulation	−0.760(0.080)**	0.400	0.468	0.547
EI * façade insulation	0.539(0.142)	1.298	1.715	2.264
EI*window	−0.329(0.080)**	0.615	0.720	0.842
EI * heating	0.506(0.077)**	1.426	1.658	1.927
EI*dhw	−0.022(0.224)	0.630	0.978	1.518
EI*combi dhw & heating	−0.122(0.043)**	0.813	0.885	0.964
EI * ventilation	−0.070(0.086)	0.789	0.933	1.103
EI * insulation	0.681(0.206)**	1.319	1.976	2.959
EI * installations	−0.317(0.123)**	0.573	0.729	0.927
EI*deep renovations	0.578(0.331)	0.967	1.782	3.283
Renovation measure* building type	**			
Single family*floor insulation	0.421(0.134)**	1.172	1.524	1.981
Single family * façade insulation	0.362(0.152)**	1.067	1.436	1.932
Single family * window	0.387(0.133)**	1.135	1.472	1.909
Single family * heating	−0.208(0.140)	0.617	0.812	1.068
Single family * dhw	−0.971 (0.299)**	0.211	0.379	0.680
Single family * combi dhw & heating	0.442(0.124)**	1.220	1.557	1.986
Single family * ventilation	0.238(0.143)	0.960	1.269	1.678
Single family * insulation	0.734(0.194)**	1.425	2.082	3.043
Single family * installations	−0.034 (0.186)	0.671	0.967	1.394
Single family * deep renovation	1.052 (0.324)**	1.519	2.863	5.398
Constant	0.922(0.079)**		2.514	

** Result is significant $p < 0.05$, R2 = 0.081 (Cox&Snell) 0.112 (Nagelkerke). Model $\chi 2(45) = 3094.123$, $p < 0.05$.

savings increases for those measures when the energy efficiency of the house increases. This confirms the findings in Figs. 4 and 9. Only for renovation measure "heating system" we found unexpected results, those show that the chance on lower than expected savings is higher for buildings with a high energy efficiency. Almost all renovation measures, except the change in ventilation system, dhw system and deep renovations demonstrate significant interaction effects with the type of building (Table 14). The interaction per building type indicate that the probability of lower than expected energy saving are more likely for multi-family dwellings. Only if the dhw system, heating system or all building installations are replaced the probability on lower than expected energy savings is more likely for single family houses, however those parameters are found to be insignificant. Those results confirm the findings shown in Figs. 5 and 10. We didn't find significant interaction effects for income and occupancy and they are therefore not included in the final regression table results (Table 14).

7. Discussion

Regarding the data used in this paper one of the strengths is that a relatively large dataset containing pre- and post-renovation energy consumption data was used. Despite this large database, the data, especially of the occupants and energy consumption, were only available on an aggregated level. Therefore, there could be other parameters that influence the energy saving effects that are not taken into account in this analysis. Further research on the influence of other parameters is required to indicate whether they also play a role. Another disadvantages of the data used in this paper is that the data is only from social housing in the Netherlands; therefore, the dwellings are all rental dwellings. This means that the occupants did not initiate the renovations themselves, which might have had significant effects on the results, because previous studies demonstrated that, in some cases, tenants behave differently than home owners [11,46]. Furthermore the occupants living in social housing in the Netherlands have on average a lower income than the average income of the Netherlands. However, since the Dutch social housing sector is relatively large (30% of the total housing stock) compared to other countries, the dataset also contained a significant number of households with an income above the national average. Therefore the results can be considered representative. Another aspect that we should take in consideration when interpreting the results of the ESG analysis and the logistic regression is that the theoretical energy consumption used in this paper is based on a quasi-steady state calculation method, although several studies mention that using a steady state calculation method is acceptable for prediction year-round energy needs [47].

Regarding the methods used in this paper, one of the strengths, in comparison to previous studies, is that both the occupant and the building characteristics are taken into account, and only dwellings with the same occupants before and after renovations were considered in the analysis. Another, strength of this paper is that we investigated both actual savings and the energy saving gap, therefore a better insight was not only provided in the actual effect of thermal renovation, but also into the aspects that need attention/improvements in the energy calculation method. To identify if a renovation measure was applied we used categories, we assumed a renovation measure was executed if the building characteristics belonged to a "better" category in the year 2014 than in 2010. One advantage of this method is that we avoid minimal changes in the database that do not contribute to a better performance, however we might also have lost some cases that fell on the edges of the categories. For this study we assume that the renovation and the level of renovation is a choice that is taken carefully considering available budget on the moment of renovation, available techniques and practical aspects. Therefore we do not distinguish the different levels of renovation (e.g. how much a building is extra insulated).

The results demonstrate that there is a significant energy reduction when no renovation measures are taken. A possible explanation could be the change in behaviour. However, another (probably more likely) explanation is errors in the monitoring process. Social housing companies in the Netherlands must update their data every year, but since this is a manual process done by many different people, errors can easily be made. Further we used a correction for degree days however this method also has drawbacks as mentioned in Azevedo et al. [43]. Despite its limitations, this research provides new insights and confirms existing theories about the reasons energy saving renovations often result in lower-than-expected energy savings.

8. Conclusion

The aim of this study was to get a better insight in the real energy savings after thermal renovations and in the reasons why they often result in lower energy savings than expected. Based on this research, we can conclude that the amount of energy saved after a thermal renovation is dependent on the energy efficiency of the dwelling prior to the thermal renovation, type of dwelling, income level of household and occupancy. However, the number of occupants per house was not found to have a significant effect. From the investigated types of renovation measures, deep thermal renovations have on average the highest energy saving gap (250 MJ), despite this deep renovations save on average (141 MJ) still the most energy. Apart from deep renovations it is impossible to conclude which thermal renovation measure is the most effective because the results show that it is dependent on indirect and direct aspects. This means that because every situation is unique, tailored thermal renovation advice is needed to decide on the most effective thermal renovation measure. Relatively energy efficient dwellings prior to a thermal renovation benefit on average more from improvements of the building installations, while dwellings that are energy inefficient prior to the thermal renovations benefit on average more from an improved building envelope. Energy savings due to thermal renovations are on average higher for single-family dwellings than for multifamily dwellings, with the exception of dhw systems. We also found indications that a high occupancy time seems to have a negative effect on the energy savings when new building installations are installed. Better instructions regarding these installations after they are fitted might be a solution to increase the energy saving effect of these renovation measures. Furthermore, we indicate that occupants with a high income save on average more energy than occupants with low income. Based on these results, one should consider that while the thermal renovations for a household with a low income might be lower than expected, they will increase comfort.

For the energy saving gap, we found like in previous studies that the energy savings for low energy efficient buildings prior to thermal renovations are not well predicted. It is important that more research is conducted to improve the assumptions we make for these buildings in order to reduce the energy saving gap and prevent lower than expected saving effects and payback times. The results also indicate that this is probably even more important for single-family dwellings than for multifamily dwellings. Furthermore, we found that maybe more attention should be paid to building installations and how occupants use them because we observe that the energy saving gap is significantly larger if occupants are more often at home and the building installations are changed.

The analysis of the occurrence of the energy performance gap before and after renovation showed that only in 7.6% of the cases a prebound and rebound effect occurred. This percentage is different per renovation measure. As expected, the prebound and rebound effect occur significantly more often in buildings that underwent a deep renovation than in buildings that underwent a single measure renovation. However, the results also show that if the occupant consumes more energy than expected before the thermal renovation, they often also consume more energy than expected after renovation and the other way around. This means that the rebound and prebound effect explain only part of the energy saving gap.

The logistic regression showed that the energy efficiency prior to the renovation, type of dwelling and occupancy have a significant effect on the probability that energy savings after thermal renovations result in lower energy savings than expected, we did not only find direct effects but also interaction effects. The influence of the energy efficiency of the building prior to the thermal renovation and the type of dwelling is dependent on the type of thermal renovation that is applied.

Overall, this paper has shown new insights towards the influence of the energy efficiency state of a building prior to thermal renovation, the type of building, the number of occupants, the income level of the occupants and the occupancy time on the actual energy savings, the energy saving gap and on the probability on lower energy savings than expected. For more accurate estimations towards energy savings after renovations, those influencing factors should be taken into account as direct and indirect (interaction) effects. The results could also be used to have more realistic expectations of the energy reduction achieved by thermal renovations, which is important for (amongst others) policy makers, clients and contractors who make use of energy performance contracting, home owners, landlords and (social) housing associations. Although this paper showed the most effective thermal renovation measures for specific household and building characteristics, the costs of the renovation measures should also be taken into account to make a realistic assessment which measure is the best to apply for a specific case. Therefore, we advise that further research towards effective thermal renovations should include the costs and benefits of the different renovation types.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2018.10.025.

References

[1] D. Majcen, L. Itard, H. Visscher, Actual and theoretical gas consumption in Dutch dwellings: what causes the differences? Energy Policy 61 (2013) 460–471.
[2] Guerra Santin, O., Actual energy consumption in dwellings; the effect of energy performance regulations and occupant behaviour. OTB, ed. S.U. Areas. 2010, Delft: TU Delft. 237.

[3] M. Delghust, Y. De Weerdt, A. Janssens, Zoning and intermittency simplifications in quasi-steady state models, Energy Procedia 78 (2015) 2995–3000.
[4] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: the gap between performance and actual energy consumption, Build. Res. Inf. 40 (3) (2012) 260–273.
[5] D. Majcen, L. Itard, H. Visscher, Actual heating energy savings in thermally renovated Dutch dwellings, Energy Policy 97 (Supplement C) (2016) 82–92.
[6] F. Filippidou, N. Nieboer, H. Visscher, Effectiveness of energy renovations: a reassessment based on actual consumption savings, Energy Effic. (2018).
[7] M. Raynoud, et al., An energy efficiency program analysis to understand the gaps between ex-ante and ex-post evaluations, 2012 International Energy Program Evaluation Conference, 2012.
[8] R. Galvin, Making the 'rebound effect' more useful for performance evaluation of thermal retrofits of existing homes: defining the 'energy savings deficit' and the 'energy performance gap', Energy Build. 69 (2014) 515–524.
[9] R. Haas, P. Biermayr, The rebound effect for space heating empirical evidence from Austria, Energy Policy 28 (6–7) (2000) 403–410.
[10] K. Gram-Hanssen, Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption? Energy Effic. 6 (2012) 447–457.
[11] Aydin, E., N. Kok, and D. Brounen, The rebound effect in residential heating. 2013. 33.
[12] K. Gram-Hanssen, Retrofitting owner-occupied housing: remember the people, Build. Res. Inf. 42 (4) (2014) 393–397.
[13] S. Sorrell, J. Dimitropoulos, M. Sommerville, Empirical estimates of the direct rebound effect: a review, Energy Policy 37 (4) (2009) 1356–1371.
[14] M. Ferreira, M. Almeida, Benefits from energy related building renovation beyond costs, energy and emissions, Energy Procedia 78 (2015) 2397–2402.
[15] F. Roberti, et al., Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process, Energy Build. 138 (2017) 1–10.
[16] H. Visscher, J. Laubscher, E. Chan, Building governance and climate change: roles for regulation and related polices, Build. Res. Inf. 44 (5-6) (2016) 461–467.
[17] A. Rasooli, L. Itard, C.I. Ferreira, A response factor-based method for the rapid in-situ determination of wall's thermal resistance in existing buildings, Energy Build. 119 (2016) 51–61.
[18] D. Majcen, Predicting energy consumption and savings in the housing stock–a performance gap analysis in the Netherlands, in: Architecture and the Built Environment, Delft University of Technology, Delft, 2016, p. 224.
[19] E. Lucchi, Applications of the infrared thermography in the energy audit of buildings: A review, Renewable Sustainable Energy Rev. 82 (2018) 3077–3090.
[20] M.H. Laurent, et al., Back to reality: how domestic energy efficiency policies in four European countries can be improved by using empirical data instead of normative calculation, in: ECEEE 2013 Summer Study - Rethink, Renew, Restart, ECEEE, France, 2013, pp. 2057–2070.
[21] BPIE, Renovation Strategies of Selected EU countries: a Status Report on Compliance with Article 4 of the Energy Efficiency Directive, B.P.I. Europe, Brussel, 2014 Editor.
[22] T. Winther, K. Gurigard, Energy performance contracting (EPC): a suitable mechanism for achieving energy savings in housing cooperatives? Results from a Norwegian pilot project, Energy Effic. 10 (3) (2017) 577–596.
[23] P. de Wilde, The gap between predicted and measured energy performance of buildings: a framework for investigation, Autom. Constr. 41 (2014) 40–49.
[24] B. Ástmarsson, P.A. Jensen, E. Maslesa, Sustainable renovation of residential buildings and the landlord/tenant dilemma, Energy Policy 63 (2013) 355–362.
[25] O. Guerra Santin, Occupant behaviour in energy efficient dwellings: evidence of a rebound effect, J. Hous. Built Environ. 28 (2) (2013) 311–327.
[26] D. Majcen, L.C.M. Itard, H. Visscher, Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: discrepancies and policy implications, Energy Policy 54 (2013) 125–136.
[27] R. Haas, H. Auer, P. Biermayr, The impact of consumer behavior on residential energy demand for space heating, Energy Build. 27 (2) (1998) 195–205.
[28] A.R. Hansen, K. Gram-Hanssen, H.N. Knudsen, How building design and technologies influence heat-related habits, Build. Res. Inf. 46 (1) (2018) 83–98.
[29] ISSO, Energieprestatie Advies Woningen (2011) in 82.3.
[30] K. Steemers, G.Y. Yun, Household energy consumption: a study of the role of occupants, Build. Res. Inf. 37 (5–6) (2009) 625–637.
[31] ECN, Energy Efficiency trends and Policies in the Netherlands, ECN, The Netherlands, 2015, p. 20.
[32] A. Field, Is ANOVA robust?, in: M. Carmichael (Ed.) Discovering Statistics Using IBM SPSS Statistics, Editor, SAGE Publications Ltd, London, 2000, pp. 444–445.
[33] O. Guerra Santin, L. Itard, H. Visscher, The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, Energy Build. 41 (11) (2009) 1223–1232.
[34] P. van den Brom, A. Meijer, H. Visscher, Performance gaps in energy consumption: household groups and building characteristics, Build. Res. Inf. (2017) 1–17.
[35] O. Guerra Santin, Behavioural patterns and user profiles related to energy consumption for heating, Energy Build. 43 (2011) 2662–2672.
[36] V. Cheng, K. Steemers, Modelling domestic energy consumption at district scale: A tool to support national and local energy policies, Environ. Modell. Software, 26 (10) (2011) 1186–1198.
[37] ECN and Rigo, Energiebeparing: Een samenspel van woning en bewoner–Analyse van de module Energie WoON 2012. 2013.
[38] J. Chen, X. Wang, K. Steemers, A statistical analysis of a residential energy consumption survey study in Hangzhou, China, Energy Build. 66 (0) (2013) 193–202.
[39] N. Kaza, Understanding the spectrum of residential energy consumption: a quantile regression approach, Energy Policy 2010 (38) (2010) 6574–6585.
[40] Y.G. Yohanis, et al., Real-life energy use in the UK: how occupancy and dwelling characteristics affect domestic electricity use, Energy Build. 40 (6) (2008) 1053–1059.
[41] A. Druckman, T. Jackson, Household energy consumption in the UK: a highly geographically and socio-economically disaggregated model, Energy Policy 36 (8) (2008) 3167–3182.
[42] F. Filippidou, N.E.T. Nieboer, H. Visscher, Effectiveness of Energy Renovations: a Reassessment Based on Actual Consumption Savings, eceee, France, 2017.
[43] J.A. Azevedo, L. Chapman, C.L. Muller, Critique and suggested modifications of the degree days methodology to enable long-term electricity consumption assessments: a case study in Birmingham, UK, Meteorol. Appl. 22 (4) (2015) 789–796.
[44] T. Kane, S.K. Firth, K.J. Lomas, How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling, Energy Build. 86 (2015) 817–832.
[45] G. Milne, B. Boardman, Making cold homes warmer: the effect of energy efficiency improvements in low-income homes a report to the Energy Action Grants Agency Charitable Trust, Energy Policy 28 (6) (2000) 411–424.
[46] Madlener, R. and M. Hauertmann, Rebound effects in German Residential heating: do ownership and income matter? FCN Working Paper, 2011. **2/2011**.
[47] V. Corrado, E. Fabrizio, Assessment of building cooling energy need through a quasi-steady state model: Simplified correlation for gain-loss mismatch, Energy Build. 39 (5) (2007) 569–579.