Towards a future sustainable housing stock
Assessment of the energy performance of dwellings of non-profit housing associations

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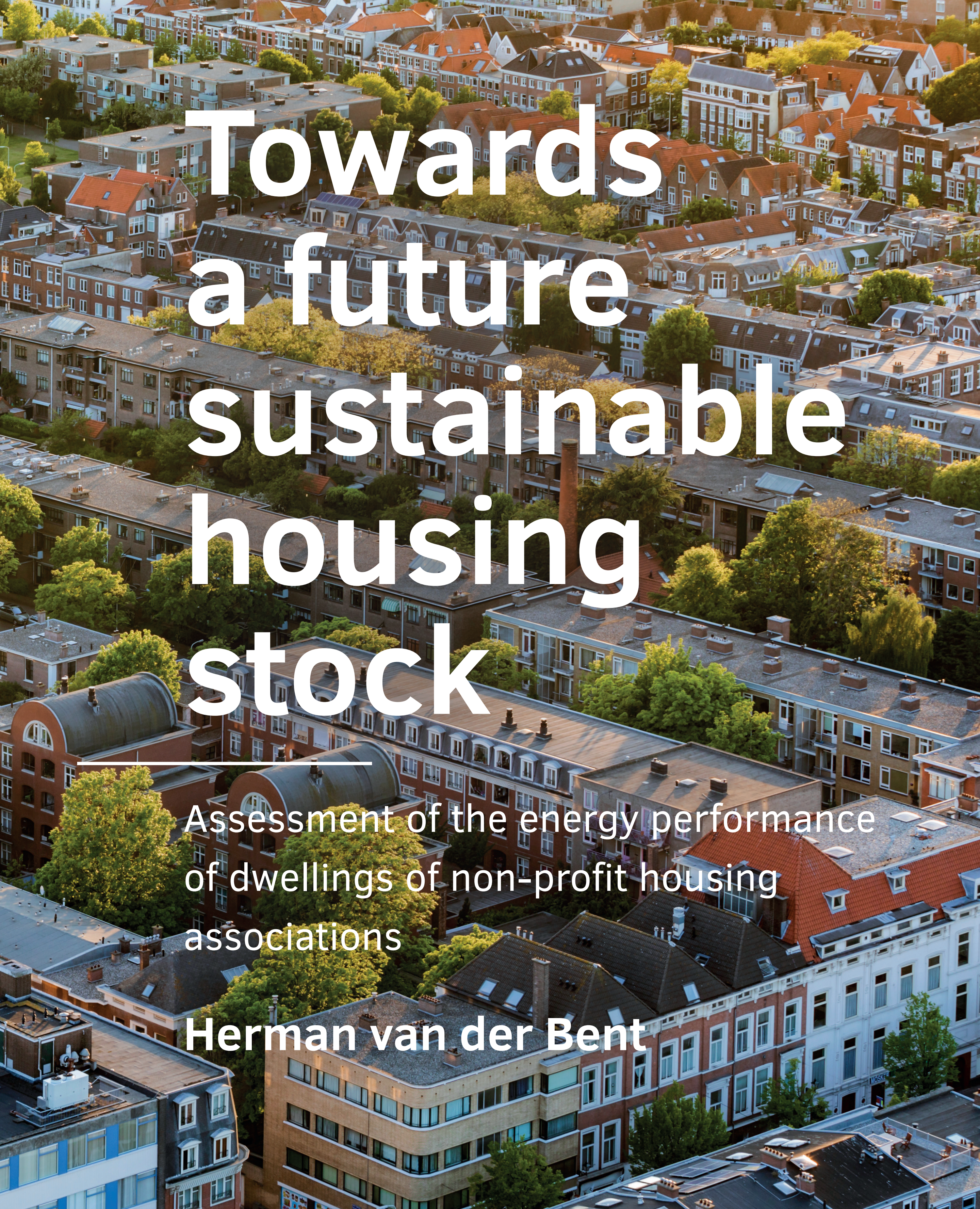

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Assessment of the energy performance of dwellings of non-profit housing associations

Dissertation

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chair of the Board for Doctorates
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Summary

Climate change asks for urgent action. For decades humankind is aware of the impact of humanity on our environment. The Brundlandt report was a major wake-up call. Furthermore, the Kyoto Protocol and Paris Agreement are major stepping stones to mitigate the effect of climate change. But time marches on. Climate change is still today an urgent matter which needs our immediate attention.

Legislation to battle climate change is in place at European and national levels. In Europe, among others, the Energy Performance of Buildings Directive (EPBD) is implemented to reduce the impact of the built environment on climate change. The energy transition in the built environment is a key strategy to mitigate the impact of our daily life on the environment. Dutch non-profit housing associations own one-third of the dwellings in the Netherlands. Other European countries with a large share of social housing are Austria 24%, Denmark 21%, Sweden 17%, UK 17%, France 16%, Norway 14%, and Finland 11%. Due to the share of the stock, changing the non-profit housing stock plays a vital role in the transition to a future sustainable housing stock.

This research examines the energy performance of the housing stock of Dutch non-profit housing associations. The energy performance of dwellings can be defined as the quality of dwellings in relation to the actual energy consumption during the operation phase of the dwelling. The aim of European and national policy is to improve the energy performance, and therewith to lower actual energy consumption, by building new dwellings with a good energy performance and by renovating the existing housing stock.

Several scientific challenges appear in understanding and improving the energy performance of dwellings of Dutch non-profit housing associations. First, there is a need to monitor the progress of changes of the energy performance in the housing stock. Monitoring the energy performance of the housing stock helps in establishing a well-founded knowledge base, enabling the evaluation and adaptation of policies aimed at increasing the energy performance of the housing stock. Second, there is a need to improve theoretical calculations of the energy performance through modelling actual energy consumption. Currently, a performance gap exists between theoretical and actual energy consumption of dwellings. Improving the calculations helps in estimating the actual energy savings of renovations and in estimating the

energy consumption of new dwellings. Third, there is a need to measure the energy performance of dwellings with heat pumps. Heat pumps are a promising solution for the future and gaining insights about different dwellings and systems helps in understanding the potential of heat pump systems in the Dutch non-profit housing stock. Fourth, there is a need to assist housing associations by benchmarking the energy performance of their housing stock in agreement with changes in policy after 2020. Creating a benchmark model helps in the measuring and evaluation of the energy performance towards a future sustainable housing stock. The aim of this thesis is to cover these challenges by assessing and understanding the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock.

The main research question of the study is therefore:

How to assess and understand the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock?

This is operationalized with four studies:

- **Study 1: Monitoring energy performance improvement:** *insights from Dutch housing association dwellings*
- **Study 2: The energy performance of dwellings of Dutch non-profit housing associations:** *modelling actual energy consumption*
- **Study 3: The energy performance of dwellings with heat pumps of Dutch non-profit housing associations**
- **Study 4: Benchmarking energy performance:** *indicators and models for Dutch housing associations*

Study 1 assesses the energy performance progress between 2017 and 2020. It contributes to the understanding of the improvement of the energy performance of dwellings of non-profit housing associations by giving insights into the development of the housing stock, the effect of changes of and within the stock, the effect of characteristics of housing associations and by relating the improvement of the energy performance to the sectoral goal. Study 2 assesses models to estimate actual energy consumption of dwellings. It contributes to the understanding of the energy performance of dwellings of non-profit housing associations by giving insights into the extent to which advanced modelling of the energy consumption can improve the

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estimation of energy savings of renovation measures. Study 3 assesses the energy performance of dwellings with heat pumps. It contributes to the understanding of the energy performance of dwellings of non-profit housing associations by giving insights into the energy performance of dwellings with heat pumps as a promising renovation measure towards a future sustainable housing stock. Study 4 assesses the benchmarking of the energy performance. It contributes to the understanding of the energy performance of dwellings of non-profit housing associations by creating a benchmark model related to the changing policy context, therewith contributing to the understanding and improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock.

Research methods

Two main data sources are used to answer the research questions in this thesis, the Shaere-database and microdata of energy consumption on address-level from the Dutch Central Bureau of Statistics (CBS). The Shaere-database is a database of energy performance data and building characteristics of over two million dwellings of non-profit housing associations, collected annually under coordination of this research project and maintained by Aedes, the umbrella organization of Dutch non-profit housing associations. The CBS collects and maintains an annual database of actual energy consumption of Dutch addresses, available in an anonymized analysis environment. The combination of these databases is the main basis for the studies performed in this thesis.

Several research methods are used to perform the four studies in this thesis. The collection of raw data, consisting of the energy performance and building characteristics of dwellings of non-profit housing associations is a basis for all studies. Studies 1 and 3, mainly consist of statistical analyses of raw data to answer the stated research questions. In study 2, besides raw data collection and statistical analysis, advanced modelling techniques are applied to reach the desired research results. A linear, a non-linear and a Gradient Boosting Model (GBM) are examined. In study 4, also raw data collections and statistical analysis were used, but action research where the researcher participated in group sessions with experts from non-profit housing associations is the main research method.

Results

Study 1, monitoring energy performance improvement: *insights from Dutch housing association dwellings*, helps to understand the improvement of the energy performance by which measures are taken and which potential is left to renovate or to replace with new construction. The research shows that the energy performance of dwellings of Dutch non-profit housing associations improved steadily between 2017 and 2020. The research shows that the effect of changes of the stock (construction and demolition) to the improvement of the average energy performance is modest (15.6%). The improvement of the average sectoral energy performance happens for 85.4% within the existing stock, mostly with traditional improvements like changing heating installations and adding insulation. The research shows that large urban housing associations drive the improvement of the average sectoral energy performance. The research concludes that the sectoral goal of an average energy-index of 1.40 in 2020 will not be achieved in the year 2020 but can be achieved at the end of 2021.

Study 2, the energy performance of dwellings of Dutch non-profit housing associations: *modelling actual energy consumption*, shows that modelling the actual energy consumption helps to understand the effectiveness of renovation measures in lowering actual energy consumption and related CO_2 emissions. The research shows a large performance gap between theoretical and actual energy consumption underlining the need for actual energy consumption modelling. However, the research shows that modelling the actual energy consumption of dwellings is challenging. The actual energy consumption was modelled with three different models, a linear regression, a non-linear regression and a GBM machine learning model. The research shows that the three different models have their own pros and cons. Linear regression models are simple and fast and estimate sectoral cross-sections very well but are not useful in analyzing the effects of detailed renovation measures. A non-linear model can estimate sectoral cross-sections and detailed renovations and uses the structure of actual consumption physics but is only able to use given relations between building features and will therefore not pick up on other relations which could improve the estimations of the effects of renovations. The non-linear model is easier to interpret, which could be a reason to prefer such a model above the other models. A Gradient Boosting Model is able to detect all kinds of relations between building features. It can find correlations and interactions that even specialists in the field are not aware of. However, the model does not use the structure of actual energy consumption physics to its advantage. Therefore, it is more difficult to interpret the results and if some renovation measures (e.g. electrical heat pumps) occur less frequently in the dataset this can result in outcomes that are unrealistic. The research recommends that combining theoretical models with empirical calibrations (grey box models) could be used to enhance the accuracy of estimations of the energy performance.

Study 3, the energy performance of dwellings with heat pumps of Dutch non-profit housing associations, shows that a statistical analysis to assess the energy performance of dwellings with heat pumps helps to understand the potential of heat pump systems in the future Dutch non-profit housing stock. In the research, the characteristics and the average actual energy consumption of dwellings with heat pumps are determined and compared to dwellings with a traditional HR107 condensing gas boiler. 3.2% of the dwellings of non-profit housing associations operates with a heat pump, consisting of all-electric heat pump systems (1.2%), hybrid systems (0.8%), gas absorption heat pumps (0.6%), gas absorption hybrid systems (0.4%) and other configurations (0.2%). Dwellings with all-electric heat pumps have an average higher building quality, no gas consumption, and higher electricity consumption, as opposed to dwellings with hybrid or gas absorption heat pumps, which have an average higher building quality, lower gas consumption, and higher electricity consumption as opposed to dwellings with a traditional HR107 gas boiler. Detailed insights are provided for dwellings with different heat pump systems and for dwellings with different building characteristics.

Study 4, benchmarking energy performance: *indicators and models for Dutch housing associations*, shows that a model to benchmark the energy performance of Dutch non-profit housing associations can be created by following a structured approach. Benchmarking is a method that can be used to measure progress and to create awareness about the performance of organizations. The benchmark model helps to support housing associations to analyse and compare the energy performance of their housing stock in agreement with active policies. Other researchers aiming at benchmarking the energy performance between organizations within their policy context, can adopt and adapt this structured approach. The final policy performance model to measure and benchmark the energy performance of Dutch non-profit housing associations consists of three indicators closely related to active policies regarding the sustainable improvement of the Dutch non-profit housing sector: (1) The average theoretical primary fossil energy consumption, (2) the average distance to the maximum theoretical heating demand, and (3) the average actual CO2 emissions from gas consumption. The first indicator is related to the current policy regarding the energy labelling of dwellings, derived from the EPBD, the NTA8800. The second indicator relates to the policy to decrease the average theoretical heat demand of dwellings. The third indicator is related to the goal for the Dutch built environment to lower actual CO_2 emissions.

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Conclusion and recommendations

The main research question of the thesis is: How to assess and understand the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock? The studies performed in this thesis show that in order to assess the energy performance of non-profit housing associations a systematic data collection method is vital. The studies are based on the SHAERE database with the energy performance characteristics of over two million dwellings collected annually and the actual energy consumption of those dwellings available in an anonymized environment at the Dutch Central Bureau of Statistics (CBS). To assess the data different analytical methods help to deliver insights. In this research, a monitoring system, advanced modelling techniques, statistical analysis of data, and a benchmark model are used. These techniques help to gain valuable insights to understand the improvement of the energy performance of dwellings of non-profit housing associations.

- Monitoring the energy performance progress helps to understand the improvement of the energy performance of dwellings of non-profit housing associations by giving insights into the development of the housing stock, the effect of changes of and within the stock, the effect of characteristics of housing associations and by relating the improvement of the energy performance to the sectoral goal.

- Using advanced modelling techniques to estimate actual energy consumption of dwellings contributes to the understanding of the extent to which a linear model, a non-linear model and a Gradient Boosting Model (GBM) can improve the estimation of the energy consumption of dwellings and therewith the energy savings of renovation measures.

- Assessing the energy performance of dwellings with heat pumps contributes to understanding the potential of heat pumps as a promising renovation measure towards a future sustainable housing stock.

- Benchmarking the energy performance contributes to the understanding of the energy performance improvement of dwellings of non-profit housing associations in relation to active policies.

The thesis recommends to continue the monitoring of the energy performance of dwellings in order to be able to assess and continuously understand the improvement of the non-profit housing sector towards a future sustainable housing stock. The thesis recommends to further improve the modelling of the actual energy consumption of dwellings to accurately measure the effect of renovations, with

advanced grey box models as direction to further explore. The thesis recommends to determine the energy performance of dwellings with specific heat pump configurations, and the thesis recommends to start or continue to benchmark the energy performance across housing stocks, therewith unleashing the potential to learn from each other.

Finally, persistent efforts are needed, both in research and in practice, towards a future sustainable housing stock, therewith contributing to the battle against climate change, with the aim to preserve a healthy earth for future generations.

Samenvatting

Klimaatverandering vraagt om dringende actie. De mensheid is zich al tientallen jaren bewust van de impact van de mensheid op onze omgeving. Het Brundlandt-rapport was een grote wake-up call. Daarnaast zijn het Protocol van Kyoto en het Akkoord van Parijs belangrijke akkoorden om het effect van klimaatverandering te verzachten. Maar de tijd gaat verder. Klimaatverandering is vandaag de dag nog steeds een urgente kwestie die onze onmiddellijke aandacht vereist.

Op Europees en nationaal niveau is er wetgeving om klimaatverandering tegen te gaan. In Europa is onder meer de Richtlijn Energieprestatie van Gebouwen (EPBD) geïmplementeerd om de impact van de gebouwde omgeving op klimaatverandering te verminderen. De energietransitie in de gebouwde omgeving is een belangrijke strategie om de impact van ons dagelijks leven op het milieu te verminderen. Nederlandse woningcorporaties zijn eigenaar van een derde van de woningen in Nederland. Andere Europese landen met een groot aandeel sociale woningen zijn Oostenrijk 24%, Denemarken 21%, Zweden 17%, VK 17%, Frankrijk 16%, Noorwegen 14% en Finland 11%. Door het aandeel van de totale voorraad speelt het veranderen van woningen van woningbouwcorporaties een belangrjke rol in de transitie naar een toekomstige duurzame woningvoorraad.

In dit onderzoek wordt gekeken naar de energieprestatie van de woningvoorraad van woningcorporaties. De energieprestatie van woningen kan worden gedefinieerd als de kwaliteit van woningen in relatie tot het daadwerkelijke energieverbruik tijdens de exploitatiefase van de woning. Het doel van Europees en nationaal beleid is het verbeteren van de energieprestatie en daarmee het verlagen van het daadwerkelijke energieverbruik door het bouwen van nieuwe woningen met een goede energieprestatie en het renoveren van de bestaande woningvoorraad.

Er doen zich verschillende wetenschappelijke uitdagingen voor bij het begrijpen en verbeteren van de energieprestatie van woningen van woningcorporaties. Ten eerste is het nodig om de voortgang van veranderingen in de energieprestatie van de woningvoorraad te monitoren. Het monitoren van de energieprestatie van de woningvoorraad helpt bij het opzetten van een gefundeerde kennisbasis, waardoor het mogelijk wordt om beleid gericht op het verbeteren van de energieprestatie van de woningvoorraad te evalueren en bij te sturen. Ten tweede is het nodig om de theoretische berekeningen van de energieprestaties te verbeteren door het werkelijke energieverbruik te modelleren. Momenteel bestaat er een kloof tussen het theoretische berekende en het werkelijke energieverbruik van woningen. Verbetering van de berekeningen helpt bij het inschatten van de daadwerkelijke energiebesparing van renovaties en bij het inschatten van het energieverbruik van nieuwe woningen. Ten derde is het nodig om de energieprestatie van woningen met warmtepompen te meten. Warmtepompen zijn een veelbelovende oplossing voor de toekomst en het verkrijgen van inzicht in verschillende woningen en systemen helpt bij het begrijpen van het potentieel van warmtepompsystemen voor de woningvoorraad van woningcorporaties. Ten vierde is er behoefte om woningcorporaties te helpen door de energieprestatie van hun woningvoorraad te benchmarken in overeenstemming met veranderingen in het beleid die ingaan na 2020. Het creëren van een benchmarkmodel helpt bij het meten en evalueren van de energieprestatie naar een toekomstige duurzame woningvoorraad. Het doel van dit proefschrift is om deze uitdagingen te dekken door het onderzoeken en begrijpen van de verbetering van de energieprestatie van woningen van woningcorporaties op weg naar een toekomstige duurzame woningvoorraad.

De centrale onderzoeksvraag van het onderzoek is dan ook:

Hoe de verbetering van de energieprestatie van woningen van corporaties te onderzoeken en te begrijpen op weg naar een toekomstige duurzame woningvoorraad?

Dit wordt geoperationaliseerd met vier onderzoeken:

- **Onderzoek 1: Monitoring energieprestatieverbetering:** *inzichten van corporatiewoningen*

- **Onderzoek 2: De energieprestatie van woningen van woningcorporaties:** *modellering van het werkelijke energieverbruik*

- **Onderzoek 3: De energieprestatie van woningen met warmtepompen van woningcorporaties**

- **Onderzoek 4: Benchmarking energieprestatie:** *indicatoren en modellen voor Nederlandse woningcorporaties*

Onderzoek 1 beoordeelt de voortgang van de energieprestatie tussen 2017 en 2020. Het onderzoek draagt bij aan het begrip van de verbetering van de energieprestatie van woningen van corporaties door inzicht te geven in de ontwikkeling van de woningvoorraad, het effect van veranderingen van en binnen de voorraad, het effect van kenmerken van woningcorporaties en door de verbetering van de energieprestatie te relateren aan de sectordoelstelling. Onderzoek 2 beoordeelt modellen om het werkelijke energieverbruik van woningen te voorspellen. Het onderzoek draagt bij aan begrip over de energieprestatie van woningen van woningcorporaties door inzicht te geven in de mate waarin geavanceerde modellering van het energieverbruik de voorspelling van energiebesparing van renovatiemaatregelen kan verbeteren. Onderzoek 3 beoordeelt de energieprestatie van woningen met warmtepompen. Het draagt bij aan het begrip over de energieprestatie van woningen van corporaties door inzicht te geven in de energieprestatie van woningen met warmtepompen als kansrijke renovatiemaatregel op weg naar een toekomstige duurzame woningvoorraad. Onderzoek 4 onderzoekt het benchmarken van de energieprestatie. Het draagt bij aan het begrip van de energieprestatie van woningen van corporaties door het creëren van een benchmarkmodel in afstemming met de veranderende beleidscontext, en draagt daarmee bij aan het begrip en de verbetering van de energieprestatie van woningen van corporaties op weg naar een toekomstige duurzame woningvoorraad.

Onderzoeksmethoden

Twee belangrijke databronnen worden gebruikt om de onderzoeksvragen in dit proefschrift te beantwoorden, de Shaere-database en microdata van het energieverbruik op adresniveau beschikbaar bij het Centraal Bureau voor de Statistiek (CBS). De Shaere-database is een database met energieprestatiegegevens en gebouwkenmerken van meer dan twee miljoen woningen van corporaties, die jaarlijks onder coördinatie van dit onderzoeksproject wordt verzameld en wordt onderhouden door Aedes, de koepelorganisatie van Nederlandse corporaties. Het CBS verzamelt en onderhoudt jaarlijks een database met het werkelijke energieverbruik van Nederlandse adressen, beschikbaar in een geanonimiseerde analyse-omgeving. De combinatie van deze databases is de belangrijkste basis voor de studies die in dit proefschrift zijn uitgevoerd.

Er zijn verschillende onderzoeksmethoden gebruikt om de vier onderzoeken in dit proefschrift uit te voeren. Het verzamelen van ruwe data, bestaande uit de energieprestatie en gebouwkenmerken van woningen van corporaties, vormt de basis voor alle onderzoeken. Onderzoeken 1 en 3 bestaan voornamelijk uit statistische analyses van ruwe data om de gestelde onderzoeksvragen te beantwoorden. In onderzoek 2 worden, naast het verzamelen van ruwe data en statistische analyse, geavanceerde modelleringstechnieken toegepast om tot de gewenste onderzoeksresultaten te komen. Er wordt gekeken naar een lineair, een niet-lineair en een Gradient Boosting Model (GBM). In onderzoek 4 is ook gebruik gemaakt van

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ruwe dataverzamelingen en statistische analyses, maar actieonderzoek waarbij de onderzoeker deelnam aan groepssessies met experts van woningcorporaties is de belangrijkste onderzoeksmethode.

Resultaten

Onderzoek 1, monitoring van energieprestatieverbetering: *inzichten van corporatiewoningen*, helpt om inzicht te krijgen in de verbetering van de energieprestatie door welke maatregelen worden genomen en welke mogelijkheden er zijn om de voorraad verder te renoveren of te vervangen door nieuwbouw. Uit het onderzoek blijkt dat de energieprestatie van woningen van woningcorporaties tussen 2017 en 2020 gestaag is verbeterd. Uit het onderzoek blijkt dat het effect van veranderingen in de voorraad (bouw en sloop) op de verbetering van de gemiddelde energieprestatie bescheiden is (15,6%). De verbetering van de gemiddelde sectorale energieprestatie gebeurt voor 85,4% binnen de bestaande voorraad, meestal met traditionele verbeteringen zoals het veranderen van verwarmingsinstallaties en het toevoegen van isolatie. Uit het onderzoek blijkt dat grote stedelijke woningbouwcorporaties de aanjager zijn van de verbetering van de gemiddelde sectorale energieprestatie. Het onderzoek concludeert dat de sectorale doelstelling van een gemiddelde energie-index van 1,40 in 2020 niet in het jaar 2020 wordt gehaald, maar eind 2021 wel kan worden gehaald.

Uit onderzoek 2, de energieprestatie van woningen van woningcorporaties: *modellering van het werkelijke energieverbruik*, blijkt dat het modelleren van het werkelijke energieverbruik helpt om inzicht te krijgen in de effectiviteit van renovatiemaatregelen bij het verlagen van het werkelijke energieverbruik en de bijbehorende CO_2-uitstoot. Het onderzoek toont aan dat er een grote kloof bestaat tussen het theoretische berekende en het werkelijke energieverbruik, die de noodzaak van het modelleren van het werkelijke energieverbruik onderstreept. Uit het onderzoek blijkt echter dat het modelleren van het werkelijke energieverbruik van woningen een uitdaging is. Het werkelijke energieverbruik is gemodelleerd met drie verschillende modellen, een lineaire regressie, een niet-lineaire regressie en een GBM machine-learning model. Uit het onderzoek blijkt dat de drie verschillende modellen hun eigen voor- en nadelen hebben. Lineaire regressiemodellen zijn eenvoudig en snel, en schatten sectorale doorsneden zeer goed in, maar zijn niet bruikbaar bij het analyseren van de effecten van gedetailleerde renovatiemaatregelen. Een niet-lineair model kan sectorale doorsneden en gedetailleerde renovaties schatten en gebruikt de structuur van de werkelijke gebouwfysica, maar kan alleen bepaalde relaties tussen gebouwkenmerken gebruiken en zal daarom geen andere relaties oppikken die de schattingen van de effecten zouden kunnen verbeteren van renovaties. Het niet-lineaire model is gemakkelijker te interpreteren, wat een reden kan zijn om een dergelijk model boven de andere modellen te verkiezen. Een Gradient Boosting Model is in staat om allerlei relaties tussen gebouwkenmerken te detecteren. Het kan correlaties en interacties vinden waarvan zelfs specialisten in het veld zich niet bewust zijn. Het model maakt echter geen gebruik van de structuur van de fysica van het werkelijke energieverbruik. Daarom is het moeilijker om de resultaten te interpreteren en als sommige renovatiemaatregelen (bijvoorbeeld elektrische warmtepompen) minder vaak voorkomen in de dataset, kan dit resulteren in onrealistische resultaten. Het onderzoek beveelt aan om theoretische modellen te combineren met empirische kalibraties om de nauwkeurigheid van voorspellingen van de energieprestatie te verbeteren.

Onderzoek 3, de energieprestatie van woningen met warmtepompen van woningcorporaties, laat zien dat een statistische analyse naar de energieprestatie van woningen met warmtepompen helpt om het potentieel van warmtepompsystemen te begrijpen voor de Nederlandse corporatievoorraad. In het onderzoek worden de kenmerken en het gemiddelde werkelijke energieverbruik van woningen met warmtepompen bepaald en vergeleken met woningen met een traditionele HR107 gasketel. 3,2% van de woningen van corporaties heeft een warmtepomp, bestaande uit volledig elektrische warmtepompsystemen (1,2%), hybride systemen (0,8%), gasabsorptiewarmtepompen (0,6%), gasabsorptie hybride systemen (0,4%) en andere configuraties (0,2%). Woningen met volledig elektrische warmtepompen hebben een gemiddeld hogere bouwkwaliteit, geen gasverbruik en een hoger elektriciteitsverbruik, in vergelijking met woningen met hybride of gasabsorptie warmtepompen, die een gemiddeld hogere bouwkwaliteit, lager gasverbruik en hoger elektriciteitsverbruik hebben, in vergelijking met woningen met een traditionele HR107 gasketel. In het onderzoek worden gedetailleerde inzichten gegeven voor woningen met verschillende warmtepompsystemen en voor woningen met verschillende gebouwkenmerken.

Onderzoek 4, benchmarking energieprestatie: *indicatoren en modellen voor Nederlandse woningcorporaties*, laat zien dat een model om de energieprestatie van Nederlandse woningcorporaties te benchmarken kan worden gecreëerd door een gestructureerde aanpak te volgen. Benchmarken is een methode om voortgang te meten en bewustzijn te creëren over de prestaties van organisaties. Het benchmarkmodel helpt woningcorporaties bij het analyseren en vergelijken van de energieprestatie van hun woningvoorraad in overeenstemming met het huidige beleid. Andere onderzoekers die de energieprestaties tussen organisaties willen benchmarken gegeven de beleidscontext, kunnen deze gestructureerde aanpak overnemen en waar nodig aanpassen. Het uiteindelijke model voor het meten en benchmarken van de energieprestaties van Nederlandse woningcorporaties bestaat

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uit drie indicatoren die nauw samenhangen met het huidige beleid ten aanzien van de duurzaming van de Nederlandse woningbouwsector: (1) Het gemiddelde theoretisch primair fossiel energieverbruik, (2) de gemiddelde afstand tot de maximale theoretische warmtevraag, en (3) de gemiddelde werkelijke CO_2-uitstoot door gasverbruik. De eerste indicator heeft betrekking op het huidige beleid ten aanzien van de energielabeling van woningen, afgeleid van de EPBD, de NTA8800. De tweede indicator heeft betrekking op het beleid om de gemiddelde theoretische warmtevraag van woningen te verlagen. De derde indicator heeft betrekking op het doel voor de Nederlandse gebouwde omgeving om de daadwerkelijke CO_2-uitstoot te verlagen.

Conclusies en aanbevelingen

De centrale onderzoeksvraag van het proefschrift is: Hoe de verbetering van de energieprestatie van woningen van corporaties te onderzoeken en te begrijpen op weg naar een toekomstige duurzame woningvoorraad? De onderzoeken die in dit proefschrift zijn uitgevoerd laten zien dat om de energieprestatie van woning-corporaties te onderzoeken, een systematische methode van gegevensverzameling essentieel is. De onderzoeken zijn gebaseerd op de SHAERE-database met de energieprestatiekenmerken van ruim twee miljoen woningen die jaarlijks worden verzameld, en het daadwerkelijke energieverbruik van die woningen, die in een geanonimiseerde omgeving beschikbaar zijn bij het Centraal Bureau voor de Statistiek (CBS). Om de gegevens te beoordelen, helpen verschillende analytische methoden om inzichten te verkrijgen. In dit onderzoek wordt gebruik gemaakt van een monitoringsysteem, geavanceerde modelleringstechnieken, statistische analyse van data en de ontwikkeling van een benchmarkmodel. Deze technieken helpen om waardevolle inzichten te verkrijgen over de verbetering van de energieprestatie van woningen van corporaties.

- Het monitoren van de voortgang van de energieprestatie helpt om grip te krijgen in de verbetering van de energieprestatie van woningen van woningcorporaties door inzicht te geven in de ontwikkeling van de woningvoorraad, het effect van veranderingen van en binnen de voorraad, het effect van kenmerken van woningcorporaties en door de verbetering van de energieprestatie te vergelijken met de sectorale doelstelling.

- Het gebruik van geavanceerde modelleringstechnieken om het werkelijke energieverbruik van woningen in te schatten draagt bij aan het inzicht in de mate waarin een lineair model, een niet-lineair model en een Gradient Boosting Model (GBM) de voorspelling van het energieverbruik van woningen kunnen verbeteren en daarmee de energiebesparing van renovatiemaatregelen beter kunnen voorspellen.

- Het beoordelen van de energieprestatie van woningen met warmtepompen draagt bij aan het begrijpen van het potentieel van warmtepompen als kansrijke renovatiemaatregel voor een toekomstige duurzame woningvoorraad.

- Het benchmarken van de energieprestatie draagt bij aan het inzicht in de energieprestatieverbetering van woningen van corporaties in relatie tot actief beleid.

Het proefschrift beveelt aan om de energieprestatie van woningen te blijven monitoren om de verbetering van de non-profit woningbouwsector naar een toekomstige duurzame woningvoorraad te kunnen blijven beoordelen. Het proefschrift beveelt aan om de modellering van het werkelijke energieverbruik van woningen verder te verbeteren om het effect van renovaties nauwkeuriger te voorspellen, met theoretische modellen gecombineerd met empirische kalibraties als richting om verder te onderzoeken. Het proefschrift beveelt aan om de energieprestatie van woningen met specifieke warmtepompconfiguraties te bepalen, en het proefschrift beveelt aan om te beginnen of door te gaan met het benchmarken van de energieprestaties over de woningvoorraad, om daarmee van elkaar te kunnen leren.

Tenslotte, er zijn aanhoudend inspanningen nodig, zowel in onderzoek als in de praktijk, om te komen tot een toekomstige duurzame woningvoorraad en daarmee bij te dragen aan de strijd tegen klimaatverandering, met als doel een gezonde aarde te behouden voor toekomstige generaties.

1 Introduction

Climate change asks for urgent action. For decades humankind is aware of the impact of humanity on our environment. The Brundlandt report (World Commission on Environment and Development, 1987) was a major wake-up call. Furthermore, the Kyoto Protocol (UNFCCC, 1997) and Paris Agreement (UNFCCC, 2015) are major stepping stones to mitigate the effect of climate change. But time marches on. Climate change is still today an urgent matter which needs our immediate attention.

These agreements were adopted in legislation at European and national levels. In Europe, among others, the Energy Performance of Buildings Directive (EPBD) was implemented. The energy transition in the built environment is a key strategy to mitigate the impact of our daily life on the environment. This challenge is large. The International Energy Agency (IEA) reports an all-time high amount of CO2 emissions in buildings in 2019, of 10 Gt CO2 (IEA, 2020). The IEA states that an enormous potential to reduce emissions from buildings remains unfulfilled due to the ongoing use of fossil fuels, ineffective energy efficiency policies and insufficient investments to make buildings sustainable. Moving the built environment towards CO_2 neutrality requires increased efforts in the renovation and adaptation of our buildings. The needed change in the building stock is also stressed by the EU as a major challenge (European Commission, 2019).

1.1 Energy transition in non-profit housing

Dutch non-profit housing associations own one-third of the dwellings in the Netherlands. Due to the share of the stock, changing the non-profit housing stock plays a vital role in the transition to a future sustainable housing stock. Other European countries with a large share of social housing are Austria 24%, Denmark 21%, Sweden 17%, UK 17%, France 16%, Norway 14%, and Finland 11% (Housing Europe, 2021). In the Netherlands, the non-profit housing stock of 2.4 million dwellings is organized in 286 non-profit housing associations in 2021. Housing associations are able to make decisions on how to manage their housing stock, but are restricted by strong central law (Woningwet, 2018) and are obliged to make performance agreements with local governments. Housing associations in the Netherlands cover a range of organisations. Some are small (only 30 dwellings), and some are large (over 80,000 dwellings). There are also important differences in, for example, the financial position of the housing associations, the geographical location, the degree of urbanity of the assets of the housing association and also the average energy performance of the assets of the housing association differs from organization to organization.

This research examines the energy performance of the housing stock of Dutch non-profit housing associations. The energy performance of dwellings can be defined as the quality of dwellings in relation to the actual energy consumption during the operation phase of the dwelling. The aim of European and national policy is to improve the energy performance and to lower actual energy consumption by building new dwellings with a good energy performance and by renovating the existing housing stock. Several scientific challenges appear in understanding the improvement of the energy performance of Dutch non-profit housing associations. In this thesis, four challenges are addressed that will be further discussed in the upcoming sections. In section 1.1.1., the need to monitor the progress of changes in the housing stock is discussed. In section 1.1.2., the need to improve theoretical estimations of the energy performance through modelling actual energy consumption is discussed. In section 1.1.3., the need to measure the energy performance of dwellings with heat pumps is discussed and in section 1.1.4., the need to assist housing associations by benchmarking the energy performance of their housing stock in agreement with changes in policy after 2020 is discussed.

1.1.1 Monitoring the energy performance

In the Netherlands, an energy agreement was signed in 2013 (Sociaal Economische Raad, 2013) and a new national climate agreement was signed in 2019 (*National Climate Agreement*, 2019). In the Dutch Energy Agreement of 2013, it was agreed that housing associations will improve the energy performance of their assets. The energy performance is measured in the energy index (or EI). This is a theoretical number which indicates the energy performance of a dwelling calculated according to the NEN 7120 (Nederlands Normalisatie-instituut, 2012), which derives from the European code, the Energy Performance Building Directive (EPBD). The energy index can be categorized in an energy label, ranging from A to G. In the Dutch Energy Agreement it has been agreed to achieve an average energy-index of 1.25 (Label B) for housing associations in 2020.

In the article “Are we moving fast enough? The energy renovation rate of the Dutch non-profit housing using the national energy labelling database” (Filipidou, Nieboer, & Visscher, 2017) it is concluded that on the basis of the progress made over the period 2010 to 2014 the target label B (EI = 1.25) will not be met in 2020. On the basis of the 2010-2014 progress, it cannot be expected that, without changes in policy, the pace will increase, because there is less and less low-hanging fruit. (Filipidou, Nieboer, & Visscher, 2017). In the research of Filippidou, Nieboer, & Visscher (2016) it was concluded that housing associations generally do not carry out major renovations, but many smaller investment projects, whether or not as part of planned maintenance work. The most frequently used changes are heating, hot water installations and glazing. Other building elements are adapted much less often. If this renovation strategy is continued at the same rate, the objectives for the sector are probably not met (Filippidou, Nieboer, & Visscher, 2016). Furthermore, researchers have different opinions whether sustainability measures need to be implemented in steps or whether large-scale renovations are needed, or whether demolition and new construction are better alternatives (Thomsen & van der Flier, 2009), (Nieboer, 2016).

In 2015 the calculation method of the energy index changed to the “*Nader Voorschrift (NV)*”. Also, the objective changed to an average energy-index of 1.40 (still energy label B) for housing associations in 2020 (Ministerie van BZK, 2016). The change in method and goal makes it more difficult to understand the progress of the average energy performance of the non-profit housing sector and the measures taken by Dutch non-profit housing associations towards 2020. A detailed monitoring of the energy performance of the non-profit housing stock delivers a solid foundation to analyse progress and to assess the effect of policies. Furthermore, the effect of demolition and new construction on the progress of the energy performance of the non-profit housing stock has not been examined before, while also the influence of different characteristics of non-profit housing associations on the improvement of the energy performance has not been examined in scientific literature. Understanding these factors helps to clarify how the energy performance of the housing stock is improved. This thesis aims to alleviate this knowledge gap in the scientific literature.

1.1.2 Modelling actual energy consumption

Monitoring the energy performance helps to understand how the housing stock is improved. However, several studies show that the estimation of the theoretical energy performance with a theoretical building energy model can deviate strongly from actual energy consumption and could lead to the systematic overestimation of potential energy savings, defined as a "performance gap" (Galvin & Sunikka-Blank, 2016; Laurent et al., 2013; Saunders, 2015; Summerfield et al., 2019; Sunikka-Blank & Galvin, 2012). The performance gap includes a "rebound" and "prebound" effect. The "rebound" effect, is described as an underestimation of the theoretical energy consumption of good energy labels compared to actual energy consumption. The "prebound" effect is described in literature as the theoretical overestimation of the energy consumption of poor energy labels compared with actual energy consumption, because inhabitants lower actual energy consumption based on the fact that the building quality is poor. Besides the rebound and prebound effect, other factors could clarify the energy performance gap, such as an outdated energy performance calculation or poor maintenance of the dwelling.

The performance gap was found in the Dutch context as well (Filippidou, Nieboer, & Visscher, 2019; Majcen, Itard, & Visscher, 2016; Majcen, Itard, & Visscher, 2013; Santin, 2010). The following examples illustrate the performance gap. The study of Majcen, Itard, & Visscher (2013) shows that the average gas consumption for the energy labels D to G is considerably lower than the theoretical consumption (Figure 1.1). At label G the actual consumption is about two times lower than the theoretical consumption. It can also be seen that the actual gas consumption in labels D, E, F and G is within the same order of magnitude.

According to Filipidou, Visscher, & Nieboer (2017) a greater number of energy-saving measures (ESM) at a single dwelling lowers the effectiveness of the measurements. This is shown in Figure 1.2. The actual realized savings in energy consumption are lower than the theoretical savings with a greater number of ESMs realized. This is another example which shows differences between the theoretical energy performance model and actual energy savings.

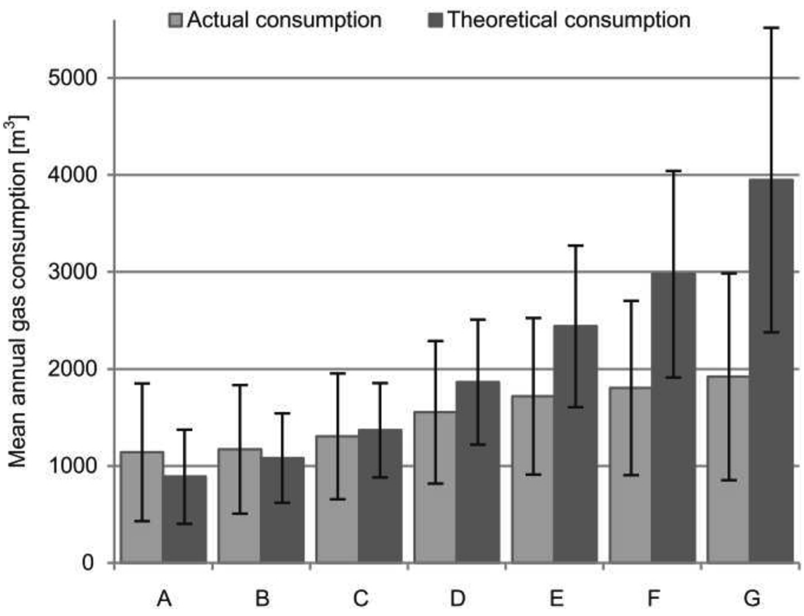

FIG. 1.1 Theoretical and actual gas consumption by energy label

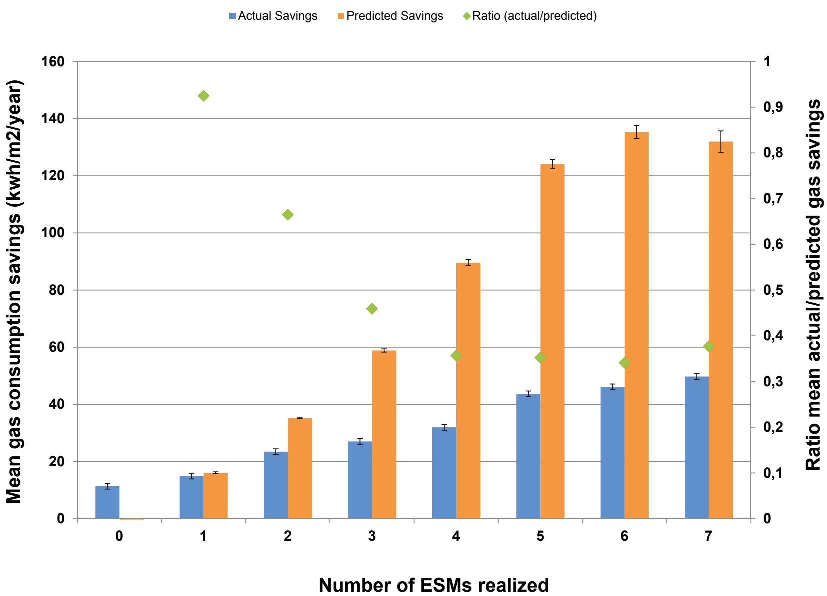

FIG. 1.2 Ratio actual/predicted gas savings by number of energy-saving measures (ESM)

In the study “Improved Governance for Energy Efficiency in Housing” (Visscher, Majcen, & Itard, 2016) it is stated that the current policy is not sufficiently contributing to the improvement of the energy performance of the sector and that more attention should be paid on the lowering the actual energy consumption and related CO_2 emissions.

Advove theoretical energy consumption estimations therewith counteracting the performance gap. Several studies explored and created actual energy consumption models. These models vary in purpose, method, number of dwellings and number of features. Some of these studies have a localised and more case-specific purpose to estimate the actual energy consumption of a group of dwellings e.g. (Amasyali & El-Gohary, 2016), (X. Li & Yao, 2021). These studies usually have a smaller number of dwellings, but can have a higher number of building features. Other studies have a more general purpose and try to create a model to estimate actual energy consumption for a broader part of the building stock (Kontokosta & Tull, 2017), (Robinson et al., 2017). These studies have a higher number of dwellings, but usually have a smaller number of building features, because detailed information is not available for all dwellings. It is unclear, to which extent empirical models provide more accurate estimations of actual energy consumption, compared to a theoretical building energy model, in order to estimate average actual energy savings of renovations. This thesis aims to alleviate this knowledge gap in the scientific literature, by examining different advanced energy models for dwellings of Dutch non-profit housing associations.

1.1.3 The energy performance of dwellings with heat pumps

Besides the advanced modelling of the actual energy performance, assessing a particular part of the housing stock could help to understand the value of renovation measures towards a future sustainable housing stock. A promising design solution is the heat pump. The spectrum of heat pump systems includes a great variety of characteristics. These characteristics influence the energy performance of the heat pump system. Differences can be found in the type of heat pump (all-electric, hybrid, gas absorption), the source of energy (gas/electricity), the source of heat extraction (air/ground/water), the configuration of the system (individual, collective), the distribution medium, the distribution temperature, and the installed power and coefficient of performance (COP) of the heat pump system. Also, the building wherein the heat pump operates can vary greatly, in size, level of insulation, and differences from other building systems like ventilation systems and photovoltaic panels (PV).

Because of the expected role of heat pumps in the energy transition, a substantial body of literature can be found about the performance and energy consumption of dwellings with heat pumps. However, most of these studies examine only a particular setup of a heat pump system. No large-scale research was published from a building stock approach examining the extent to which different heat pumps are present in the building stock, with a description of the characteristics of these dwellings and the energy consumption of different heat pump systems. This thesis aims to alleviate this gap in scientific literature.

1.1.4 Benchmarking the energy performance in changing policy

In section 1.1.1., the need to monitor the progress of changes in the housing stock is discussed. In section 1.1.2., the need to improve theoretical estimations of the energy performance through modelling actual energy consumption is discussed and in section 1.1.3., the need to measure the energy performance of dwellings with heat pumps is discussed. Assessing these questions helps to understand how the energy performance of the non-profit housing stock changes and could be improved. To support housing associations to improve the energy performance of their housing stock in a policy context, benchmarking could be used. Benchmarking is a method to measure progress and to create awareness about the performance of organizations. Benchmarking the energy performance of the housing stocks of Dutch housing associations aims to measure the progress and create awareness towards reaching decarbonization goals in the housing stock. A benchmark is organized between housing associations to assess the improvement of the energy performance of Dutch housing associations from 2021 and beyond. National policy on the sustainable development of the Dutch built environment enters a new phase in 2021. A new national climate agreement was signed in 2019 (National Climate Agreement, 2019) and a new method to determine the energy performance of dwellings became in force in 2021, the NTA8800 (NEN, 2018). No research was published regarding the process of creating a benchmark about the energy performance of dwellings of housing organizations, within their specific policy context. This thesis aims to alleviate this gap in scientific literature.

1.2 Problem definition and aim of the thesis

As outlined in the previous paragraphs several scientific challenges appear in understanding and improving the energy performance of dwellings of Dutch non-profit housing associations. First, there is a need to monitor the progress of changes of the energy performance in the housing stock. Monitoring the energy performance of the housing stock helps in establishing a well-founded knowledge base, enabling the evaluation and adaptation of policies aimed at increasing the energy performance of the housing stock. Second, there is a need to improve theoretical calculations of the energy performance through modelling actual energy consumption. Currently, a performance gap exists between theoretical and actual energy consumption of dwellings. Improving the calculations helps in estimating the actual energy savings of the renovations of dwellings and in estimating the energy consumption of new dwellings. Third, there is a need to measure the energy performance of dwellings with heat pumps. Heat pumps are a promising solution for the future and gaining insights about different dwellings and systems helps in understanding the potential of heat pump systems in the Dutch non-profit housing stock. Fourth, there is a need to assist housing associations by benchmarking the energy performance of their housing stock in agreement with changes in policy after 2020. Creating a benchmark model helps in the measuring and evaluation of the energy performance towards a future sustainable housing stock. The aim of this thesis is to cover these challenges by assessing and understanding the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock.

1.3 Research questions

The main research question of this thesis is:

How to assess and understand the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock?

This research question is divided into sub-questions grouped into four studies: the monitoring of the energy performance, the modelling of the actual consumption, the measuring of the energy performance of dwellings with heat pumps and the benchmarking of the energy performance. These are introduced accordingly.

Study 1

Monitoring energy performance improvement: *insights from Dutch housing association dwellings*

- **RQ 1:** How did the energetic quality of the Dutch non-profit housing stock develop between 2017 and 2020?
- **RQ 2:** What is the effect of changes of the stock (construction and demolition) and changes within the stock (renovations) on the energy performance of the Dutch non-profit housing stock from 2017 to 2020?
- **RQ 3:** How do characteristics of non-profit housing associations explain the progress of the energy performance of the non-profit housing sector from 2017 to 2020?
- **RQ 4:** Did the Dutch non-profit housing sector meet its agreed goal on the average energy performance in 2020?

Research questions 1, 2, 3, and 4 contribute to the understanding of the improvement of the energy performance of dwellings of non-profit housing associations by giving insights in the development of the housing stock, the effect of changes of and within the stock, the effect of characteristics of housing associations and by relating the improvement of the energy performance to the sectoral goal.

Study 2

The energy performance of dwellings of Dutch non-profit housing associations:
modelling actual energy consumption

- **RQ 5:** To what extent do a linear regression model, a non-linear regression model, a machine learning model (GBM) and a theoretical building energy model differ in terms of their predictions of the actual energy consumption of dwellings?

- **RQ 6:** To what extent do a linear regression model, a non-linear regression model, a machine learning model (GBM) and a theoretical building energy model predict the energy consumption of dwellings when individual renovation measures are analysed?

Research questions 5 and 6 contribute to the understanding of the energy performance of dwellings of non-profit housing associations by giving insights into the extent to which advanced modelling of the energy consumption can improve the estimation of energy savings of renovation measures.

Study 3

The energy performance of dwellings with heat pumps of Dutch non-profit housing associations

- **RQ 7:** To what extent are dwellings with different heat pump systems present in the Dutch non-profit housing sector?

- **RQ 8:** What are the characteristics of dwellings with different heat pump systems compared to dwellings with a traditional condensing gas boiler (HR107)?

- **RQ 9:** What is the actual average energy consumption of dwellings with heat pumps compared to dwellings with a traditional condensing gas boiler (HR107)?

Research questions 7, 8, and 9 contribute to the understanding of the energy performance of dwellings of non-profit housing associations by giving insights in the energy performance of dwellings with heat pumps as a promising renovation measure towards a future sustainable housing stock.

Study 4

Benchmarking energy performance: *indicators and models for Dutch housing associations*

– **RQ 10:** How to benchmark the energy performance of Dutch non-profit housing associations in relation to the policy context beyond 2020?

Research question 10 contributes to the understanding of the energy performance of dwellings of non-profit housing associations by creating a benchmark model related to the changing policy context, therewith contributing to the understanding and improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock.

1.4 Data and methods

In this research two main data sources are used, the Shaere-database and microdata of energy consumption on address level from the CBS (Dutch Central Bureau of Statistics). They are used in the four studies as shown in Table 1.1.

TABLE 1.1 Research data

	Shaere	CBS
Study 1: Monitoring energy performance improvement: insights from Dutch housing association dwellings	X	
Study 2: The energy performance of dwellings of Dutch non-profit housing associations: modelling actual energy consumption	X	X
Study 3: The energy performance of dwellings with heat pumps of Dutch non-profit housing associations	X	X
Study 4: Benchmarking energy performance: indicators and models for Dutch housing associations	X	X

The Shaere database

Aedes, the Dutch umbrella organization of housing associations, maintains a database for energy performance data of dwellings of non-profit housing associations called Sociale Huursector Audit en Evaluatie van Resultaten Energiebesparing (Social Rented Sector Audit and Evaluation of Energy Saving Results) abbreviated SHAERE. The energy performance of dwellings and underlying building characteristics are collected. Every housing association is asked to voluntarily deliver a structured dataset of their dwellings annually. This was supported by two software providers which offer data management software for the energy performance of dwellings in the Dutch non-profit housing sector. The result is a database of over two million dwellings annually for the period 2017-2021. During this research, the data collection and administration of the raw data were executed within this research project.

CBS

The Dutch Central Bureau of Statistics (CBS) collects actual energy consumption values for gas and electricity from Dutch network operators on an address level annually. The actual energy consumption data on an address level are accessible for research in an anonymized analysis environment, where the addresses are anonymized with an identification code to comply with privacy regulations.

These two databases are combined as shown in Figure 1.3.

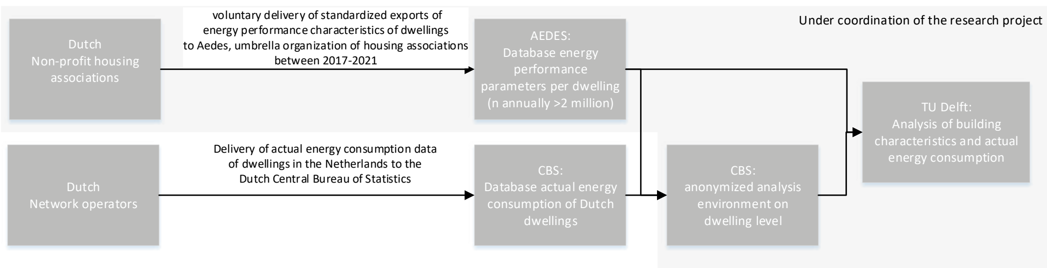

FIG. 1.3 Data collection and combination

Several research methods are used in the different studies. The collection of raw data, consisting of the energy performance and building characteristics of dwellings of non-profit housing associations is a basis for all studies. Studies 1 and 3, mainly consist of statistical analyses of raw data to answer the stated research questions. In study 2, besides raw data collections and statistical analysis, advanced modelling techniques are applied to reach the desired research results. A linear regression, a non-linear regression and a gradient Boosting Method (GBM) are used. In study 4, also raw data collections and statistical analysis were used, but action research where the researcher participated in group sessions with experts from non-profit housing associations is the main research method. The applied research methods are summarized in Table 1.2.

TABLE 1.2 Research methods

	Raw data collection	Statistical analysis	Advanced modelling	Action research
Study 1: Monitoring energy performance improvement: insights from Dutch housing association dwellings	X	X		
Study 2: The energy performance of dwellings of Dutch non-profit housing associations: modelling actual energy consumption	X	X	X	
Study 3: The energy performance of dwellings with heat pumps of Dutch non-profit housing associations	X	X		
Study 4: Benchmarking energy performance: indicators and models for Dutch housing associations	X	X		X

1.5 Scientific and societal contribution

In this section, the scientific and societal contribution of the research are explained. The main research question is: How to assess and understand the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock? This is operationalized with four studies. The scientific and societal contribution of these studies are displayed in Table 1.3.

TABLE 1.3 Scientific and societal contribution

	Scientific contribution	Societal contribution
Study 1: Monitoring energy performance improvement: insights from Dutch housing association dwellings	- Approach to monitor the energy performance - Insights into factors clarifying the progress of the energy performance	- Detailed data of the energetic quality of Dutch non-profit dwellings. - Progress tracking towards sectoral goal.
Study 2: The energy performance of dwellings of Dutch non-profit housing associations: modelling actual energy consumption	- Approach to model actual consumption with a linear regression, a non-linear regression and a Gradient Boosting Model (GBM) . - List of limitations and recommendations to improve the modelling of the actual consumption.	- Insight into the energy performance gap. - Awareness of the potential value of advanced modelling in estimating energy savings from renovation measures.
Study 3: The energy performance of dwellings with heat pumps of Dutch non-profit housing associations	- Buildings stock approach to measure the energy performance of dwellings with heat pumps.	- Insights into the performance and characteristics of dwellings with heat pumps.
Study 4: Benchmarking energy performance: indicators and models for Dutch housing associations	- Structured approach to create a benchmark model. - A model to benchmark the energy performance grounded in a policy context.	- A benchmark model applicable to benchmark the energy performance of Dutch non-profit housing associations.

Study 1: Monitoring energy performance improvement: *insights from Dutch housing association dwellings delivers scientific contributions*
The study delivers an approach to monitor the energy performance, which could be adopted and adapted by other researchers examing (parts of) housing stocks. The study also delivers insights into factors clarifying the progress of the energy performance, especially the effect of demolition and new construction on the progress of the energy performance of the non-profit housing stock and the influence of different characteristics of non-profit housing associations on the improvement of the energy performance. The study delivers an important social contribution by delivering detailed data of the energetic quality of the Dutch non-profit housing stock. Finally, the study delivers a societal contribution by tracking the progress of the energy performance towards the Dutch sectoral goal.

Study 2: The energy performance of dwellings of Dutch non-profit housing associations: *modelling actual energy consumption delivers scientific contributions*
The study delivers an approach to model actual consumption with a linear regression, a non-linear regression and a Gradient Boosting Model (GBM), which could be adopted and adapted by other researchers aiming at modelling the actual energy consumption of dwellings. The study delivers a list of limitations and recommendations to improve the modelling of the actual consumption. The study delivers an important social contribution by delivering insight into the energy performance gap present in the Dutch non-profit housing stock under the energy performance model, the NEN 7120 NV. The study aims at creating social awareness of the potential value of advanced modelling techniques in estimating energy savings from renovation measures.

Study 3: The energy performance of dwellings with heat pumps of Dutch non-profit housing associations
The study delivers a scientific contribution by initiating a buildings stock approach to measure the energy performance of dwellings with heat pumps. The study delivers a social contribution within the Dutch context by delivering insights into the performance and characteristics of dwellings with heat pumps. Heat pumps are an important design solution for the future Dutch housing stock.

Study 4: Benchmarking energy performance: *indicators and models for Dutch housing associations*
The study delivers a scientific contribution by describing a structured approach to create a benchmark model. The study shows how to create a model to benchmark the energy performance grounded in a changing policy context. The study delivers a social contribution by delivering a model to benchmark the energy performance of Dutch non-profit housing associations, grounded in the changing policy context, the climate agreement 2019 and the new energy performance calculation method, the NTA8800.

1.6 Structure of the thesis

The structure of the thesis is straightforward. Four studies are presented in chapters 2, 3, 4, and 5. Chapter 6 describes the overarching conclusions, limitations and recommendations of this thesis.

- **Chapter 2:** Monitoring energy performance improvement: insights from Dutch housing association dwellings
- **Chapter 3:** The energy performance of dwellings of Dutch non-profit housing associations: modelling actual energy consumption
- **Chapter 4:** The energy performance of dwellings with heat pumps of Dutch non-profit housing associations
- **Chapter 5:** Benchmarking energy performance: indicators and models for Dutch housing associations
- **Chapter 6:** Overall conclusions, limitations and recommendations.

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2 Monitoring energy performance improvement

Insights from Dutch housing association dwellings

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ABSTRACT

The Energy Performance of Buildings Directive enhanced the sustainable improvement of dwellings in Europe. Nations formulated measurable goals to improve the housing stock and monitoring systems were developed to give insights into the improvements. In The Netherlands, non-profit housing associations agreed to improve the quality of their housing stock of 2.4 million dwellings to an average Dutch energy label B (energy-index=1.40) in 2020. Progress towards this goal was assessed using an annual monitoring system based on 2.0 million energy performance calculations of 264 Dutch non-profit housing associations between 2017 and 2020. The assessment includes a detailed description of the development of the state of the stock over time, it assesses the effect of changes of the stock (construction and demolition) and changes within the stock (renovations) to the energy performance, and it shows how different characteristics of non-profit housing associations explain the progress of the energy performance of the non-profit housing sector between 2017 to 2020. Gained insights are useful as an extensive frame of reference for other researchers and are a baseline of information for the future sustainable development of the Dutch non-profit housing stock.

PRACTICE RELEVANCE The assessment of the development of the energetic quality of dwellings of Dutch non-profit housing associations reveals that large urban housing associations drive the sectoral improvement. They own a large share of the Dutch non-profit housing stock and their dwellings have on average a lower quality. However, the improvement of their dwellings between 2017 and 2020 is higher than for smaller housing associations, which already have on average a higher energetic quality. While the construction and demolition of dwellings contribute to 15.6% of the annual improvement, most of the improvement of the energy performance happens in the existing stock, mostly with traditional measures like the installation of high-efficiency gas boilers and improved insulation. The rate of adding photovoltaic solar systems is increasing rapidly through the years, while futureproof systems like heat pumps and external heating are only steadily adopted in the sector.

KEYWORDS monitoring, energy performance, energy-index, building retrofits, building stock, non-profit housing associations

2.1 Introduction

To stimulate a more sustainable built environment the Energy Performance of Buildings Directive was enforced in the European Union (European Commission, 2010). European countries adopted regulations from the Energy Performance of Buildings Directive into national legislation and national goals were formulated to improve the energy performance of the housing stock. Several researchers share results from national monitoring systems to discuss sustainable developments in housing stocks of different European countries: Gangolells et al. (2016) analysed 130.000 dwellings in Spain from 2013-2014 in terms of energy label, building type, and building year. They describe the state of the stock but do not give detailed information on building parameters and do not describe developments over time. Csoknyai et al. (2016) analysed energy performance calculations from Bulgaria, Serbia, Hungary, and the Czech Republic between 2004-2009 as part of the Episcope project. They describe in detail the characteristics of the housing stock but do not include developments over time. They include descriptive U-values and analyse domestic hot water and heating systems, although information is limited. In the Czech Republic 32% is connected to district heating, 31% electrical systems, 23% natural gas, and only 0.2% solar thermal. Serghides et al. (2016) describe the situation in Cyprus 2014. The data set covers 2484 dwellings. They give detailed information about the quality of parts of the envelope, ranging from 0.6 and 6.1 W/m^{2}K. Around 60% of the dwellings use decentralised electric heating, other dwellings use natural gas, oil, and heating with wood/biomass. Hjortling et al. (2017) analyze 186.021 energy performance certificates (EPC's) from Sweden issued between 2007 and 2015. They include a detailed description of the building stock, but it is a static description without developments over time. The analysis includes insights into energy demands by building type and by region. Streicher et al. (2018) analyse 10.400 EPC's issued in Switzerland between 2007-2015. They include a detailed description of the quality of the envelope of dwellings. U-values range on average from 0.4 to approximately 2.4 W/m^{2}K, also described in detail by average surface area and by building period for the floor, walls, roofs, and windows. Also, heating systems are discussed by building type and building year. Oil and gas systems are most dominant, but electrical systems and also heat pumps are present in the Swiss building stock. Ahern and Norton (2019) discuss 463,582 EPC's from Ireland present in 2014. They describe in detail the quality of the building envelope in terms of U-values by building type and building period, of floors, walls, roofs, and windows, and the effects of renovations. Although these assessments give useful insights about the sustainable state of (parts of) housing stocks in Europe, none of these studies assessed change over time or analyzed the effects of construction and demolition to the stock. Improved monitoring and analyses of housing stocks could alleviate these knowledge gaps. Generating insights from longitudinal analysis enables the adaptation of strategies to speed up the improvement of the building stock as it shows which measures currently (do not) have a substantial impact. In this paper we show recent insights from a longitudinal monitoring system of the energy performance of the Dutch non-profit housing stock.

In the Netherlands, a large share of the housing stock is owned by non-profit housing associations. They own 2.4 million dwellings which is one-third of the total housing stock. Other European countries have non-profit housing as well but generally smaller shares of the total housing stock (Housing Europe, 2017). When the European Union agreed in 2008 on goals to reduce the impact of human activities on the climate by 2020 (European Commission, 2007) these were translated into several sectoral covenants for the Dutch non-profit housing sector. Agreements were made in 2008 (VROM, 2008) and in 2012 (VROM, 2012). These agreements were incorporated in the Dutch Energy agreement in 2013 (*Energieakkoord voor duurzame groei*, 2013). Among others, it was agreed to improve the average energy performance of dwellings of non-profit housing associations to an average energy label B in 2020 (energy-index=1.25). The energy-index is the Dutch translation of the Energy Performance of Buildings Directive (European Commission, 2010). Progress until 2015 was published by Filippidou et al. (2017). In 2015 the determination method of the energy-index changed (NEN, 2014) and also the related goal towards an average energy label B changed to an average EI NV of 1.40 in 2020 (Blok, 2016). Since the change in method and goal in 2015, no further scientific research was published to give insights into the development of the energy performance of Dutch non-profit housing associations.

TABLE 2.1 Dutch calculation method of the energy performance of dwellings over time

Period	Calculation method energy performance	Publisher	Indicator energy label & unit	Sector goal 2020 average energy label B
2009-2014	NEN 7120	(NEN, 2009)	Energy-index [-]	EI=1.25
2015-2020	NEN 7120 NV	(NEN, 2014)	Energy-index NV [-]	EI NV=1.40
2021 à	NTA 8800	(NEN, 2020)	Primary fossil energy demand [kWh/m^2]	-

The energy-index NV is the main indicator to measure the energy performance of dwellings in The Netherlands from 2015 to 2020. The energy-index (EI) is a dimensionless number, calculated with the following formula:

$$Energy\ index\ (EI) = \frac{E_{Ptot} * 0.84}{248 * A_g + 87 * A_{vl} + 5844}$$

Where:

E_{Ptot} = Building related energy use in MJ
A_g = Floor area in m^2
A_{vl} = Heat loss area in m^2

The building-related energy use is calculated with a theoretical building energy model. The denominator determines an energy budget based on the floor area and heat loss area of a dwelling. The energy-index is a division of the building-related energy use and the energy budget. Energy-indexes translated to corresponding energy labels are presented in the results section in Table 2.3.

Several studies show that the estimation of the building-related energy use with a theoretical building energy model can deviate strongly from actual energy consumption and could lead to the systematic overestimation of potential energy savings (Sunikka-Blank & Galvin, 2012; Laurent et al., 2013; Saunders, 2015; Galvin & Sunikka-Blank, 2016; Summerfield et al., 2019). These studies describe the performance gap both as a “prebound” effect (theoretical overestimation of the energy consumption of poor energy labels compared with actual energy consumption) and the “rebound” effect (underestimation of the energy consumption of good energy labels compared to actual energy consumption). The performance gap was found in the Dutch context as well (Santin, 2010; Majcen et al., 2016; Filippidou et al., 2019). Nonetheless, the average energy-index is the formal indicator to assess the improvement of the energy performance of dwellings of Dutch non-profit housing associations.

Filippidou et al. (2017) concluded, based on the progress made from 2010 to 2014, that the goal of an average EI=1.25 for the Dutch non-profit housing stock will not be met in 2020. Filippidou et al. (2016) concluded that housing associations in the period up to 2014 generally did not carry out major renovations, but many smaller investment projects, mostly as part of planned maintenance work. The most frequently applied changes are heating, hot water installations, and glazing. Other researchers have differing views to which extent energy performance measures need to be implemented in small or large-scale renovations or whether demolition and new construction are better alternatives (Thomsen & Flier, 2009; Nieboer, 2016).

Several elements of the development of the energy performance of Dutch non-profit housing associations are unclear. First, it is not clear how the energetic quality develops between 2017 and 2020. Alleviating this knowledge gap helps to understand which energy-saving measures are applied and how they contribute to the sustainable development. Second, the effects of changes of the stock (construction and demolition) were not examined in previous studies. Alleviating this knowledge gap helps other researchers to estimate the effect of construction and demolition on the improvement of the energy performance of the housing stock compared to renovations of the housing stock. Third, it is unknown which characteristics of housing associations, for example, the size, financial position, or location, explain the improvement of the average energy performance of the non-profit housing sector. Alleviating this knowledge gap helps other researchers to assess the development of housing stocks owned by non-profit organizations in other European Countries as well. Fourth, it is not clear if the agreed goal for the Dutch non-profit housing stock is met in 2020. Alleviating this knowledge gap is useful within the Dutch societal context. These unclear elements lead to the following research questions:

1. How did the energetic quality of the Dutch non-profit housing stock develop between 2017 and 2020?

2. What is the effect of changes of the stock (construction and demolition) and changes within the stock (renovations) on the energy performance of the Dutch non-profit housing stock from 2017 to 2020?

3. How do characteristics of non-profit housing associations explain the progress of the energy performance of the non-profit housing sector from 2017 to 2020?

4. Did the Dutch non-profit housing sector meet its agreed goal on the average energy performance in 2020?

2.2 Data & Method

In Europe, countries have their own data and methods to monitor the energy performance of their building stock. In the Netherlands, Aedes (the Dutch umbrella organization of housing associations) started in 2010 a monitoring system for dwellings of non-profit housing associations called *Sociale Huursector Audit en Evaluatie van Resultaten Energiebesparing* (Social Rented Sector Audit and Evaluation of Energy Saving Results) abbreviated SHAERE, which was used by the TU Delft for research purposes (Filippidou et al., 2017). After the change of the method in 2015, the structure of data collection changed. In collaboration with Aedes data collection started in 2017. Every housing association was asked to voluntarily deliver a structured dataset of their dwellings annually. This was supported by two software providers which offer data management software for the energy performance of dwellings in the Dutch non-profit housing sector. The data collected is not the official energy label, which is stored in the national energy label database as opposed to other researchers using national energy label databases e.g. (Hjortling et al., 2017; Streicher et al., 2018; Ahern & Norton, 2019). The Dutch national database contains the energy labels of dwellings which are approved mostly once every ten years and have different underlying calculation methods, as mentioned in Table 2.1. Differences between the calculation methods make it unreliable to compare dwellings.

The energy performance of dwellings and the underlying building characteristics were collected under the calculation method in force between 2015 and 2020, the NEN 7120 NV. This is the latest, most up-to-date data, although not officially approved in the national energy label database. In this data, all dwellings are comparable under the same measurement scale and are comparable with the average sector goal of an average energy label B in 2020, an average energy-index NV of 1.40.

Figure 2.1 shows the number of Dutch housing associations and dwellings that were analysed between 2017 and 2020. From every dwelling the energy-index NV (NEN, 2014) is available, with relevant clarifying indicators: building year, building type, thermal capacity, heat loss coefficient and heat loss area of floor, roof, façade, windows, and doors, airtightness of the building envelope, ventilation system, heating system, heating system temperature, tap water system, cooling system, solar panels area, and solar heating area. This dataset is the main source of data for this article.

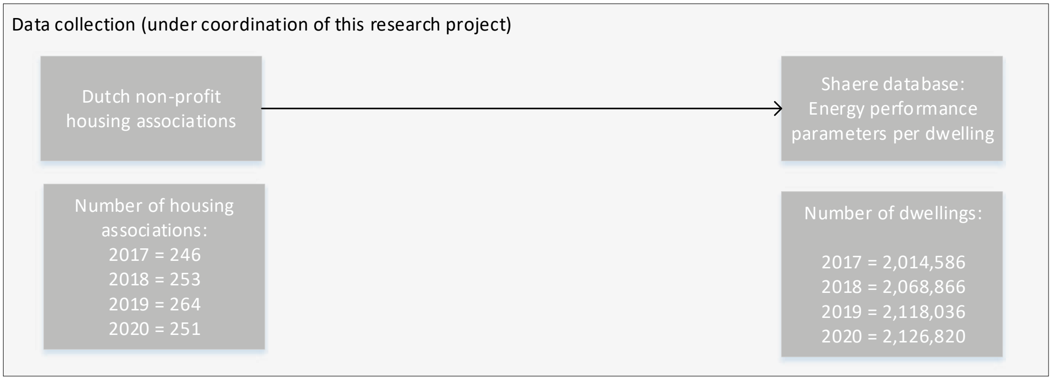

FIG. 2.1 Data collection

There are quality issues involving the reliability and discrepancies in EPCs and therefore caution must be advised when using this data. For example, Hårsman et al. (2016) and Hardy and Glew (2019) analysed the quality of official EPC's in Sweden and the UK respectively. Hardy and Glew (2019) describe inconsistencies present in energy performance certificates through lodgement errors and discrepancies in building characteristics by comparing registered EPC's from the same dwelling. They estimate an error range of 36 to 62% of all registered EPC's. Hårsman et al. (2016) conclude that the quality of firms who assess and issue the EPC has a big influence on the quality of the issued EPC's. These quality issues are expected to occur in the present dataset as well, although Dutch housing associations are obliged to use certified assessors for all energy performance calculations, to assure data quality.

Second, a dataset with descriptive parameters of housing associations was made available for this research by Aedes. From every housing association systematic information is available on: the size (classification of number of dwellings), location (province), financial position (sufficient, mediocre, weak) based on information of the Dutch guarantee fund of the non-profit housing sector, and degree of urbanity (rural to urban).

The average energy-index of 2017, 2018, 2019, and 2020 is calculated as the mean of the available dwellings in the SHAERE database. The improvement of the energy-index year by year is explained by discussing changes of the sample, changes of the stock, and changes within the stock (Figure 2.2). Hereafter, the improvement of the energy-index year by year is explained with the characteristics of housing associations (Figure 2.2). The results are described in the next section.

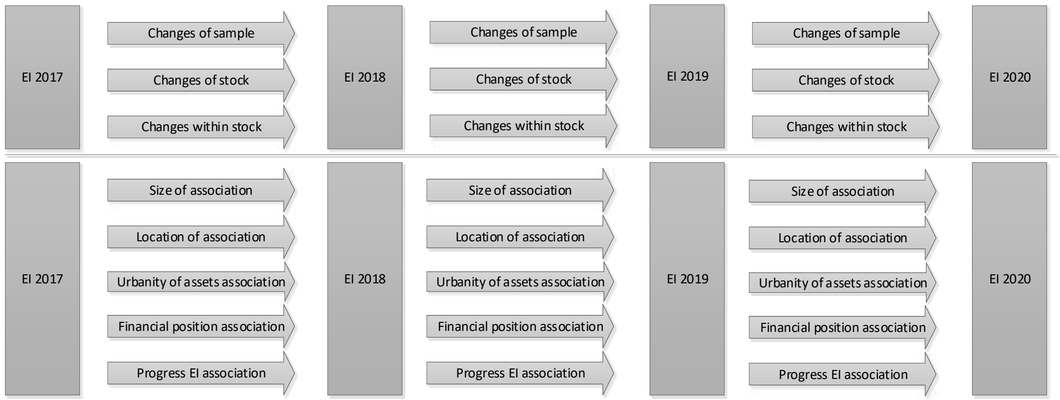

FIG. 2.2 Method

2.3 Results

The results are presented in four sections. First, the average state of the Dutch non-profit housing stock from 2017 to 2020 is described, to give insights into the sustainable development of the Dutch non-profit housing stock. Second, the changes of the sample, changes of the stock, and changes within the stock are presented to give insights into the contribution of construction, demolition, and the renovation of existing dwellings to the improvement of the average energy performance. Third, the characteristics of housing associations are considered, to give insights into how the size and nature of housing associations influence the progress of the average energy performance. Fourth, the actual progress made between 2017 and 2020 is assessed in relation to the agreed goal of an energy-index of 1.40 in 2020.

2.3.1 The state of the Dutch non-profit housing stock

The development of the stock from 2017 to 2020 is explained by the characteristics of the dwellings in the SHAERE database. This includes the energy-index, general characteristics, average level of insulation, heating and tap water systems, ventilation systems, solar systems, and cooling systems.

Energy-index: Table 2.2 shows that the average energy-index NV improves between 2017 and 2020 from an average of 1.73 to an average of 1.51 in 2020.

TABLE 2.2 Energy-index

	2017	2018	2019	2020	Δ'17-'20
Average EI NV	1.73	1.65	1.57	1.51	-0.22

Energy Performance Certificate: The energy-index is classified into classes. Table 2.3 shows that dwellings with an Energy Performance Certificate A++ to B, which are better than the Dutch goal of an energy-index of 1.40, improve with around 6% annually to 47.8% of the total stock of dwellings of non-profit housing associations in 2020.

TABLE 2.3 Energy Performance Certificates

% of stock in classes	2017	2018	2019	2020	Δ'17-'20
Label A++ (EI NV=<0.60)	0.3%	0.5%	1.0%	1.5%	1.1%
Label A+ (EI NV=0.61-0.80)	0.9%	1.3%	1.8%	2.5%	1.6%
Label A (EI NV=0.81-1.20)	13.9%	17.2%	21.1%	24.5%	10.6%
Label B (EI NV=1.21-1.40)	15.5%	17.5%	18.8%	19.3%	3.8%
Label C (EI NV=1.41-1.80)	31.7%	31.5%	30.0%	28.3%	-3.3%
Label D (EI NV=1.81-2.10)	16.4%	14.8%	13.2%	11.9%	-4.4%
Label E (EI NV=2.11-2.40)	10.1%	8.8%	7.5%	6.6%	-3.5%
Label F (EI NV=2.41-2.70)	5.7%	4.6%	4.6%	3.1%	-2.7%
Label G (EI NV>2.71)	5.5%	3.8%	3.8%	2.2%	-3.3%

General characteristics: The general characteristics of dwellings of non-profit housing associations change slightly over the years (Table 2.4). The share of apartments increases slightly and also the average size of single dwellings increases by 2.0 m^2. The building type in the Netherlands is 98.6% heavy, which means concrete or bricks. The airtightness of the dwellings improves significantly over the years.

TABLE 2.4 General Characteristics

Characteristics	2017	2018	2019	2020	Δ'17-'20
Apartments (% stock)	54.9%	56.8%	57.1%	57.5%	2.6%
Single dwelling (% stock)	45.1%	43.2%	42.9%	42.5%	-2.6%
Apartment size m^2	71.1	71.2	71.1	71.1	0
Single dwelling size m^2	92.8	93.7	94.3	94.8	2.0
Building type heavy (% stock)	98.0%	98.5%	98.6%	98.6%	0.6%
Airtightness QV10 $dm^3/s.m^2$	2.08	1.90	1.83	1.75	-0.33

Insulation: The degree of insulation of the dwellings improves between 2017 and 2020, however, the absolute levels of insulation are on average still quite low (Table 2.5). Looking at floor insulation, 50.8% of the stock has poor or no insulation present. Another 25.2% has an insulation degree up to R=2.00 m^2K/W, which is still a poor insulation grade. Insulation levels of the facade are slightly higher, but still, large portions of the stock have a (very) poor quality, 26.3% and 46.8% respectively. Insulation levels of the roof are a bit higher, but 20.5% and 42.0% have a (very) poor insulation quality in 2020. The insulation of glazing is measured in the U-value. The levels of insulation are for a large part better than double glazing, however in 2020 single glazing can be found in 32.8% of the stock. In 2020 1.6% of the dwellings have only single glazing, 6.3% have more than 50% of the glazing area with single glazing and another 24.9% have double glazing, but with less than 50% of the glazing area with single glazing. The insulation of doors is not very common with only 5.3% being insulated. When compared with minimum requirements in the Dutch building code 2015 for newly built dwellings, the floor (R=3.5 m^2K/W), facade (R=4.5 m^2K/W) roof (R=6.0 m^2K/W), glazing/doors (U=1.65 W/m^2K), a very large part of the stock is below these requirements.

TABLE 2.5 Level of insulation

	2017	2018	2019	2020	Δ'17-'20
	(% stock)	(% stock)	(% stock)	(% stock)	(% stock)
Floor					
No or very poor (R=0-1 m^2K/W)	52.7%	52.0%	51.2%	50.8%	-1.8%
Poor quality (R=1-2 m^2K/W)	26.1%	25.8%	25.6%	25.2%	-0.9%
Weak quality (R=2-3 m^2K/W)	14.4%	14.7%	14.8%	14.8%	0.4%
Average quality (R=3-4 m^2K/W)	4.5%	5.0%	5.4%	5.8%	1.3%
Good quality (R=4-5 m^2K/W)	1.4%	1.5%	1.8%	2.0%	0.5%
High quality (R=>5 m^2K/W)	0.9%	1.0%	1.2%	1.5%	0.6%

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TABLE 2.5 Level of insulation

	2017 (% stock)	2018 (% stock)	2019 (% stock)	2020 (% stock)	Δ'17-'20 (% stock)
Facade					
No or very poor (R=0-1 m²K/W)	28.9%	28.0%	27.3%	26.3%	-2.6%
Poor quality (R=1-2 m²K/W)	47.4%	47.1%	46.8%	46.8%	-0.6%
Weak quality (R=2-3 m²K/W)	17.3%	17.7%	17.9%	18.2%	0.9%
Average quality (R=3-4 m²K/W)	4.6%	5.0%	5.3%	5.5%	0.9%
Good quality (R=4-5 m²K/W)	1.3%	1.5%	1.8%	2.0%	0.7%
High quality (R=>5 m²K/W)	0.5%	0.6%	0.9%	1.2%	0.6%
Roof					
No or very poor (R=0-1 m²K/W)	25.8%	23.9%	22.2%	20.5%	-5.4%
Poor quality (R=1-2 m²K/W)	43.8%	43.7%	42.9%	42.0%	-1.8%
Weak quality (R=2-3 m²K/W)	20.3%	21.3%	21.7%	22.0%	1.7%
Average quality (R=3-4 m²K/W)	6.3%	6.8%	7.6%	8.3%	2.0%
Good quality (R=4-5 m²K/W)	2.2%	2.4%	2.8%	3.2%	1.0%
High quality (R=>5 m²K/W)	1.6%	2.0%	2.9%	4.0%	2.5%
Glazing					
Single glazing (U>5.11 W/m²K)	2.6%	2.1%	1.8%	1.6%	-0.9%
>50% single glazing (U=4.01-5.10 W/m²K)	7.7%	7.2%	6.9%	6.3%	-1.3%
>50% double glazing (U=2.91-4.00 W/m²K)	26.3%	26.2%	25.6%	24.9%	-1.4%
Double glazing (U=2.01-2.90 W/m²K)	40.3%	40.2%	39.5%	38.9%	-1.5%
HR+ or HR++(U=1.41-2.00 W/m²K)	22.7%	23.9%	25.6%	27.3%	4.6%
Triple glazing (U<1.40 W/m²K)	0.5%	0.5%	0.7%	1.0%	0.5%
Doors					
Not insulated (U>2.01 W/m²K)	95.0%	95.0%	94.9%	94.7%	-0.3%
Insulated(U=<2.00 W/m²K)	5.0%	5.0%	5.1%	5.3%	0.3%

Heating and tap water systems: The heating systems in dwellings of Dutch non-profit housing associations are mostly condensing gas boilers (Table 2.6). The condensing HR107 gas boiler is most popular with 79.8% of the total housing stock in 2020. This percentage is still increasing, while lower efficiency gas boilers such as the conventional non-condensing gas boiler (CR) and improved non-condensing gas boiler (VR) are replaced. More innovative heating systems such as combined heat and power systems (CHP), external heat, heat pumps, or biomass systems are slowly gaining ground in the Dutch non-profit housing sector, but the traditional heating system with gas is very dominant. The popularity of low-temperature distribution systems increases related to the uptake of innovative heating systems. However, with 4.7% this is still a small percentage. Looking at the tap water systems the popularity of the combined gas boiler systems is imminent and still rising (77.7%).

The use of older systems like geysers and electrical tap water heating systems is decreasing.

TABLE 2.6 Heating and tap water systems

	2017 (% stock)	2018 (% stock)	2019 (% stock)	2020 (% stock)	Δ'17-'20 (% stock)
Heating system					
Local or central electrical heating	0.1%	0.1%	0.1%	0.2%	0.1%
Local heating oil/gas/wood	2.5%	2.2%	1.7%	1.5%	-1.0%
CR non-condensing gas boiler	1.1%	0.9%	0.6%	0.5%	-0.6%
VR non-condensing gas boiler	10.8%	8.8%	6.9%	5.3%	-5.5%
HR100 condensing gas boiler	2.6%	2.1%	1.7%	1.4%	-1.2%
HR104 condensing gas boiler	1.1%	0.8%	0.7%	0.5%	-0.6%
HR107 condensing gas boiler	72.6%	75.6%	78.1%	79.8%	7.2%
Combined heat and power, CHP	0.2%	0.2%	0.2%	0.1%	-0.1%
External heat	7.3%	7.5%	7.7%	8.0%	0.7%
Heat pump	1.6%	1.8%	2.2%	2.6%	1.0%
Biomass	0.0%	0.0%	0.1%	0.1%	0.1%
Heating system temperature					
High	87.1%	86.9%	86.6%	86.0%	-1.1%
Low	3.6%	3.8%	4.3%	4.7%	1.1%
Unknown	9.3%	9.3%	9.2%	9.3%	0.0%
Tap water system					
Collective system	5.2%	5.5%	5.8%	5.9%	0.7%
External heat	6.0%	6.3%	6.7%	7.0%	1.0%
Electrical heating	5.1%	5.0%	5.0%	5.0%	-0.1%
Heat pump	0.7%	0.7%	0.9%	1.2%	0.5%
Gas boiler	77.3%	77.6%	77.7%	77.7%	0.4%
Geyser	5.8%	4.9%	3.9%	3.2%	-2.6%

Ventilation systems: Ventilation systems applied in the Dutch non-profit housing sector are still very traditional (Table 2.7). 32.8% have no installed ventilation system, although this is decreasing. 61.2% have a mechanical outflow system installed. Only 6.0% has a balanced ventilation system, which has mechanical inflow and outflow. Heat from outgoing air is used to preheat incoming air, thereby lowering the energy demand of a dwelling.

TABLE 2.7 Ventilation systems

	2017	2018	2019	2020	Δ'17-'20
Natural	39.5%	36.9%	34.8%	32.8%	-6.7%
Mechanical outflow	56.0%	58.1%	59.7%	61.2%	5.2%
Mechanical in/outflow	4.5%	5.1%	5.5%	6.0%	1.5%

Solar systems: Solar systems (Table 2.8) are increasingly popular in the Dutch non-profit housing sector. Photovoltaic panels increase by 1.4%, 2.6% and 3.0% annually. This is a steep rise and given only 10.4% of the dwellings have PV panels in 2020 there is still a lot of potential to raise this level. Panels to generate solar heat are less popular. 2.3% of the sector has panels for solar heating. The average size of 2.5 square meters is smaller than the PV panels with 10.2 square meters.

TABLE 2.8 Solar systems

	2017	2018	2019	2020	Δ'17-'20
Solar power					
Solar power (% stock)	3.4%	4.8%	7.4%	10.4%	7.1%
Solar power average area in m^2	8.9	9.1	10.4	10.2	1.3
Solar heating					
Solar heating (% stock)	1.9%	2.1%	2.2%	2.3%	0.4%
Solar heating average area m^2	2.4	2.4	2.5	2.5	0.1

Cooling systems: Cooling systems are not popular in the Dutch non-profit housing sector, but are slowly being adopted. 1.0% have a cooling system in 2020 (Table 2.9).

TABLE 2.9 Cooling systems

	2017	2018	2019	2020	Δ'17-'20
Cooling system (% stock)	0.5%	0.6%	0.8%	1.0%	0.5%

2.3.2 How do changes of and in the stock explain the improvement of the energy-index?

As shown in Table 2.2, the average energy-index between 2017 and 2020 improves from 1.73 to 1.51 in 2020. The difference can be explained by changes of the sample, changes of the stock, and changes within the stock (Table 2.10). The changes of the sample are responsible for a small increase of the energy-index. Changes of the stock are responsible for 15.6% of the improvement of the energy-index and the other 85.4% of the improvement is caused by changes within the stock. This is explained in the following sections.

TABLE 2.10 Improvement of the energy-index

Progress EI	ΔEI '17-'18	ΔEI '18-'19	ΔEI '19-'20	ΔEI '17-'20	%'17-'20
Changes of the sample	+0.002	0.000	0.000	+0.002	0.9%
Changes of the stock	-0.013	-0.012	-0.009	-0.034	-15.6%
Changes within the stock	-0.071	-0.061	-0.054	-0.186	-85.4%
Total change	-0.082	-0.073	-0.063	-0.218	-100%

Changes of the sample: The change of the sample of housing associations in the SHAERE database of 2017 and 2018 has an effect on the average energy-index between 2017 and 2018. 11 housing associations did participate in 2017 but not in 2018, and 18 new housing associations delivered data in 2018. The effect on the change in energy-index between 2017 and 2018 is EI=+0.002. This effect is positive and it means that only because of the change of the sample the EI in 2018 is 0.002 higher than in 2017. In 2019 one housing association did not participate and 13 new housing associations delivered data. In 2020 five new housing associations delivered data. However, these changes of the samples did not have a significant effect on the progress of the average EI.

Change of the stock: Table 2.11 shows that 15.6% of the improvement of the energy-index is explained by changes of the stock. This consists of newly built dwellings, purchased, sold, and demolished dwellings or administrative corrections. These are described accordingly.

TABLE 2.11 Development energy-index by changes of the stock

Progress EI	ΔEI '17-'18		ΔEI '18-'19	ΔEI '19-'20	ΔEI '17-'20	%'17-'20
New built dwellings		-0.007	-0.008	-0.006	-0.021	-9.7%
Purchase/merger/administrative		-0.001	+0.001	+0.002	+0.002	0.9%
Demolition/sale/administrative		-0.005	-0.005	-0.005	-0.015	-6.8%
Total change of the stock		-0.013	-0.012	-0.009	-0.034	-15.6%
Total change		-0.082	-0.073	-0.063	-0.218	-100%

New-build dwellings Annually non-profit housing associations built new dwellings. These dwellings appear in the SHAERE database, however with a small time delay. In this assessment, newly added dwellings between 2010 and 2020 are seen as new-build and are together responsible for 9.7% of the improvement of the energy-index (Table 2.11). The quality of these dwellings increases annually with accordingly a lower average energy-index. In table 2.12, the main characteristics of new-build dwellings from 2017 to 2020 are given. These characteristics can be seen as still quite traditional, although solar PV is a standard solution for new-build dwellings.

Purchase and administrative corrections: Dwellings can also be added to the stock by purchase or administrative corrections. It is not possible to distinguish between dwellings which are purchased or added by administrative corrections. However, with -0.9% the impact on the sectoral improvement is low.

Demolition, sale, and administrative corrections: Parallel to added dwellings, also dwellings are removed from the stock. It is not possible to identify which dwellings are demolished, sold, or removed from the data for administrative reasons because this information cannot be subtracted from the database. However, the impact of the dwellings absent in the database can be calculated by measuring the effect as if they would be present in the next year. This effect is EI -0.005 for all years. The removal of dwellings has therewith a significant impact on the improvement of the average energy-index.

TABLE 2.12 Characteristics of new built dwellings

Characteristics of new-build dwellings	2017	2018	2019	2020
Number of dwellings	11715	11286	8507	2477
Energy-index average	0.70	0.63	0.60	0.49
Heating system: Condensing gas boiler HR107	55.7%	48.0%	31.2%	17.9%
Heating system: Electrical heating	1.2%	8.8%	6.4%	8.6%
Heating system: External heat	25.1%	20.9%	19.4%	24.9%
Heating system: Heat pump	16.2%	20.9%	42.6%	48.6%
Heating system: Other	1.7%	1.4%	0.5%	0.0%
Hot tap water system: Gas boiler	58.1%	48.9%	32.0%	18.4%
Hot tap water system: Electrical	1.3%	8.3%	13.1%	10.7%
Hot tap water system: External heat	29.5%	23.3%	23.4%	26.4%
Hot tap water system: Heat pump	11.0%	19.6%	31.4%	44.5%
Hot tap water system: Other	0.0%	0.0%	0.1%	0.0%
Insulation level floor (average R in m^2K/W)	4.0	4.2	4.5	4.4
Insulation level roof (average R in m^2K/W)	5.3	5.5	5.9	6.3
Insulation level facade (average R in m^2K/W)	4.4	4.6	4.9	5.1
Insulation level windows (average U in W/m^2K)	1.7	1.7	1.4	1.7
Insulation level doors (average U in W/m^2K)	2.7	2.6	2.6	2.3
Ventilation system: Natural	7.2%	0.6%	0.1%	0.0%
Ventilation system: Mechanical outflow	67.9%	65.9%	56.3%	46.3%
Ventilation system: Mechanical in/outflow	24.9%	33.5%	43.7%	53.7%
Solar power system	61.5%	80.6%	86.2%	90.2%
Solar heating system	0.9%	0.9%	0.5%	3.3%
Cooling system	6.3%	10.3%	23.3%	22.2%

Changes within the stock: Besides changes of the sample and changes of the stock the major part of the sectoral improvement of the energy-index is due to improvements of the existing stock (85.4%). In this section, the relative importance of changes within the existing stock is explained, expressed in the contribution to the improvement of the energy-index of applied energy-saving measures. The improvement of dwellings with multiple changes is attributed evenly over these changes. Table 2.13 shows the absolute contribution of changes within the stock to the total development of the energy performance. Improved heating systems and improved insulation are responsible for a large part of the sectoral energy-index improvement. The contribution of solar systems is 10.1% and its share is rising through the years. Other minor improvements which are not specified in the database (e.g. the installation of a thermostat in a dwelling), are responsible for 6.4% of the sectoral improvement.

TABLE 2.13 Development energy-index by changes within the stock

Changes within the stock	ΔEI '17-'18	ΔEI '18-'19	ΔEI '19-'20	ΔEI '17-'20	%'17-'20
Heating systems	-0.024	-0.016	-0.013	-0.052	-23.9%
Hot tap water systems	-0.009	-0.009	-0.005	-0.023	-10.6%
Ventilation systems	-0.006	-0.005	-0.005	-0.017	-7.8%
Solar systems	-0.006	-0.006	-0.010	-0.022	-10.1%
Airtightness	-0.003	-0.002	-0.003	-0.008	-3.7%
Insulation	-0.019	-0.015	-0.014	-0.049	-22.5%
Other	-0.005	-0.007	-0.002	-0.014	-6.4%
Total change within the stock	-0.071	-0.061	-0.054	-0.186	-85.4%
Total change	-0.082	-0.073	-0.063	-0.218	-100%

Innovative retrofits: We define innovative retrofits as retrofits with an innovative heating solution (CHP, Biomass, external heat, and heat pumps), added balance ventilation, or added solar systems. Table 2.14 shows the effect of these retrofits is 15.6% of the total sectoral energy-index improvement.

TABLE 2.14 Development energy-index by innovative retrofits

Innovative retrofits	ΔEI '17-'18	ΔEI '18-'19	ΔEI '19-'20	ΔEI '17-'20	%'17-'20
CHP, biomass, external heat, heat pumps	-0.004	-0.003	-0.004	-0.011	-5.0%
Balanced ventilation	-0.000	-0.000	-0.000	-0.001	-0.3%
Solar systems	-0.006	-0.006	-0.010	-0.022	-10.1%
Total innovative retrofits	-0.010	-0.009	-0.014	-0.034	-15.6%
Total change	-0.082	-0.073	-0.063	-0.218	-100%

Administrative corrections: Not all improvements of the energy-index are expected to be related to actual improvements of dwellings. A portion of the improvements shown in Table 2.13 could be seen as administrative corrections. The total effect of these administrative corrections cannot be deduced from the dataset.

2.3.3 How do characteristics of housing associations explain the improvement of the EI?

This section explains how different characteristics of housing associations explain the improvement of the energy-index between 2017 and 2020. The key factors are size, location, degree of urbanity, and financial position. In tables 2-15 to 2-18 for each characteristic the following are shown: the average energy-index 2017-2020, the average percentage of dwellings of the stock, the total improvement of the energy-index 2017-2020, and the percentage of the contribution of the energy-index improvement to the improvement of the total stock.

Size of the housing association. Looking at the size of housing associations shows the importance of the order of magnitude (Table 2.15). On average large housing associations (XL>25000 dwellings) have a high energy-index. They are the only group higher than the average of the total sector in every year. Together they own 35% of the non-profit housing stock. However, because of their size they are also responsible for a large part (39%) of the total sector improvement.

TABLE 2.15 Progress energy-index by size of housing association

Size in number of dwellings	Average EI 2017	Average EI 2018	Average EI 2019	Average EI 2020	Average % stock	ΔEI '17-'20	% ΔEI '17-'20
XL (>25000)	1.80	1.70	1.63	1.56	35%	-0.24	39%
L (10000-25000)	1.71	1.64	1.56	1.50	29%	-0.21	28%
M (5000-10000)	1.71	1.63	1.55	1.49	22%	-0.22	22%
S (2500-5000)	1.59	1.54	1.47	1.42	9%	-0.17	7%
XS (1000-2500)	1.59	1.53	1.46	1.40	4%	-0.20	3%
XXS (<1000)	1.62	1.58	1.48	1.42	0%	-0.19	0%
Total sector	1.73	1.65	1.57	1.51	100%	-0.22	100%

Location of the housing association. Looking at the location of housing associations across the Netherlands by province it shows the order of magnitude as well (Table 2.16). Two provinces (Noord-Holland and Zuid-Holland) have 45% of the non-profit housing stock and both have an average EI higher than average. Together they are responsible for 49% of the progress between 2017 and 2020. In some provinces good progress has been made (Utrecht, Limburg, Groningen, Drenthe) or has been made in the past (Flevoland, and Gelderland), but because of the order of magnitude the impact of these provinces is overshadowed by the provinces Noord-Holland and Zuid-Holland.

TABLE 2.16 Progress energy-index by location

Province	Average EI 2017	Average EI 2018	Average EI 2019	Average EI 2020	Average % stock	ΔEI '17-'20	% ΔEI '17-'20
Noord-Holland	1.79	1.68	1.58	1.52	22%	-0.27	27%
Zuid-Holland	1.81	1.72	1.66	1.60	23%	-0.21	22%
Noord-Brabant	1.64	1.58	1.54	1.48	14%	-0.16	11%
Limburg	1.74	1.67	1.58	1.48	7%	-0.25	8%
Utrecht	1.84	1.73	1.65	1.58	6%	-0.26	7%
Gelderland	1.56	1.51	1.46	1.41	10%	-0.15	7%
Overijssel	1.65	1.58	1.50	1.46	6%	-0.20	5%
Friesland	1.71	1.65	1.59	1.50	4%	-0.20	4%
Groningen	1.80	1.72	1.56	1.47	2%	-0.33	4%
Drenthe	1.63	1.55	1.46	1.35	2%	-0.28	3%
Zeeland	1.68	1.56	1.50	1.44	2%	-0.25	2%
Flevoland	1.41	1.35	1.28	1.24	1%	-0.17	1%
Total sector	1.73	1.65	1.57	1.51	100%	-0.22	100%

Degree of urbanity of the assets of the housing association. Looking at the address density of dwellings of housing associations, the same pattern arises as with the size and location of housing associations (Table 2.17). A large part (almost 70%) of the stock is located in dense cities which also have on average dwellings with the highest energy-index. Housing associations operating in areas with a lower address density have a better energy-index, but are still higher than the average goal of 1.40.

TABLE 2.17 Progress energy-index by address density

	Average EI 2017	Average EI 2018	Average EI 2019	Average EI 2020	Average % stock	ΔEI '17-'20	%ΔEI '17-'20
Urban	1.83	1.71	1.65	1.58	36%	-0.25	40%
Urban-suburban	1.72	1.65	1.55	1.50	33%	-0.22	34%
Suburban	1.61	1.55	1.50	1.46	12%	-0.15	8%
Suburban-rural	1.63	1.57	1.51	1.43	16%	-0.20	15%
Rural	1.69	1.60	1.51	1.44	3%	-0.24	3%
Total	1.73	1.65	1.57	1.51	100%	-0.22	100%

Financial strength of the housing association. Looking at the financial strength of housing associations, it shows that the group of housing associations with a weak financial strength have a high energy-index (Table 2.18). However, the sector impact is modest, because it is a relatively small percentage of the total housing stock.

Housing associations with sufficient and mediocre financial strength are largely responsible for the progress of the sector.

TABLE 2.18 Progress energy-index by financial strength

	Average EI 2017	Average EI 2018	Average EI 2019	Average EI 2020	Average % stock	ΔEI '17-'20	%ΔEI '17-'20
Sufficient	1.70	1.61	1.57	1.51	45%	-0.18	37%
Mediocre	1.74	1.67	1.56	1.49	51%	-0.25	56%
Weak	1.90	1.73	1.73	1.71	5%	-0.19	4%
Total	1.73	1.65	1.57	1.51	100%	-0.22	100%

2.3.4 How does this relate to the goal of the energy performance of 1.40?

The research of Filippidou et al. (2017) shows that the annual improvement of the energy-index followed a linear line between 2010 and 2015. The goal was an average EI=1.25 (Figure 2.3). In 2015 the determination method of the energy-index changed (NEN, 2014). Also, the related goal changed to an average EI of 1.40 for housing associations in 2020 (Blok, 2016).

With an average energy-index of 1.51 halfway 2020 and a linear extrapolation, the goal of EI=1.40 is not achieved in the year 2020 but can be achieved at the end of 2021.

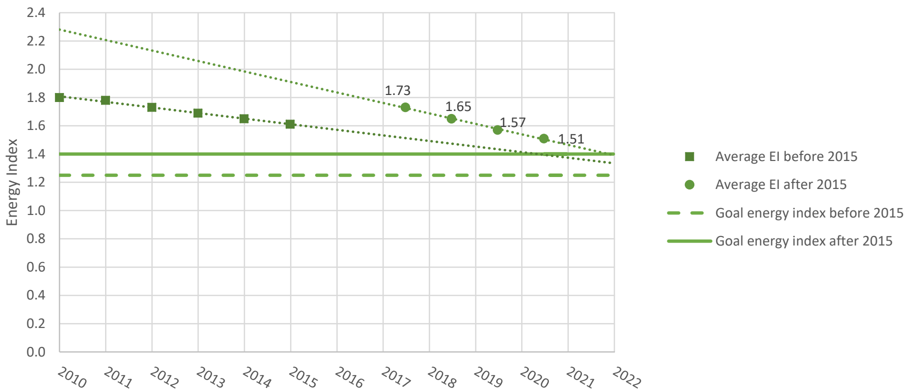

FIG. 2.3 Progress average energy-index Dutch non-profit housing sector

2.4 Discussion

This assessment gives insights into the energy performance of the Dutch non-profit housing sector over the period 2017 to 2020. The stated research questions could be answered with an analysis based on a large and consistent dataset. However, several studies have shown that the estimation of the theoretical energy consumption within the energy-index can deviate strongly from actual energy consumption and could lead to the systematic overestimation of potential energy savings. The realized savings in actual energy consumption are lower than expected, and thus also lower saved CO_2 emissions (Sunikka-Blank & Galvin, 2012; Laurent et al., 2013; Saunders, 2015; Galvin & Sunikka-Blank, 2016; Summerfield et al., 2019). Based on previous research (Santin, 2010; Majcen et al., 2016; Filippidou et al., 2019), this performance gap is expected to be present in the Dutch non-profit housing sector between 2017 and 2020 as well. Closing the performance gap between theoretical and actual energy consumption needs continuous efforts, to improve the accuracy of predictions of actual energy savings by constructing new dwellings and renovating the existing housing stock.

As described in the introduction, other researchers reported on the energy performance of (parts of) national housing stocks as well: (Csoknyai et al., 2016; Gangolells et al., 2016; Serghides et al., 2016; Hjortling et al., 2017; Streicher et al., 2018; Ahern & Norton, 2019). These assessments of the sustainable state of (parts of) housing stocks in Europe give useful insights for the development of future policies. Without a comparable research framework and research period is it difficult to draw conclusions about differences between the energetic quality of the different housing stocks, and more specifically non-profit housing stocks. What our research adds to these other researches is the development of the energy performance over time, together with a description of the change in the underlying building characteristics and their contribution to the change in energy performance. Other researchers present static descriptions of housing stocks. Monitoring the annual rate of change enables adapting strategies to speed up the improvement of the building stock as it shows which measures currently have, or don’t have a substantial impact. Ditto, monitoring the effects of demotion and construction of dwellings helps to assess the impact of this strategy. Monitoring the contribution of characteristics of housing associations is especially useful within the Dutch context. Housing associations own one-third of all Dutch dwellings and have a high level of organization compared to private homeowners. Therefore housing associations act as a flywheel in the acceleration towards a Dutch sustainable built environment.

Although other European countries usually have a smaller non-profit housing stock (Housing Europe, 2017), taking a closer look at the contribution of housing associations within their national context could be beneficial as well.

At last, as shown in table 2.1, in 2021 the Dutch definition of the energy performance of dwellings changed once more with the new calculation method, the NTA8800. This will make it more difficult to extrapolate findings based on the energy-index to future monitoring of the energy performance of dwellings of Dutch non-profit housing associations. However, the underlying building parameters will not change. Future policies for Dutch non-profit housing associations based on the Dutch Climate Agreement (*National Climate Agreement*, 2019) will focus on building parameters of dwellings instead of an average sectoral energy performance. Examples of these policies are the “Startmotor” (100.000 dwellings on district heating), the “Renovatieversneller” (acceleration of the renovation speed by grouping projects), and the “Standaard” (a maximum energy demand for the building envelope). These policies benefit from a continuation of a detailed monitoring system like SHAERE.

2.5 Conclusions

We analyzed the role of Dutch non-profit housing associations in delivering change, towards a more sustainable built environment. We found that the energy performance of dwellings of Dutch non-profit housing associations improved steadily between 2017 and 2020 nearly reaching the goal of an average energy-index of 1.40 in 2020. Housing associations deliver change by improving the energetic quality of their dwellings. The effect of changes of the stock (construction and demolition) to the improvement of the average energy performance is modest (15.6%). The improvement of the average sectoral energy performance happens for 85.4% within the existing stock, mostly with traditional improvements like changing heating installations and adding insulation. Innovative solutions like photovoltaic solar systems, combined heat and power systems, biomass systems, heat pumps, and external heating, are responsible for a relatively small part of the sectoral improvement (15.6%). The influence of these innovative systems in the future could be significantly higher, with the already found positive rate of change of photovoltaic systems and the steady growth of heat pumps and external heating. We also found that large urban housing associations drive the improvement of the average sectoral energy performance. These housing associations own a large share of the stock, have on average a lower energetic quality, but also make more progress between 2017 and 2020. Differences between housing associations in different regions ask for a more diverse policy approach beyond 2020. Future policies as pursued by the Dutch Climate Agreement (*National Climate Agreement*, 2019) could accommodate this diversification. Future policies benefit from continuous monitoring of the energetic quality of the building stock, like the SHAERE monitoring system. The monitoring system shows which measures currently have, or don’t have, a substantial impact, therewith enabling the adaptation of strategies to speed up the improvement of the building stock. This not only applies to the Dutch non-profit housing stock but to all building stocks moving towards a sustainable future.

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Competing interests

The authors have no competing interests to declare.

Author contributions

The first author was responsible for conceptualization, data collection, methodology, analysis, and writing. The second author was responsible for funding, review, and editing. The third and fourth authors contributed in review and editing.

Availability of data

Data used in the research project is not publically available, due to restrictions of ownership.

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3 The energy performance of dwellings of Dutch non-profit housing associations

Modelling actual energy consumption

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ABSTRACT

In Europe, the energy performance of dwellings is measured using theoretical building energy models based on the Energy Performance of Buildings Directive (EPBD), which estimates the energy consumption of dwellings. However, literature shows large performance gaps between the theoretically predicted energy consumption and the actual energy consumption of dwellings. The goal of this paper is to investigate the extent to which empirical models provide more accurate estimations of actual energy consumption when compared to a theoretical building energy model, in order to estimate average actual energy savings of renovations. We used the Dutch non-profit housing stock to demonstrate the results. We examined three empirical models to predict the actual energy consumption of dwellings: a linear regression model, a non-linear regression model, and a machine learning model (GBM). This paper shows that these three models alleviate the performance gap by giving a good prediction of actual energy consumption on sectoral cross-sections. However, these models still have shortcomings when predicting the effects of specific renovation interventions, for example newly introduced heat pumps.

The non-linear and machine learning model (GBM) outperform the theoretical model in terms of estimating energy savings through renovation interventions.

KEYWORDS Energy performance, non-profit housing, empirical prediction models, actual energy consumption

HIGHLIGHTS
– Modelling energy savings of renovations in the Dutch non-profit housing stock
– Assessment of 1.6 million dwellings, 21 building features and 3 empirical models
– Empirical models outperform the theoretical building energy model
– Shortcomings exist when predicting effects of specific energy-saving interventions

3.1 Introduction

The Energy Performance of Buildings Directive (EPBD) (European Commission, 2010) aims to decrease the energy consumption and related carbon emissions of buildings. This directive provides standards for the energy performance of buildings. The NEN 7120 (NEN, 2014) is the Dutch translation of the energy performance of buildings standards that was in force between 2011 and 2020. The NEN 7120 describes a theoretical building energy model of the energy consumption of dwellings (henceforth: 'the theoretical model'). This theoretical energy consumption model provides the basis for the energy labels granted to dwellings, ranging from A to G (with A being the best label). In the Netherlands, objectives to decrease the energy consumption of dwellings were prescribed in accordance with this theoretical model in the so-called Energy Agreement 2008, which was an Agreement between relevant stakeholders, such as government agencies, NGOs and big companies (VROM, 2008), and they were updated in 2013 (Sociaal Economische Raad, 2013). For non-profit housing associations, it was agreed that an average B-grade energy label would be achieved by 2020. No agreements were made to achieve actual energy consumption reduction or to achieve any analogous actual carbon emission reductions. Several studies in the Netherlands and in Europe have shown that the results of forecasting actual energy consumption, using the theoretical model, can deviate strongly from reality and lead to systematic overestimation of potential energy savings (Sunikka-Blank & Galvin, 2012), (Filippidou, Nieboer, & Visscher, 2019). This leads to a performance gap between the theoretical energy consumption and the actual energy consumption of dwellings.

3.1.1 The performance gap in a European context

This performance gap between theoretically-calculated energy consumption in accordance with the EPBD and actual energy consumption was already identified in the early stages of the conceptualisation of the legislation. Two reasons for the performance gap are the “prebound effect” and “rebound effect”. The prebound effect means a lower energy consumption than theoretically assumed in buildings with a poor energy performance because inhabitants do not heat the whole dwelling. The rebound effect means that dwellings with a high energy performance use more energy than theoretically assumed, because inhabitants think that the dwelling is energy efficient. A study in 2012 on 3,400 German homes indicates the existence of these effects (Sunikka-Blank & Galvin, 2012). This study concluded that dwellings use 30% less actual heating energy compared to the theoretical model, identified as the prebound effect. Contrarily, the rebound effect was identified in buildings with a high-energy performance standard. Saunders (2015) reveals the presence of very large energy efficiency rebound magnitudes, calling into question the energy use forecasts relied upon by international bodies investigating climate change mitigation policies. Laurent et al. (2013) compared theoretical energy consumption from national standard energy performance calculations to the actual consumption of four European countries: The United Kingdom, France, Germany, and The Netherlands. The reasons for the difference in theoretical and actual consumption are discussed in terms of behaviour, technological performance and the application of the theoretical models. They also point out the possible effect when theoretical calculations are used in European and national energy efficiency policies. The paper provides examples of the potential impact of using calculations grounded on empirical data instead of on calculation based on normative assumptions. In later research, a connection was made to fuel poverty, where the inhabitants of dwellings do not have sufficient financial means to fully heat their dwellings (Galvin & Sunikka-Blank, 2016). They conclude that low income, in combination with a high prebound effect, suggests fuel poverty. Aranda, Zabalza, Llera-Sastresa, Scarpellini, and Alcalde (2018) investigate the performance gap for social housing and found that the gap is larger in social housing. Considering the characteristics of social housing and the different consumption patterns of households with a more vulnerable economic status, they demonstrate that this type of household usually lives in surroundings at a temperature below the average thermal comfort level, and found that the prediction by the theoretical simulation was 40% to 140% higher than the actual energy consumption. A study conducted in the United Kingdom (Summerfield et al., 2019) modelled energy demand and energy ratings and compared these with gas consumptions across the English residential sector. They conclude that energy labelling and national theoretical energy models are useful for energy policies, but limited empirical validation of energy estimations are available in the housing sector.

The study used a data sample of 2.5 million gas-heated dwellings in the United Kingdom and compared the theoretical and actual energy consumption. The data suggests savings from upgrading dwellings to at least a C-grade energy label would be substantially lower than expected. Cozza et al. (2020) also found large rebound and prebound effects in Switzerland. These findings raise questions regarding assumptions used in models and EPC ratings, including occupancy and space heating patterns, and have implications for the development of energy models and policy regarding energy efficiency programmes.

3.1.2 The performance gap in Dutch social housing

In this study, we use the performance gap in Dutch dwellings provided by non-profit housing associations as a case study. The performance gap between theoretical and actual energy consumption has been studied for the Dutch social housing sector as well (Santin, 2010), (Majcen, Itard, & Visscher, 2013), (Itard & Majcen, 2014), (Majcen, Itard, & Visscher, 2016), (van den Brom, Meijer, & Visscher, 2018), (Filippidou et al., 2019). Santin (2010) investigates the effect of building factors and occupant behaviour on the actual energy consumption of dwellings by using linear regression methods. Majcen, Itard, & Visscher (2013) extend this research by examining the difference between theoretical and actual consumption, also using linear regression methods. They conclude that large differences are present. Itard & Majcen (2014) implement this knowledge for housing associations in Amsterdam and conclude that actual gas consumption for the D to G-grade labels is considerably lower than the theoretical consumption. For G-grade labels, the theoretical consumption is about 2.5 times higher than actual consumption. They also conclude that the actual gas consumption for D, E, F and G-grade labels is virtually identical. Hereafter, (Majcen et al., 2016) took a closer look at dwellings that were renovated between 2010 and 2013, available in the SHAERE database of the Dutch non-profit housing stock, which contains 300,000 dwellings in this period. Their results showed large performance gaps for dwellings with poor insulation, local heating systems, changes to condensing boiler systems and natural ventilation systems. Majcen et al., (2016) showed once more that the theoretical calculation method cannot be considered accurate compared to actual consumption. Filippidou et al. (2019) reassessed the effectiveness of energy measures based on actual consumption data with a dataset of up to 1.2 million dwellings belonging to Dutch non-profit housing associations from 2010 to 2014. Their results reveal actual energy savings through several efficiency measures and they address the importance of an accurate estimation when renovations are planned or realized. They also found that a greater number of renovations to a single dwelling lowers the effectiveness of the measures.

The actual energy savings are lower than expected, which in turn results in fewer carbon emissions being saved.

Visscher, Majcen, and Itard (2016) state that the current policy, using theoretical models which estimate the energy performance, is not sufficiently contributing to the improvement of the energy performance of the sector and that more attention should be paid to the actual performance. In 2015 an improved theoretical calculation method for the energy performance of dwellings was enforced: the so-called, “Nader Voorschrift” (in English: the Specified Regulation) (NEN, 2014). This updated calculation method has not been analysed to the same extent as the above-mentioned research between 2010 to 2015. In the cited studies, linear regression methods have been used, but more advanced forms of the modelling of actual energy consumption have not been examined.

3.1.3 Advanced modelling of actual energy consumption

The modelling of the actual energy consumption of dwellings is a subject of research in several studies. (Z. Li, Han, & Xu, 2014; Sun, Haghighat, & Fung, 2020; Tardioli, Kerrigan, Oates, O‘Donnell, & Finn, 2015) (X. Li & Yao, 2021) all provide frameworks to classify these models. Models are classified as white-box, grey-box and black-box models. White-box models use a theoretical structure to calculate an outcome, e.g. given the theoretical calculation according to the EPBD. These models are transparent and have an understandable behaviour. Grey-box models use both a theoretical structure and empirical data to estimate an outcome. Black-box models use only empirical data to build a model. A basic linear model is an example (Cozza et al., 2020), but also several advanced machine learning techniques are available to model the energy consumption of dwellings (Tardioli et al., 2015). These advanced models are promising, because, as opposed to linear models, they can model interactions between building characteristics to estimate the average actual energy consumption. This improves the accuracy of the estimation. However, these models lack transparency and understandable behaviour, as opposed to white-box models. Grey-box methods aim to combine a theoretical building model with empirical actual consumption data to build up a model to estimate the actual energy consumption of dwellings (Amasyali & El-Gohary, 2018). Promising examples are given by Hörner and Lichtmeß (2017), calibrating theoretical estimations with six empirically derived parameters, and by (van den Brom, 2020), calibrating theoretical estimations with fourteen empirically derived parameters.

Several studies explored and created actual energy consumption models. These models vary in purpose, method, number of dwellings and number of features. Some of these studies have a localised and more case-specific purpose to estimate the actual energy consumption of a group of dwellings e.g. (Amasyali & El-Gohary, 2016), (X. Li & Yao, 2021). These studies usually have a smaller number of dwellings, but can have a higher number of building features. Other studies have a more general purpose and try to create a model to estimate actual energy consumption for a broader part of the building stock (Kontokosta & Tull, 2017), (Robinson et al., 2017). These studies have a higher number of dwellings, but usually have a smaller number of building features, because detailed information is not available for all dwellings. In both localized, case-specific modelling, and in general modelling, different forms of white, grey and black-box models are applied. Linear regression models are often used as a baseline in research. Non-linear models could be used to combine empirical data with a theoretical structure and several black-box machine learning techniques are available to estimate the actual consumption of dwellings. Amasyali and El-Gohary (2018) show in their research that black box modelling is becoming increasingly popular, amongst others due to the rapid increase of data availability. Amasyali and El-Gohary (2018) also mention that black box models can be used for different purposes. Black box models focussing on the residential sector require more attention since the research efforts on this area are (compared to other areas) still limited. There are different modelling techniques that can be applied for data-driven modelling. Bourdeau et al. (2019) identified six single techniques: autoregressive models, statistical regressions, k nearest neighbours, decision trees, support vector machines and neural networks, or combinations of these methods. The most suitable method for a data-driven model is depending on the types of buildings, available data, modelling purpose, required accuracy and foresting horizon. A universal protocol to select the most optimal method is still lacking (Bourdeau et al., 2019).

3.1.4 Purpose of this research

The goal of this paper is to investigate the extent to which empirical models provide more accurate estimations of actual energy consumption when compared to a theoretical building energy model, in order to estimate average actual energy savings of renovations. We define more accurate estimations as (A) average estimations on cross-sections of the non-profit housing sector closer to average actual energy consumption, (B) a higher correlation between estimated and actual consumption, and (C) a positive qualitative interpretation of estimated energy savings of renovations from a reference dwelling. We use dwellings of Dutch non-

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profit housing associations as a case study. We examined three empirical models to predict the actual energy consumption of dwellings: a linear regression model, a non-linear regression model, and a machine learning model (Gradient Boosting Model or GBM), compared them to the theoretical building energy model and the actual energy consumption.

Research questions:

1. To what extent do a linear regression model, a non-linear regression model, a machine learning model (GBM) and a theoretical building energy model differ in terms of their predictions of the actual energy consumption of dwellings?

2. To what extent do a linear regression model, a non-linear regression model, a machine learning model (GBM) and a theoretical building energy model predict the energy consumption of dwellings when individual renovation measures are analysed?

In this research, we use data from Dutch non-profit housing associations to demonstrate the potential of empirical models to reduce the performance gap. We show the results on cross-sections of the Dutch non-profit housing sector and we show a case study of a single dwelling. Reducing the performance gap will help housing associations to choose renovations based on actual energy savings. This is also helpful for policymakers to estimate the actual effects of renovations on the energy savings and corresponding saved carbon emissions.

3.2 Materials and Methods

3.2.1 Data collection

To demonstrate the potential of empirical data, the SHAERE database is used. The process of data collection and handling is schematized in Figure 3.1. Dutch non-profit housing associations voluntarily delivered a standardised dataset of their dwellings with building features derived from the theoretical energy performance calculation. The collection of the Data was performed in cooperation with Aedes, the Dutch umbrella organization of non-profit housing associations.

Data was delivered by 254 housing associations in 2017, which cover 2,006,475 dwellings. These databases are rare but not unique; for example, the UK and Denmark also have large databases which include data on building characteristics and actual annual energy consumption. Table 3.1 provides oversight of the building features per dwelling in the SHAERE database, consisting of building-related features. The Dutch Central Bureau of Statistics (CBS) collects actual energy consumption values for gas and electricity from Dutch network operators on an address level. The available data is specified in Table 3.2. The actual energy consumption data on an address level was provided by the CBS in an anonymized analysis environment, where the addresses are anonymized with an identification code. The CBS converted available addresses in the SHAERE database to the same identification codes, where after the anonymized identification codes were coupled. Data on the energy consumption of dwellings with district heating systems are not available at the CBS, hence these dwellings are not included in the analysis. The dataset was cleaned of dwellings that were missing actual energy consumption and with clear deviant building features. This delivers a dataset with 1,669,523 million dwellings, which is the main dataset for this analysis.

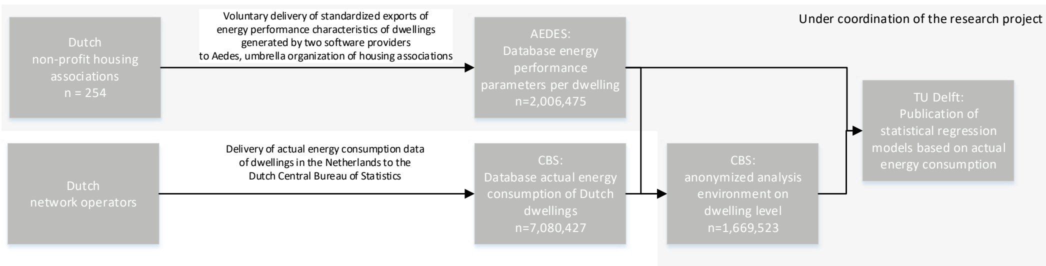

FIG. 3.1 Schematization of the data collection

TABLE 3.1 Dataset: building features

Features of dwellings	Description	Independent variables in models?
Address	Anonymized address identification code	No
Energy index NV	Classified into energy label, A++ to G	No
Theoretical energy consumption	Gas in m^3, electricity in kWh, district heating in GJ.	No
Building year	1600-2017	Linear and GBM
Building subtype	Apartments 1 level or 2 levels, with an outer shell to floor or/and roof, located in the corner or in-between, or terraced house corner or in-between, or Semi-detached, or detached.	Linear and GBM
Living area	Living are in m^2	Yes
Heat loss area: floor	Calculated by 1/insulation level floor (Rc) x floor area (m^2)	Yes
Heat loss area: roof	Calculated by 1/insulation level roof (Rc) x roof area (m^2)	Yes
Heat loss area: facade	Calculated by 1/insulation level facade (Rc) x area façade (m^2)	Yes
Heat loss area: facade to unheated spaces	Calculated by 1/insulation level facade (Rc) x area facade to unheated spaces (m^2)	Yes
Heat loss area: windows	Calculated by insulation level doors (U) x area doors (m^2)	Yes
Heat loss area: doors	Calculated by insulation level windows (U) x area windows (m^2)	Yes
Airtightness of outer shell	Calculated by QV10 ($dm^3/m^2/s$) x area of floor, roof, facade, facade to unheated spaces, windows and doors.	Yes
Ventilation system	Natural ventilation: Standard (A1), pressure control (A2). Natural in/mechanical out: (C1), time control (C3) pressure control (C4). Mechanical in/out: Standard (D1), (D1/D2), central heat recovery system (D2), time control (D4b), CO_2 control (D5b). Combined system (E1). Unknown.	Yes
Heating system	Communal, individual, district heating, unknown.	Yes
Heating generator	CR boiler, CHP, HR100 boiler, HR104 boiler, HR107 boiler, electric heating, local gas/wood/oil, micro-CHP, VR, heat pump, unknown.	Yes
Heating system temperature	High, low, very low, air, unknown.	Yes
Tap water system	Empty, communal, individual, district heating	Yes
Tap water generator	Empty, CR boiler, electric flow though, electric boiler, heat pump other source, heat pump source ventilation air, combi boiler with micro-CHP, combi boiler, boiler< 70kW, tap water boiler, geyser, HR100/HR104 boiler, HR107 boiler, VR, CHP.	Yes
Cooling system	Not present or present	Yes
Heat recovery system shower	Not present or present	Yes
PV panels area	Present in area m^2	Yes
Solar heating panels area	Present in area m^2	Yes

TABLE 3.2 Data set: actual energy consumption

Features actual consumption	Description	Independent variables in models?
Address	Anonymized address identification code	No
Actual gas consumption	Gas consumption in m^3/y	Dependent
Actual electricity consumption	Electricity consumption in kWh/y	Dependent
District heating	Not present or present	No

Estimations of theoretical energy consumption from the theoretical building model were consciously not included as parameters in the empirical models. Although this is possible, we think estimating actual energy consumption (and savings) should be based on the physical building parameters. Also characteristics of inhabitants, for example number of people, economic status, time at home, average indoor temperature and behavioural aspects, were consciously not included in the modelling, because when non-profit housing associations renovate dwellings, they want to know the average energy savings related to the building features, regardless of the characteristics of the inhabitants.

3.2.2 Method

The main dataset available in the anonymised analysis environment of the CBS was used to build up three models: a linear regression model, a non-linear regression model, and a Gradient Boosting model, which predict the actual energy consumption of dwellings for gas and electricity.

3.2.3 Linear regression model

A linear regression model was made, to give a basic understanding of the relationship between the building features and the actual energy consumption. However, a linear regression model is not equipped to deal with interactions between features, and therefore will not be able to detect underlying relations between building features, for example between the level of insulation and the performance of the source of heat generation. A linear regression model, as schematized in Figure 3.2, was used to estimate gas consumption and electricity consumption.

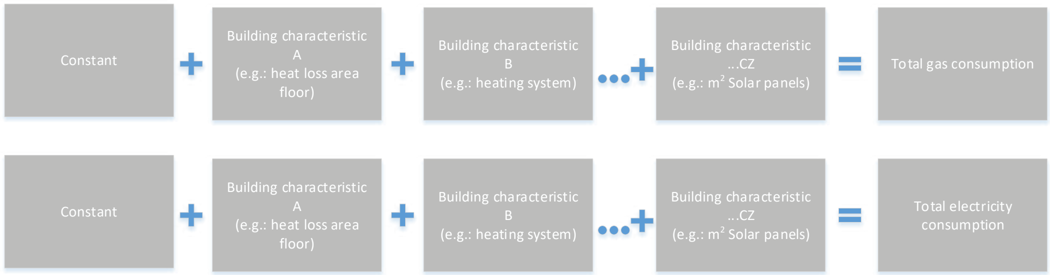

FIG. 3.2 Schematization of linear regression

3.2.4 Non-linear regression model

Secondly, a non-linear regression model was made. This provides a more accurate reflection of how building features relate to the actual energy consumption. The model structure follows a breakdown of gas consumption in heating and hot tap water, and the electricity consumption follows a breakdown in electricity used for heating (if applicable) and electric consumption for installations and household consumption. This is fairly similar to the EPBD's theoretical energy performance calculation. The non-linear model is capable to cover the prescribed interactions between building features: for example, between the level of insulation and the performance of the source of heat generation. Because of its prescribed structure, it can be considered a grey-box model. The Levenberg-Marquardt method was used to perform the non-linear regression. The Levenberg-Marquardt method is a technique to iteratively solve nonlinear least-squares problems between a nonlinear function and measured data. The Levenberg-Marquardt method is a combination of two minimization methods: the gradient descent method (updating parameters in steepest-descent direction) and the Gauss-Newton method, (assuming the least-squares function is locally quadratic, and finding the minimum of the quadratic) (Gavin, 2013). The non-linear equation is schematized in Figure 3.3.

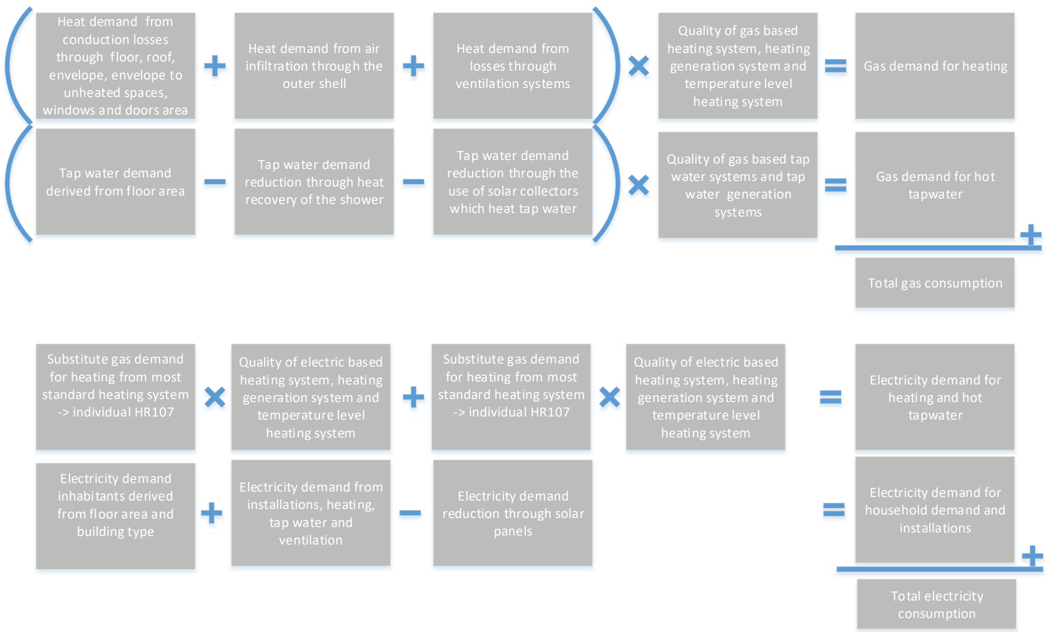

FIG. 3.3 Schematization non-linear regression

3.2.5 Gradient Boosting Model (GBM)

Thirdly, a gradient boosting model was used to estimate the energy consumption of dwellings. The gradient boosting model is based on decision trees. It is an intuitive technique with high forecasting accuracy (if a comprehensive input dataset is available) (Bourdeau et al., 2019). GBM uses boosting techniques: in the process, multiple simple decision trees are developed, with each successive tree modelling the residuals of the precedent one (Bourdeau et al., 2019). There are many alternative machine learning methods available, however, gradient boosting is a frequently-used machine-learning method in practice if, for example, we look at popular machine-learning websites like Kaggle.com (2021). Support vector machines and artificial neural networks are also often applied, however, they are harder to tune than the gradient boosting machine learning algorithm (Touzani, Granderson, & Fernandes, 2018). Although we are aware that the gradient boosting method is not the optimal machine-learning method, we believe it is suitable to test the power of a purely data-driven model, fed with empirical data. The gradient boosting model consists of three parts: 1. A loss function to be optimized; 2. A weak learner to make predictions; 3 an additive model to add weak learners to minimize the loss function. Simply stated, the gradient boosting model combines the power of weak learners to generate a strong model. To tune hyperparameters, a confusion matrix was created. The values tested for the GBM model are: Interaction Depth: 3, 5, 10. Number of trees: up to 1000. Shrinkage 0.1, 0.01. Bag fraction: 0.65, 0.80. Minimum observations in node: 5, 10 (Singh, 2018). The confusion matrix compares the model's actual values with the predicted values, the model with the best prediction on the training set has been chosen to test on the test set. The model learns from a training set (70%) how to predict actual consumption for gas and electricity and verifies its prediction capability on a test set (30%). The test set delivered an r^2 of 0.36, compared to an r^2 of 0.37 on the training set which indicates there is no overfitting. An r^2 of 0.36 indicates that only a part of the actual consumption on a dwelling level can be explained through its building characteristics, which is expected because occupant behaviour was not included in the model.

3.3 Results

The three models all give an estimation of both gas and electricity consumption for the dwellings of Dutch non-profit housing associations. The results of these estimations are compared to actual and theoretical consumption on several cross-sections of the Dutch non-profit housing sector.

3.3.1 Modelled estimations of gas and electricity consumption compared to actual consumption

To assess the modelled estimations of gas and electricity consumption, we compare several cross-sections of the Dutch non-profit housing sector. In figure 3.4, a comparison is made for the gas and electricity consumption of dwellings of non-profit housing associations, grouped by energy label. The graph of gas consumption by energy label clearly shows the performance gap between actual consumption and theoretical consumption. Both the linear model, non-linear model and machine learning model (GBM) are well equipped to estimate the average gas consumptions of these dwellings grouped by energy label. None of these models has the energy label as one of its independent variables, but still, the estimations have the same order of magnitude for actual consumption for all groups of energy labels. The estimation of actual electricity consumption shows a different picture. The theoretical model estimates the building-related energy consumption, which with improved energy labels is declining. The actual consumption also includes electricity used for appliances and therefore is not directly comparable with the theoretical building-related estimation. However, the actual consumption of electricity is more or less equal between all groups and not declining as estimated by the theoretical building energy model. It is expected that there is also a gap between the theoretical building-related electricity estimations and the actual building-related electricity consumption because it cannot be expected that the household appliances alone are responsible for this deviation. The linear model, non-linear model and machine learning model (GBM) are well equipped to estimate the average electricity consumptions of these dwellings grouped by energy label.

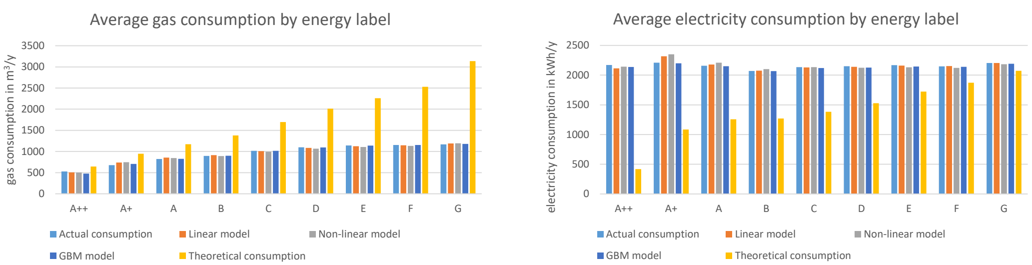

FIG. 3.4 Actual, modelled and theoretical consumption of gas and electricity by energy label.

We can extend the comparison of the actual consumption, the theoretical consumption, and the estimates of the linear model, non-linear model and machine learning model (GBM) by looking at other cross-sections of the Dutch non-profit housing stock by archetype, type of heating system, and building year. These are shown in Figure 3.5. In all cross-sections, the theoretical energy consumption gives a very high overestimation for actual gas consumption and an underestimation of actual electricity consumption. The comparison of the theoretical electricity consumption with the empirical models and actual electricity consumption have to be interpreted with care since the theoretical energy consumption does not take electricity use from appliances into account and the other models and actual electricity consumption do take this into account. All three regression models are able to estimate mean actual gas and electricity consumption very well.

FIG. 3.5 Actual, modelled and theoretical consumption of gas and electricity by archetype, heating system, building year.

Apart from these sectoral cross-sections, we can also look at the correlations of modelled predictions and actual energy consumption. We want to point out that the models do not aim to estimate the actual consumption of one single dwelling (because of the great variance due to the influence of the occupants), but aim to estimate the average energy consumption given its building characteristics. In Table 3.3, we present the correlation of the modelled energy consumption and actual consumption for individual dwellings, and two groups of dwellings (grouped per postcode zone and per housing association) where the influence of occupant behaviour becomes more averaged out.

TABLE 3.3 Correlation (R) of actual gas and electricity consumption by modelled gas and electricity consumption

	Gas consumption				Electricity consumption			
Categorization	Linear model	Non-linear model	GBM model	Theoretical model	Linear model	Non-linear model	GBM model	Theoretical model
Individual dwelling	0.53	0.48	0.56	0.40	0.39	0.39	0.41	0.14
Postcode zone	0.82	0.76	0.75	0.28	0.72	0.70	0.61	0.05
Housing association	0.79	0.74	0.86	0.43	0.70	0.69	0.74	0.11

Given the correlations in Table 3.3, we see that on an individual dwelling level, the correlation of the three models is low, but this is also expected, due to great variance of occupant behaviour. However, the numbers show that all three empirical models outperform the theoretical model. This is also the case for the average energy consumption of dwellings grouped by postcode zone and per housing association. The poor correlations between the estimated and actual energy consumption of the theoretical model are once more an indication that the theoretical model is a poor estimator of actual energy consumption. The Gradient Boosting Model gives the best estimation between estimated and actual energy consumption.

3.3.2 Estimating actual energy savings through renovation measures

We examined the predictive capacity of the empirical models in greater detail. To do this, we applied the linear regression model, the non-linear regression model and the machine learning model (GBM) to a reference dwelling, with 23 different renovation measures. This gives an insight into the differences of the estimations of energy savings by the three models. We compared the results with the theoretical estimation.

A semi-detached corner dwelling built with a traditional brick construction with average dimensions is used as a reference dwelling. This reference dwelling is used to give an example, but any other dwelling could have been used as well. The parameters of this dwelling are listed in Table 3.4. The renovation measures applied are listed in Table 3.5. The renovation measures are both single measures as well as combined renovation measures. These renovations describe a range of renovations applied to dwellings owned by Dutch non-profit housing associations.

TABLE 3.4 Building parameters of the reference dwelling

Building element	Start parameter
Dwelling type	Corner dwelling
Construction type	Concrete/brick
Living area (m2)	92.7
Floor area (m2)	46.1
Roof area (m2)	52.7
Facade area (m2)	82.9
Façade area to unheated space (m2)	1.3
Window area (m2)	19.0
Door area (m2)	4.3
QV10 (dm3/m2)	3.2
Insulation level floor area (Rc)	0.7
Insulation level roof area (Rc)	0.7
Insulation level facade area (Rc)	0.7
Insulation level window area (U)	5.1
Insulation level door area (U)	3.4
Heating system	Individual system
Heat generator	HR107 boiler
Distribution temperature heat	High temperature
Tap water system	Individual system
Generator hot tap water	Gas combi boiler
Shower water heat recovery system	No
Ventilation system	A1
PV-panels (m2)	0
Solar collector (m2)	0

TABLE 3.5 Renovation measures

Nr.	Renovation parameter
1	Insulation level floor (Rc = 2)
2	Insulation level floor (Rc = 5)
3	Insulation level roof (Rc = 2)
4	Insulation level roof (Rc = 5)
5	Insulation level facade (Rc = 2)
6	Insulation level facade (Rc = 5)
7	Insulation level windows double glazing (U = 2.9)
8	Insulation level windows HR++ glass (U = 1.8)
9	Insulation level doors (U = 2)
10	Shower water heat recovery system
11	Low temperature heating (LT)
12	Ventilation system with heat recovery (D1)
13	Solar collector (3 m^2)
14	PV-panel (8 m^2)
15	Deep basic shell (1+3+5+7+9)
16	Deep high shell (2+4+6+8+9)
17	Deep basic + installations (10+11+12+13+14+18)
18	Deep high + installations (10+11+12+13+14+19)
19	Heat pump heating system
20	Heat pump tap water system
21	Heat pump, both heating as hot tap water (19+20)
22	Deep basic + installations + heat pump (17+21)
23	Deep high + installations + heat pump (18+21)

The results of the calculated gas and electricity consumption by the three different models are listed in Figure 3.6.

Through this reference dwelling, we can see the differences in the effectiveness of different renovation measures. We also see differences between the three empirical models and the theoretical model. Some differences originate from the structure of the models, some in the model settings and some differences are not understood. Hereunder, we describe the most relevant results for these renovation measures.

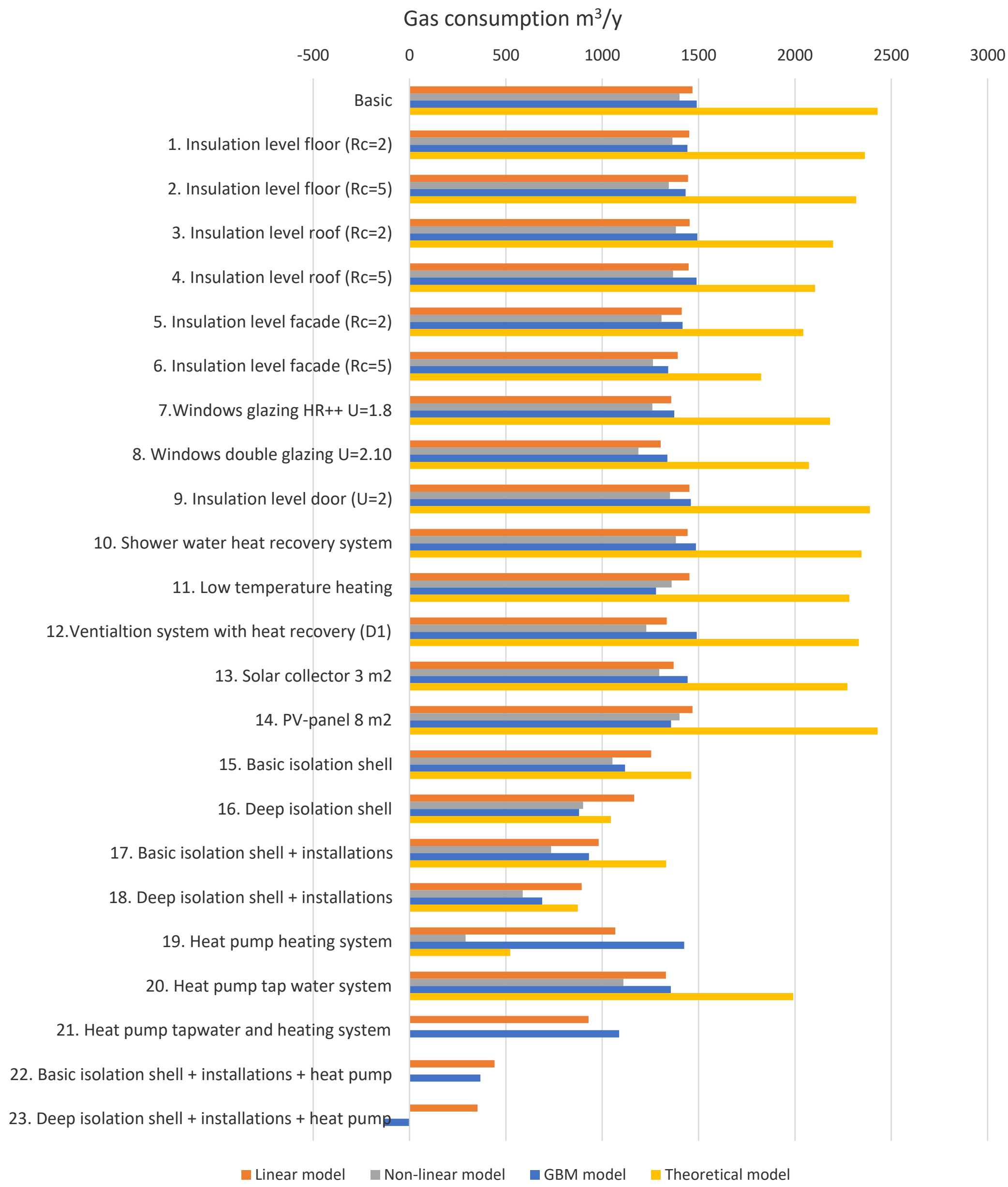

FIG. 3.6 Estimated energy consumption after renovation measure

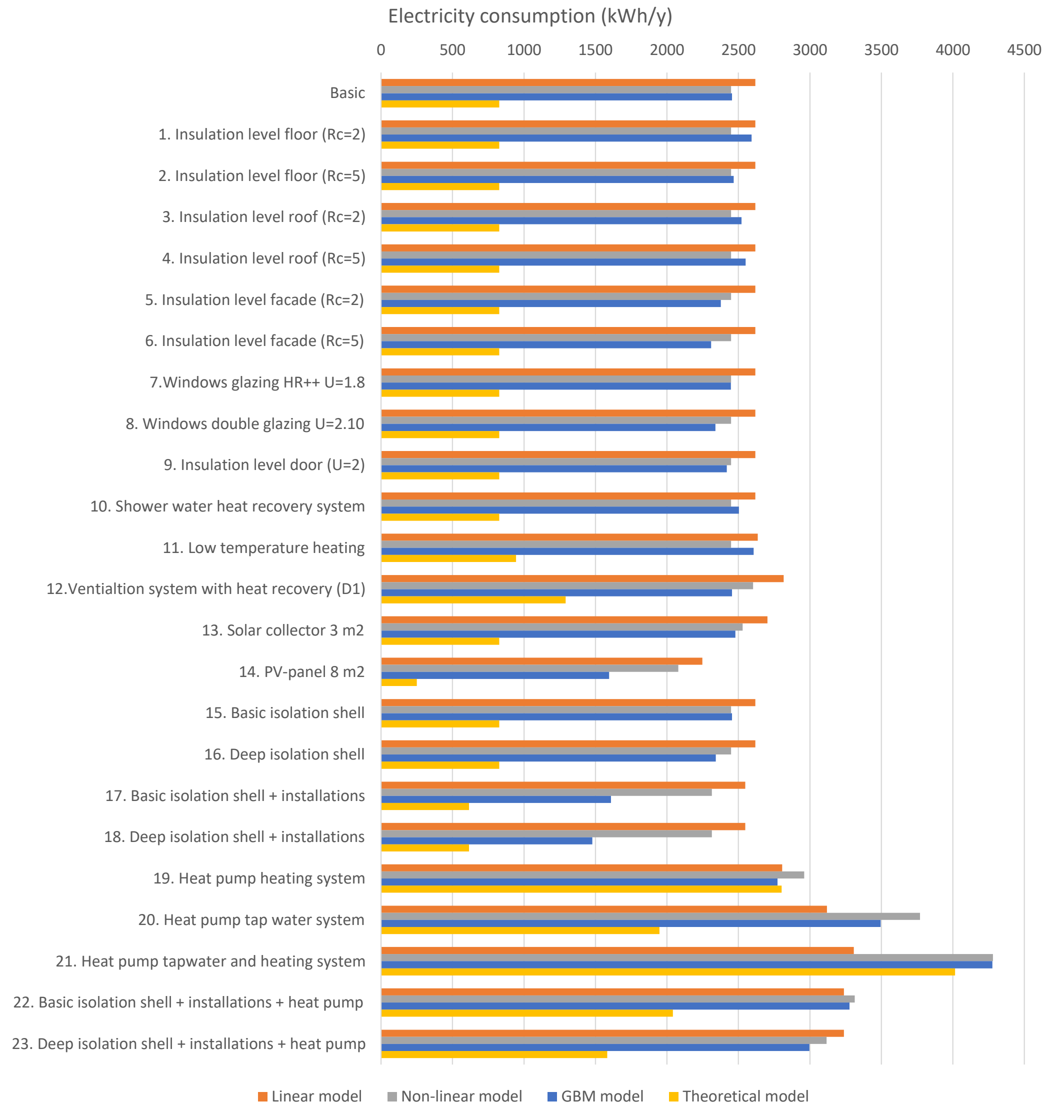

FIG. 3.6 Estimated energy consumption after renovation measure

1 **The basic dwelling:** Theoretically, the gas consumption is 2400 m^3/y, but all three empirical models show it is around 1450 m^3y/, which means there is a lot less saving potential than theoretically calculated. This once more illustrates the performance gap between theoretically calculated and actual energy consumption. The building-related electricity consumption is theoretically around 800 kWh/y. All three empirical models show this is about 2500 kWh/y (including consumer-related electricity consumption).

2 **Insulation (no. 1-9):** Improving insulation components delivers theoretically high gas savings, depicted by the declining theoretical gas consumption. These savings are much lower in all three empirical models, also because the gas consumption of the basic dwelling is already much lower. This means energy savings from insulation are theoretically overestimated. If we look at the different insulation measures, we see that gas savings through improving the insulation level of the façade (5, 6) and windows (7, 8) are more efficient than improvements of the insulation level of the floor or the roof. Improving the insulation level of doors (9) is a small renovation, but still effective.

3 **Installations (no. 10-14):** When we look at changing installations, we see that shower water heat recovery systems (10) have a low impact on gas savings. Adding heat recovery systems in ventilation (12) has an average impact but is not clearly picked up by the GBM model. Adding a solar collector system of 3 m^2 (13) has a moderate impact on gas savings. Adding PV panels of 8 m^2 (14) has a high impact on electricity savings, which is detected by all three models and in accordance with the theoretical model.

4 **Combined renovation measures (no. 15-18):** Improving insulation levels to a basic level (15) is already effective, compared to raising insulation levels to high levels (16). Combined improvements on the insulation of the shell lead to high savings, around 40 to 50% on gas savings. However, this effect is empirically much lower than theoretically assumed. Combined improvements on the insulation of the shell combined with improved installations (18, 19) lead to high savings, around 50 to 60%. This is much less than theoretically assumed.

5 **Heat pumps:** We see differences between the empirical models in renovation measures with a heat pump (19, 20, 21, 22, 23), both on gas savings and on an increase in electricity consumption. The differences between the models are significant and not completely understood. One reason could be the unclear distinction between electric, hybrid and gas-fired heat pumps in the data. Secondly, we believe, since this is a new type of renovation, that introduction effects may invalidate some of the empirical data. These differences in the predictions are problematic because it is therefore not possible to give a good prediction of the actual energy savings by installing heat pumps.

3.4 Conclusion and discussion

The goal of this paper is to investigate the extent to which empirical models provide more accurate estimations of actual energy consumption when compared to a theoretical building energy model, in order to estimate average actual energy savings of renovations. We defined more accurate estimations as (A) average estimations on cross-sections of the non-profit housing sector closer to average actual energy consumption, (B) a higher correlation between estimated and actual consumption, and (C) a positive qualitative interpretation of estimated energy savings of renovations from a reference dwelling. We used the dwellings owned by Dutch non-profit housing associations to demonstrate the potential of empirical models. We found a large performance gap between the theoretical building energy estimations and actual energy consumption for the dwellings owned by Dutch non-profit housing associations. This is in accordance with previous studies (Cozza et al., 2020; Filippidou et al., 2019; Majcen et al., 2013; Summerfield et al., 2019). Opposed to these other studies we examined three empirical models to predict the actual energy consumption of dwellings: a linear regression model, a non-linear regression model and a machine learning model (Gradient Boosting Model or GBM), and compared them to the actual energy consumption. Following our definition of more accurate estimations, we found that on cross-sectoral levels, all three empirical models have significantly higher accuracy than the theoretical building energy model. The empirical models also have higher correlations between estimated and actual consumption. A case study of the three different empirical models revealed that the order of magnitude of the estimations of gas and electricity consumption is significantly more accurate than the theoretical building energy model, but differences in the estimations for several renovation measures questions the accuracy of these empirical models on a detailed level, especially for newly-introduced systems like heat pumps.

Looking at the three different empirical models we conclude that they have their own pros and cons. Linear regression models are simple and fast and estimate sectoral cross-sections very well but are not useful in analysing the effects of detailed renovation measures. A non-linear model can estimate sectoral cross-sections and detailed renovations and uses the structure of actual consumption physics but is only able to use given relations between building features and will therefore not pick up on other relations which could improve the estimations of the effects of renovations. The non-linear model is easier to interpret, which could be a reason to prefer such a model above the other models. A Gradient Boosting Model is able to detect all kinds of relations between building features. It can find correlations and interactions which even specialists in the field are not aware of. However, the model does not use the structure of actual energy consumption physics to its advantage. Therefore, it is more difficult to interpret the results and if some renovation measures (e.g. electrical heat pumps) occur less frequently in the dataset this can result in outcomes that we know from practice are unrealistic. This could cause doubt by the engineers/specialists using the model and they will interpret the results as less reliable.

There are limitations to this research. The first limitation is the availability and quality of data. Energy consumption data about dwellings with district heating systems were not available and therefore excluded in the research. The quality of the data for newly introduced systems, like heat pumps, is limited and therefore questions the estimations at a detailed building level. And finally, when building an empirical energy building model, enough cases should be available to average out occupant behaviour. We believe the SHAERE data set of 1.6 million dwellings is sufficient, but for specific renovations, the availability of data is limited. The second limitation is the use of different modelling techniques. We analysed a linear, non-linear and gradient boosting model. However, other modelling techniques (Amasyali & El-Gohary, 2018), (X. Li & Yao, 2021) are available and also different choices can be made within the linear, non-linear and gradient boosting model method to improve the quality of the estimations. The modelling of confidence intervals is challenging and was not included in this research. The third limitation is the applicability of the estimations generated by the models. The detailed case study revealed that the estimations of the different empirical models lack accuracy for certain renovation measures and therefore the estimations are not mature enough to be used over the theoretical building energy model, although the theoretical building model shows a large performance gap and therefore also has its limitations.

We make the following recommendations for further research. Firstly, since the quality of the data is decisive for the quality of the model, we recommend a more detailed collection of data on dwellings with heat pumps to improve the predictions of the actual energy consumption of these dwellings. We argue the same for dwellings using district heating systems because these could not be included in this research. If other researchers would like to build empirical energy consumption models, they should use large datasets to average out the influence of occupant behaviour. Secondly, we recommend further examining the possibilities of both the non-linear and Gradient Boosting Model, or a combination of these two. These models perform more accurate than the linear regression model because they are able to model relations between building characteristics when they estimate the actual energy consumption. The structure from the non-linear model and the flexibility of the GBM model both have their advantages and a combination could take advantage of them both. Adding confidence intervals to estimations is challenging, but would help to interpret the quality of the estimations, and is therefore recommended. Thirdly, combining theoretical models with empirical calibrations (grey box models) could also be used to enhance the accuracy of the theoretical building energy models. Promising examples are given by Hörner and Lichtmeß (2017) and van den Brom (2020). Including behavioural parameters in the empirical models could be useful in order to understand the origin of the performance gap in greater detail. It would also increase the accuracy of estimations of specific dwellings where these parameters are known, for example for privately owned dwellings.

We recommend that policymakers increase research efforts to build empirical building energy models. The theoretical energy building model which is currently enforced has a high performance gap between the modelled and actual energy consumption, which leads to the ineffective renovation of dwellings, where energy savings are not actually realised. We recommend that policymakers should start/maintain a representative monitoring system, like the SHAERE database, as a basis for empirical building energy models. Modelling energy consumption using actual energy consumption data is the key solution to reduce the energy performance gap and therewith to accurately predict the actual energy savings from different types of renovations.

Appendix A: Model parameters linear regression

Building Characteristic	Gas			Elektra		
	Unst. B	Std. Error	Sig.	Unst. B	Std. Error	Sig.
Constant	4213.3	44.07	**	1568.5	100.5	**
Floorarea	3.5	0.02	**	13.8	0.1	**
Building Envelope						
Heat loss area floor	0.3	0.00	**	0.0	0.0	*
Heat loss area roof	0.3	0.01	**	-0.4	0.0	**
Heat loss area envelope	0.7	0.01	**	0.3	0.0	**
Heat loss area envelope to unh.	0.3	0.02	**	0.1	0.1	*
Heat loss area windows	2.6	0.02	**	1.7	0.0	**
Heat loss area doors	2.7	0.05	**	1.1	0.1	**
Airthightness QV10 area	0.1	0.00	**	0.1	0.0	**
Building characteristic						
Building year	-1.6	0.02	**	-0.5	0.0	**
Mixed light construction	-65.0	8.32	**	-183.0	20.8	**
Stone/concrete construction	-4.9	2.31	*	6.6	5.9	
Wood skeleton construction	25.3	17.25		389.0	78.6	**
Appartment 1 level, corner-roof	39.6	1.87	**	-44.1	4.8	**
Appartment 1 level, corner-roof-floor	182.5	19.18	**	220.4	50.3	**
Appartment 1 level, corner-middle	-2.7	1.53	*	-35.9	3.9	**
Appartment 1 level, corner-floor	142.7	1.92	**	86.4	4.9	**
Appartment 1 level, inbetween-roof	-17.2	1.45	**	-53.5	3.7	**
Appartment 1 level, inbetween-roof-floor	115.0	14.98	**	144.1	39.4	**
Appartment 1 level, inbetween-floor	84.7	1.51	**	52.6	3.9	**
Appartment 1+ level, corner-roof	49.8	4.18	**	-113.1	10.7	**
Appartment 1+ level, corner-roof-floor	185.3	21.82	**	39.9	56.2	
Appartment 1+ level, corner-middle	54.3	10.89	**	-1.4	27.6	
Appartment 1+ level, corner-floor	208.7	7.50	**	151.3	19.2	**
Appartment 1+ level, inbetween-roof	-27.5	2.72	**	-75.6	6.9	**
Appartment 1+ level, inbetween-roof-floor	42.8	15.26	**	-69.1	39.4	
Appartment 1+ level, inbetween-middle	-0.8	5.85		5.1	14.8	
Appartment 1+ level, inbetween-floor	102.1	4.39	**	217.4	11.1	**
Terraced house corner	210.5	1.43	**	342.3	3.7	**
Terraced house not corner	106.9	1.13	**	326.6	2.9	**
Semi-detached	244.9	2.46	**	399.5	6.3	**
Detached	340.1	8.16	**	575.4	21.0	**

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Appendix A: Model parameters linear regression

Building Characteristic	Gas			Elektra		
	Unst. B	Std. Error	Sig.	Unst. B	Std. Error	Sig.
Ventilation system						
Unknown	-110.8	13.18	**	58.9	37.7	
Natural ventilation: Standard (A1)	13.2	0.78	**	-62.4	2.0	**
Natural ventilation: pressure control (A2)	-93.2	7.82	**	-80.5	20.1	**
Natural in/mechanical out: time control (C3)	46.9	2.48	**	-32.9	6.2	**
Natural in/mechanical out: pressure control (C4)	-45.9	1.79	**	-15.1	4.6	**
Mechanical in/out: Standard (D1)	-120.2	2.00	**	136.2	5.1	**
Mechanical in/out: (D1/D2)	-122.3	20.85	**	-22.4	54.7	
Mechanical in/out: central heat recovery system (D2)	-150.4	3.61	**	111.0	9.1	**
Mechanical in/out: time control (D4b)	-124.7	5.65	**	116.1	15.1	**
Mechanical in/out: CO2 control (D5b)	-89.8	10.13	**	71.5	24.8	**
Combined system (E1)	-22.3	8.07	**	-123.3	19.8	**
Heating system						
Empty	-150.8	21.11	**	-97.9	38.23	**
Collective	15.9	19.10		108.0	28.86	**
Individual	-107.1	19.25	**	41.8	29.35	
Heating generator						
Empty	-5.9	17.68		104.2	28.99	**
CR boiler	90.9	19.77	**	-125.2	30.78	**
CHP	-192.3	21.98	**	-290.4	34.54	**
HR100 boiler	81.4	19.55	**	-155.7	29.73	**
HR104 boiler	72.4	19.68	**	-140.7	30.27	**
HR107 boiler	53.7	19.46	**	-129.2	29.36	**
Electric heating	-512.0	23.25	**	1570.4	51.18	**
Local gas/wood/oil	-13.8	19.82		-199.7	30.44	**
micro-CHP	57.9	29.88		-467.5	64.77	**
VR boiler	117.2	19.47	**	-84.8	29.38	**
Heatpump	-347.7	19.95	**	58.6	31.46	
Heating system temperature						
High temperature	-38.5	6.51	**	-33.1	15.35	*
Low temperature	-54.4	6.91	**	-16.2	16.36	
Air	-72.9	15.48	**	233.6	39.33	**
Very low temperature	-232.5	8.81	**	205.2	22.35	**

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Appendix A: Model parameters linear regression

Building Characteristic	Gas			Elektra		
	Unst. B	Std. Error	Sig.	Unst. B	Std. Error	Sig.
Tapwater system						
Empty	-170.7	78.41	*	-246.3	200.23	
Collective	-20.4	6.44	**	-73.0	13.46	**
Individual	34.6	15.29	*	540.6	38.86	**
Tapwater generator						
Empty	-456.0	26.16	**	256.0	46.02	**
CR boiler	-501.6	26.98	**	252.8	48.58	**
Electric flow though	-398.0	38.70	**	255.4	96.13	**
Electric boiler	-720.2	29.51	**	591.9	58.50	**
Heatpump, other source	-741.1	29.80	**	1153.4	60.15	**
Heatpump, source ventilation air	-749.7	29.82	**	705.6	59.84	**
Combiboiler with micro-CHP	-531.2	41.69	**	-189.1	94.91	*
Combibolier	-611.1	29.36	**	-202.7	58.03	**
Boiler< 70kW	-561.8	30.23	**	-191.7	60.92	**
Tap water boiler	-611.8	29.48	**	-217.6	58.47	**
Geyser	-630.1	29.48	**	-192.2	58.33	**
HR100/HR104 boiler	-437.8	28.76	**	227.4	53.66	**
HR107 boiler	-423.4	26.08	**	203.6	45.81	**
VR boiler	-185.0	26.82	**	266.1	48.42	**
CHP	-570.7	33.86	**	40.9	78.52	
Cooling system						
Cooling system	-78.3	5.78	**	70.0	15.27	**
Solar systems						
PV panels area	-1.8	0.15	**	-46.3	0.39	**
Solar heating panels area	-32.6	0.85	**	28.5	2.18	**

*Sig: *<0.05, **<0.01*

Appendix B: Model parameters non-linear regression

Building characteristic	Gas		Elektra	
	Estimate	Std. Error	Estimate	Std. Error
Constant (C)	0.0	0.0E+00	809.6	2.8E+01
Floorarea (FA)	1.5	1.4E+05	13.8	7.3E+06
Building envelope				
Heat loss area floor (HAF)	0.7	5.6E+03	0.0	0.0E+00
Heat loss area roof (HAR)	0.1	2.0E+03	0.0	0.0E+00
Heat loss area envelope (HAE)	1.2	9.2E+03	0.0	0.0E+00
Heat loss area envelope to unh. (HAEU)	0.8	8.6E+03	0.0	0.0E+00
Heat loss area windows (HAW)	4.2	3.0E+04	0.0	0.0E+00
Heat loss area doors (HAD)	10.4	7.6E+04	0.0	0.0E+00
Airthightness QV10 area (QV10)	0.3	3.5E+03	0.0	0.0E+00
Building characteristic				
Empty (EC)	0.9	5.5E+04	0.0	0.0E+00
Mixed light construction (MLC)	0.9	5.2E+04	0.0	0.0E+00
Stone/concrete construction (SCC)	0.9	5.5E+04	0.0	0.0E+00
Wood skeleton construction (WSC)	0.9	5.0E+04	0.0	0.0E+00
Appartment 1 level, corner-roof (A1CR)	0.0	0.0E+00	-404.2	1.7E-02
Appartment 1 level, corner-roof-floor (A1CRF)	0.0	0.0E+00	-147.3	7.8E+00
Appartment 1 level, corner-middle (A1CM)	0.0	0.0E+00	-384.4	3.9E+01
Appartment 1 level, corner-floor (A1CF)	0.0	0.0E+00	-264.2	6.4E+01
Appartment 1 level, inbetween-roof (A1IR)	0.0	0.0E+00	-420.4	2.1E+01
Appartment 1 level, inbetween-roof-floor (A1RF)	0.0	0.0E+00	-223.2	8.1E+05
Appartment 1 level, inbetween-middle (A1IM)	0.0	0.0E+00	-351.4	4.4E+01
Appartment 1 level, inbetween-floor (A1IF)	0.0	0.0E+00	-303.5	0.0E+00
Appartment 1+ level, corner-roof (A2CR)	0.0	0.0E+00	-473.0	6.1E+01
Appartment 1+ level, corner-roof-floor (A2CRF)	0.0	0.0E+00	-293.0	2.1E+01
Appartment 1+ level, corner-middle (A2CM)	0.0	0.0E+00	-346.4	1.4E+01
Appartment 1+ level, corner-floor (A2CF)	0.0	0.0E+00	-182.0	1.1E-01
Appartment 1+ level, inbetween-roof (A2IR)	0.0	0.0E+00	-438.9	3.8E+01
Appartment 1+ level, inbetween-roof-floor (A2RF)	0.0	0.0E+00	-410.0	0.0E+00
Appartment 1+ level, inbetween-middle (A2IM)	0.0	0.0E+00	-359.4	0.0E+00
Appartment 1+ level, inbetween-floor (A2IF)	0.0	0.0E+00	-121.0	2.1E+01
Terraced house corner (TSC)	0.0	0.0E+00	35.7	1.9E+01
Terraced house not corner (TSNC)	0.0	0.0E+00	-12.7	2.1E+01
Semi-detached (SD)	0.0	0.0E+00	95.1	2.1E+01
Detached (DH)	0.0	0.0E+00	0.0	0.0E+00

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Appendix B: Model parameters non-linear regression

Building characteristic	Gas		Elektra	
	Estimate	Std. Error	Estimate	Std. Error
Ventilation system				
Unknown (VU)	3.0	2.2E+04	1.0	2.5E+01
Natural ventilation: Standard (A1)	4.9	3.4E+04	344.9	1.8E+01
Natural ventilation: pressure control (A2)	3.8	2.7E+04	281.0	2.7E+01
Natural in/mechanical out: Standard (C1)	4.7	3.3E+04	376.2	0.0E+00
Natural in/mechanical out: time control (C3)	5.4	4.0E+04	348.4	4.3E+01
Natural in/mechanical out: pressure control (C4)	4.1	2.9E+04	335.8	4.1E+01
Mechanical in/out: Standard (D1)	2.5	1.7E+04	498.2	0.0E+00
Mechanical in/out: (D1/D2)	2.3	1.5E+04	277.7	4.7E+01
Mechanical in/out: central heat recovery system (D2)	2.2	1.4E+04	477.3	1.5E+01
Mechanical in/out: time control (D4b)	2.7	1.8E+04	485.2	4.9E+05
Mechanical in/out: CO2 control (D5b)	3.9	2.7E+04	439.0	4.4E+01
Combined system (E1)	4.6	3.2E+04	241.9	2.1E+01
Heating system				
Empty (HSE)	-0.107	7.7E+03	0.0	0.0E+00
Collective (HSC)	1.045	5.6E+04	0.0	0.0E+00
Individual (HSI)	0.940	5.4E+04	0.0	0.0E+00
Heating generator				
CR boiler (HGCR	0.967	6.2E+04	7.4	3.8E+01
CHP (HGCHP)	0.551	3.0E+04	-142.0	6.0E+05
HR100 boiler (HGHR100)	0.951	6.2E+04	14.9	2.2E+01
HR104 boiler (HGHR107)	0.938	6.1E+04	31.2	0.0E+00
HR107 boiler (HGHR107)	0.937	6.1E+04	36.5	4.5E+01
Electric heating (HGEH)	-0.072	1.2E+04	1.7	3.8E+01
Local gas/wood/oil (HGLGWO)	0.870	5.7E+04	-54.6	2.1E+01
micro-CHP (HGMCHP)	0.931	6.0E+04	-286.0	5.4E+01
VR boiler (HGVR)	1.017	6.6E+04	84.5	2.9E+01
Heatpump (HGHP)	0.333	2.1E+04	0.7	2.0E+01
Heating system temperature				
Empty (TE)	1.009	6.7E+04	1.5	3.8E+01
High temperature (HT)	0.940	6.3E+04	2.4	4.6E-02
Low temperature (LT)	0.904	6.1E+04	0.6	2.0E+01
Air (AIR)	0.946	6.5E+04	1.0	0.0E+00
Very low temperature (VLT)	-0.436	1.7E+04	0.9	2.1E+01

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Appendix B: Model parameters non-linear regression

Building characteristic	Gas		Elektra	
	Estimate	Std. Error	Estimate	Std. Error
Tapwater system				
Empty (TSE)	1.348	1.7E+05	0.0	0.0E+00
Collective (TSC)	1.654	2.0E+05	0.0	0.0E+00
Individual (TSI)	1.497	1.6E+05	0.0	0.0E+00
Tapwater generator				
Empty (TGE)	2.218	2.1E+05	1.0	3.4E+01
CR boiler (TGCR)	2.044	1.8E+05	-141.6	5.7E+00
Electric flow though (TGEF)	2.806	2.3E+05	0.8	7.7E-03
Electric boiler (TGEB)	1.186	1.2E+05	0.9	6.6E+01
Heatpump, other source (TGHPO)	0.384	1.6E+04	1.3	1.9E+01
Heatpump, source ventilation air (TGHPV)	0.554	2.9E+04	0.9	3.8E+01
Combiboiler with micro-CHP (TGMCHP)	2.392	2.4E+05	-52.6	2.4E-02
Combibolier (TGCB)	1.438	1.3E+05	-59.8	7.5E+01
Boiler< 70kW (TGB<70)	1.689	1.6E+05	-36.9	7.0E+00
Tap water boiler (TGWB)	1.503	1.4E+05	-76.9	9.8E+00
Geyser (TGG)	1.418	1.4E+05	25.9	2.1E+01
HR100/HR104 boiler (TGHR100)	2.850	2.8E+05	-190.5	3.9E-01
HR107 boiler (TGHR107)	2.335	2.1E+05	-205.8	6.0E+01
VR boiler (TGVR)	3.797	3.8E+05	-124.3	2.2E+00
CHP (TGCHP)	0.784	2.8E+04	-320.5	2.3E+01
Other systems				
Heat recovery shower water (HRS)	-0.099	5.3E+03	0.0	0.0E+00
Solar heating panels area (SHPA)	-16.274	1.3E+06	26.9	5.1E+06
PV panels area (PVA)	0.0	0.0E+00	-46.2	1.8E+01
Cooling system (CS)	0.0	0.0E+00	110.5	2.1E+01

Actual gas consumption (AGS) in $(m_3/y) = ((\beta_{hlf} * haf + \beta_{hlr} * har + \beta_{hle} * hae + \beta_{hleu} * haeu + \beta_{hlw} * haw + \beta_{hld} * had + \beta_{qv10} * QV10 + FA * (\beta_{VU} * VU+\beta_{A1} * A1+ \beta_{A2} * A2+ \beta_{C1} * C1+ \beta_{C3} * C3+ \beta_{C4} * C4+ \beta d_1 * D1+ \beta_{D1/D2} * D1/D2+ \beta_{D2} * D2+ \beta_{D4b} * D4b+ \beta_{D5b} * D5b+ \beta_{E1} * e1)) * (\beta_{HSE} * HSE+ \beta_{HSC} * HSC+ \beta_{HSI} * HSI+ \beta_{HSEH} * HSEH) * (\beta_{HGCR} * HGCR+ \beta_{HGCHP} * HGCHP+ \beta_{HGHR100} * HGHR100+ \beta_{HGHR104} * HGHR104+ \beta_{HGHR107} * HGHR107+ \beta_{HGLGWO} * HGLGWO+ \beta_{HGMCHP} * HGMCHP+ \beta_{HGVR} * HGVR+ \beta_{HGHP} * HGHP) * (\beta_{TE} * TE+ \beta_{HT} * HT+ \beta_{LT} * LT+ \beta_{AIR} * AIR+ \beta_{VLT} * VLT+ \beta_{VLT} * VLT) * (\beta_{MLC} * MLC+\beta_{SCC} * SCC+\beta_{WSC} * WSC+ \beta_{ESC} * ESC)+((\beta_{FA} * FA+\beta_{SHPA} * SHPA+ \beta_{HRS} * HRS) * (\beta_{TSE} * TSE+ \beta_{TSC} * TSC+ \beta_{TSI} * TSI+) * (\beta_{TGE} * TGE+\beta_{TGCR} * TGCR+\beta_{TGEF} * TGEF+\beta_{TGEB} * TGEB+\beta_{TGHPO} * TGHPO+\beta_{TGHPV} * TGHPV+ \beta_{TGMCHP} * TGMCHP+\beta_{TGCB} * TGCB+ \beta_{TGB<70} * TGB<70+\beta_{TGTWB} * TGTWB+\beta_{TGG} * TGG+\beta_{TGHR100} * TGHR100+\beta_{TGHR107} * TG107+\beta_{TGVR} * TGVR+\beta_{TGCHP} * TGCHP))$

Actual electricity consumption (AEC) in $(kWh/y) = AGS_{heat(HS=HSI,\ HG=HGHR107)} * (\beta_{TE} * TE+ \beta_{HT} * HT+ \beta_{LT} * LT+ \beta_{AIR} * AIR+ \beta_{VLT} * VLT+ \beta_{VLT} * VLT) * (\beta_{HGHP} * HGHP+ \beta_{HGEH} * HGEH)+AGS_{tap(TS=TSI,\ TGTG=TGHR107)} * (\beta_{TSE} * TSE+ \beta_{TSC} * TSC+ \beta_{TSI}) * (\beta_{TGEF} * TGEF+\beta_{TGEB} * TGEB+\beta_{TGHPO} * TGHPO+ \beta_{TGHPV} * TGHPV)+FA * (\beta_{A1} * A1+ \beta_{A2} * A2+ \beta_{C1} * C1+ \beta_{C3} * C3+ \beta_{C4} * C4+ \beta d_1 * D1+ \beta_{D1/D2} * D1/D2+ \beta_{D2} * D2+ \beta_{D4b} * D4b+ \beta_{D5b} * D5b+ \beta_{E1} * e1)+FA(\beta_{HGCR} * HGCR+ \beta_{HGCHP} * HGCHP+ \beta_{HGHR100} * HGHR100+ \beta_{HGHR104} * HGHR104+ \beta_{HGHR107} * HGHR107+ \beta HGLGWO * HGLGWO+ \beta HGMCHP * HGMCHP+ \beta HGVR * HGVR)+FA * (\beta_{TGE} * TGE+\beta_{TGCR} * TGCR+\beta_{TGMCHP} * TGMCHP+ \beta_{TGCB} * TGCB+\beta_{TGB<70} * TGB<70+\beta_{TGTWB} * TGTWB+\beta_{TGG} * TGG+\beta_{TGHR100} * TGHR100+\beta_{TGHR107} * TG107+\beta_{TGVR} * TGVR+\beta_{TGCHP} * TGCHP)+ \beta_{shpa} * SHPA+ \beta_{pva} * PVA+ \beta_{cs} * CS+FA(\beta_{A1CR} * A1CR+\beta_{A1CRF} * A1CRF+\beta_{A1CM} * A1CM +\beta_{A1CF} * A1CF+\beta_{A1IR} * A1IR+ \beta_{A1RF} * A1RF+ \beta_{A1IM} * A1IM+ \beta_{A1IF} * A1IF+\beta_{A2CR} * A2CR +\beta_{A2CRF} * A2CRF+\beta_{A2CM} * A2CM +\beta_{A2CF} * A2CF+\beta_{A2IR} * A2IR+ \beta_{A2RF} * A2RF+ \beta_{A2IM} * A2IM+ \beta_{A2IF} * A2IF +\beta_{TSC} * TSC+\beta_{TSNC} * TSNC+\beta_{SD} * SD+\beta_{DH} * DH)$

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4 The energy performance of dwellings with heat pumps of Dutch non-profit housing associations

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ABSTRACT

Achieving energy efficiency in the built environment requires extensive efforts in the renovation and adaptation of housing stock. A promising design solution is the heat pump. While gas boiler systems are commonly used in Dutch non-profit housing stock, the share of dwellings with a heat pump grew from 1.6% in 2017 to 3.2% in 2021. However, building characteristics and the energy consumption of dwellings with a heat pump are unclear. Therefore, a dataset of 69,422 dwellings with different types of heat pumps has been examined and compared to dwellings with a traditional HR107 condensing gas boiler. This research reports average characteristics and the average actual energy consumption of dwellings with all-electric, hybrid, and gas absorption heat pump systems. Dwellings with a heat pump system are on average of higher building quality, their gas consumption is lower, and their electricity consumption is higher than dwellings with an HR107 condensing gas boiler. Detailed insight is provided for dwellings with different heat pump systems and for dwellings with different building characteristics. Further research to determine the energy performance of dwellings with specific heat pump configurations is recommended in light of the energy transition in the built environment.

KEYWORDS

Heat pump systems, energy consumption, housing stock, non-profit housing.

4.1 Introduction

The International Energy Agency (IEA) reports that the amount of worldwide CO_2 emissions from buildings was at an all-time high in 2019 at 10 Gt CO_2 (IEA, 2020). The IEA states that the enormous potential to reduce emissions from buildings remains unfulfilled due to the ongoing use of fossil fuels, ineffective energy efficiency policies, and insufficient investments to make buildings sustainable. Moving the built environment towards CO_2 neutrality requires increased efforts in the renovation and adaptation of buildings. Further to the Paris Climate Agreement (UNFCCC, 2015), the European Commission (2019) coined the need to renovate building stock as a major challenge. Within the Netherlands, efforts to battle this major challenge are outlined in the National Climate Agreement (2019), aiming at a CO_2 neutral built environment by 2050. The so-called neighbourhood approach is a dominant policy instrument, aiming at determining the future dominant source of heat at neighbourhood level. Currently, the housing stock is mostly heated by natural gas boilers. Examples of future heat sources are geothermal heat, waste heat from the industry sector, biomass (although part of political debate), and all-electric solutions. Heat pumps are considered to be a promising design solution.

The European Heat Pump Association (EHPA) reports strong growth in the heat pump market in Europe (EHPA, 2020); the number has increased to 13.2 million buildings with heat pumps in 2019. Also, the Dutch Central Bureau of Statistics (CBS) reports a strong growth of heat pumps in the Dutch building stock: 400,000 in 2019 (CBS, 2021; CBS Statline, 2021). This includes heat pump systems for both the utility and the residential sector and includes systems only used for cooling. The CBS also presents predictive primary energy savings and savings of CO_2 emissions, based on theoretical performance factors of heat pumps and the CO_2 factors of the current energy mix. However, they argue that there is a lack of literature on the actual performance of heat pumps in practice (CBS, 2021). In the Netherlands, a monitoring system (SHAERE) is used to monitor changes in the housing stock of the Dutch non-profit housing sector (van der Bent, Visscher, Meijer, & Mouter, 2021). Over 87% of Dutch non-profit housing stock was heated by gas boiler heating systems in 2020. The monitoring system also reports an increase in the use of heat pumps for heating from 1.6% of the non-profit housing sector in 2017, to 2.6% of the non-profit housing sector in 2020. However, the characteristics and energy consumption of dwellings with a heat pump is unclear. This is problematic given the expected replacement of the currently dominant heating system, a HR107 condensing gas boiler, through the afore-mentioned neighbourhood approach. The lack of detailed information about the installation and energy performance of heat pumps in dwellings is problematic, both within the Dutch context and in the European context, as other countries see the use of heat pump systems as promising future solutions as well (Gupta & Irving, 2014; Krützfeldt, Vering, Mehrfeld, & Müller, 2021; Wang & He, 2021; Zhuravchak, Nord, & Brattebø, 2022). This research aims to give insights into the knowledge gaps considering different heat pump systems, different building characteristics, and the actual energy consumption of dwellings that have heat pump systems.

4.1.1 Different heat pump systems and building characteristics

There is a spectrum of heat pump systems, all with a great variety of characteristics. These characteristics are of importance because they influence the energy performance of the heat pump system. Differences can be found in the type of heat pump (all-electric, hybrid, gas absorption), the source of energy (gas/electricity), the source of heat extraction (air/ground/water), the configuration of the system (individual, collective), the distribution medium (water/air), the distribution temperature, and the installed power and coefficient of performance (COP) of the heat pump system. Also, the building wherein the heat pump operates can vary greatly in size, in the level of insulation, and through differences with other building systems like ventilation systems and photovoltaic panels (PV). Also, the user of the building has a great influence on the actual performance of a heat pump system (Caird, Roy, & Potter, 2012; Roy & Caird, 2013) and lastly, the fine-tuning of the installation also influences its performance (Deng, Wei, Liang, He, & Zhang, 2019; Gleeson, 2016). A recent study by Kieft, Harmsen, & Hekkert (2021) analyses the Technological Innovation System of heat pumps in existing Dutch housing stock. They state that multiple types of heat pumps are available to replace the natural gas boilers in existing houses, but the individual all-electric heat pump and the hybrid heat pump are the most prominent. They state that all-electric heat pumps are used to replace gas boilers, because of their high efficiency of up to four times the original electricity input. They also state that dwellings in the Netherlands are generally heated with water as a transport medium. Therefore, only heat pumps that transport heat through water are considered to be a viable large-scale option, as opposed to air-to-air heat pump systems used in Mediterranean climates (Domínguez-Amarillo, Fernández-Agüera, Peacock, & Acosta, 2020). Other researchers propose the use of hybrid heat pumps (Bagarella, Lazzarin, & Noro, 2016) or gas absorption heat pumps (Famiglietti, Toppi, Pistocchini, Scoccia, & Motta, 2021). These systems benefit from a higher COP but are also able to generate enough heat in winter conditions. Kieft, Harmsen, & Hekkert (2021) explain that heat pump systems using air as a source to extract heat from outside air are mostly used in the Dutch building stock, because of costs and ease of installation. Heat pumps extracting heat from the ground (and storing heat in the ground in the summer) are also a viable design option, but due to higher installation costs and space requirements, where aquifers need to be installed at a reasonable distance from each other, these systems are not frequently used within the existing housing stock. Lastly, Kieft, Harmsen, & Hekkert (2021) describe three building characteristics that are important while investigating dwellings with heat pumps: the insulation level of the dwellings, the distribution system, and the presence of PV panels.

4.1.2 The energy consumption of dwellings with heat pump systems

Because of the expected role that heat pumps will have in the energy transition, a substantial body of literature can be found about the performance and energy consumption of dwellings with heat pumps. However, most of these studies examine only one particular set-up of a heat pump system. Some examples are given. O'Hegarty, Kinnane, Lennon, and Colclough (2021) examine the performance of air-to-water heat pumps. They reviewed the actual performance of 378 dwellings with heat pumps and found that the average seasonal performance was significantly lower than the performance stated in the product description. Shirani et al. (2021) used a model to evaluate the performance of ventilation-based exhaust air heat pumps and reported reductions of electricity consumption of up to 40%. Biglia, Ferrara, and Fabrizio (2021) report on the performance of groundwater heat pumps in 300 non-profit housing apartments in an Italian residential district, which also reported a lower performance than expected. They stress the need for system optimization to increase performance. Famiglietti et al. (2021) executed a life cycle assessment, comparing a condensing boiler and a gas absorption heat pump. They report a decrease of up to 27% of CO2 emissions, mainly due to the system's lower gas consumption. Lu et al. (2020) report energy savings of up to 43.5% when gas absorption heat pumps are applied in residential buildings, compared to the natural gas boiler. Bianco, Scarpa, & Tagliafico (2017) analysed the prospective energy consumption and CO2 emissions of air-to-air electric heat pump systems in Italy with an end-use approach model. They report long terms gas savings in the order of 20%.

4.1.3 Research questions

No large-scale research has yet been published with a building stock approach, examining the extent to which different heat pumps are present in building stock, with a description of the characteristics of these dwellings, and the energy consumption of different heat pump systems, while comparing research results with dwellings that have traditional gas condensing boilers. Considering the importance of the differences between heat pump systems and the building characteristics that influence the actual consumption of these dwellings, as discussed above, the following research questions have been raised:To what extent are dwellings with different heat pump systems present in the Dutch non-profit housing sector?

1. To what extent are dwellings with different heat pump systems present in the Dutch non-profit housing sector?

2. What are the characteristics of dwellings with different heat pump systems compared to dwellings with a traditional condensing gas boiler (HR107)?

3. What is the actual average energy consumption of dwellings with heat pumps compared to dwellings with a traditional condensing gas boiler (HR107)?

Answering the first research question will alleviate the knowledge gap concerning the types of heat pumps installed in dwellings. The second research question will alleviate the knowledge gap concerning the building characteristics of dwellings with heat pumps, and the third research question will alleviate the knowledge gap concerning the actual energy consumption of dwellings with heat pumps compared to dwellings with a traditional heating system.

4.2 Materials and method

The SHAERE database was used to determine the characteristics of dwellings with heat pumps and traditional condensing gas boilers in the Dutch non-profit housing sector. This database is the monitoring system for the energy performance of dwellings owned by Dutch non-profit housing associations (van der Bent et al., 2021), which has had a new data structure since the implementation of the NTA8800 in January 2021 (NEN, 2020). Data were collected in 2021 by Aedes, the umbrella organization for housing associations, in cooperation with this research project. Data about the energy performance indicators of 246 Dutch non-profit housing associations covering two million dwellings were collected in the database, covering 95% of the Dutch non-profit housing sector. Relevant indicators for this research are shown in Table 4.1.

This dataset is combined with a second dataset of the actual gas and electricity consumption in the year 2020 (Table 4.2), available at address level in an anonymized analysis environment from the Dutch Central Bureau of Statistics (CBS). Figure 4.1 shows how these two databases have been combined in this research.

TABLE 4.1 Dataset relevant building features

Features of dwellings	num./nom.	Description
Address	nom.	Anonymized address identification code
Energy label value EP2	num.	Theoretical primary fossil energy consumption In kWh/m^2
Heat demand of the shell	num.	Theoretical heat demand in kWh/m^2
Building year	num.	1600-2021
Building type	nom.	Single-family or multi-family
Ventilation system	nom.	A1, A2, C1, C3, C4, D1, D1/D2, D2, D4b, D5b, E1, unknown
Heating system	nom.	Empty, collective, individual, external heating
Heating generator and secondary system	nom.	CR boiler, VR boiler, HR100 boiler, HR104 boiler, HR107 boiler, CHP, Electric heating, local gas/wood/oil, heat pump electric, heat pump gas absorption
Hot tap water system	nom.	Empty, collective, individual, external heating
Hot tap water generator	nom.	Empty, CR boiler, VR boiler, HR100/HR104 boiler, HR107 boiler, CHP, electric flow though, electric boiler, heat pump electric, heat pump gas, combi boiler, boiler< 70kW, gas boiler, geyser
Heating distribution system	nom.	Floor heating, radiators, other
PV panels area	num.	In area m^2
Solar heating panels area	num.	In area m^2

TABLE 4.2 Data set actual energy consumption

Features actual consumption	num./nom.	Description
Address	nom.	Anonymized address identification code
Actual gas consumption	num.	Total gas consumption at the address in m^3/y in 2020
Actual electricity consumption	num.	Total electricity consumption at the address in kWh/y in 2020
External heating	nom.	Not present or present

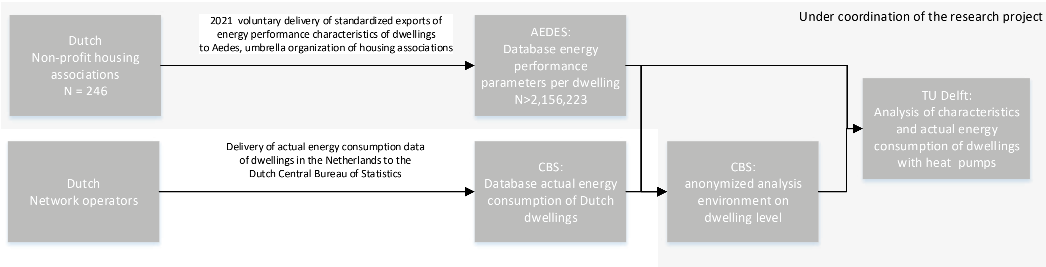

FIG. 4.1 Process of data collection and analysis

The dataset with relevant building features gives the general characteristics of dwellings and specific building features related to the use of heat pumps. In the case of heat pumps, the heating generator and the hot tap water generator specify the type of heat pump system: all-electric, gas absorption or hybrid. Also, the heating distribution system is specified. Specific descriptions of the heat source (air/water/ground), distribution temperature, power, and COP are not available in the database. The building year was used to estimate whether a heat pump was installed during the construction of a dwelling or during a renovation. A dwelling built before the year 2000 is regarded as a renovated dwelling with a heat pump, while dwellings built in, or after, the year 2000 are regarded as dwellings where the heat pump was installed during the construction of the dwelling. In the results section, the characteristics and energy consumption of dwellings with a standard HR107 natural gas boiler, used for both heating and hot tap water, are presented for reference purposes.

The dataset with dwellings with heat pumps was cleaned up for irregularities. First, dwellings with incomplete building data were removed from the dataset, which led to a dataset of 69,422 dwellings with heat pumps. Second, the dwellings were combined with the dataset on actual gas and electricity consumption in 2020, where this data was available in the CBS analysis environment. This delivered a dataset of 45,426 dwellings. The actual consumption of gas and electricity for the year 2018 and 2019 was checked to determine irregularities in the data. The use of the average energy consumption for these years was considered, but it was concluded that the consumption data from 2020 was the most complete and therefore, the most reliable set of data. It was considered to convert actual energy consumption using the heat degree method to a standardised energy consumption, that is normally used for gas consumption. In 2020, this factor would be 2508/2620, meaning fewer heat degree days than in a standardised year. This factor was not used because adjusting both gas and electricity consumption for heat degree days would undermine the estimation of the electricity consumption for other building installation systems and for household appliances, and would lead to non-comparability with heat pump systems using gas: the hybrid heat pumps and gas absorption heat pumps. Therefore, the results are presented as the non-corrected average gas and electricity consumption in 2020. The disadvantage of this is that the research does not show a standardized energy consumption, but the advantage is that a clearer comparison can be made between dwellings with gas boilers and dwellings with heat pumps.

4.3 Results

4.3.1 Different heat pump systems in dwellings

As mentioned in the introduction, an uptake of heat pumps in the non-profit housing sector was found in the years 2017 to 2020 from 1.6% in 2017 to 2.6% in 2020. In 2021, 3.2% of the dwellings in the Dutch non-profit housing sector had a heat pump system, a total of 69,422 dwellings. These dwellings are divided into five groups, each with a different heat pump system:

1. **All-electric:** Electric heat pump system for both heating and hot tap water, or combined with an extra electric heating system

2. **Hybrid:** Electric heat pump system combined with a gas fired heating system for heating or hot tap water

3. **Gas absorption:** Gas absorption heat pump system, combined with only gas fired systems for heating or hot tap water

4. **Gas absorption hybrid:** Gas absorption heat pump system, combined with electric system for heating or hot tap water

5. **Other:** Both gas and electric heat pump systems combined with external heating or biomass systems.

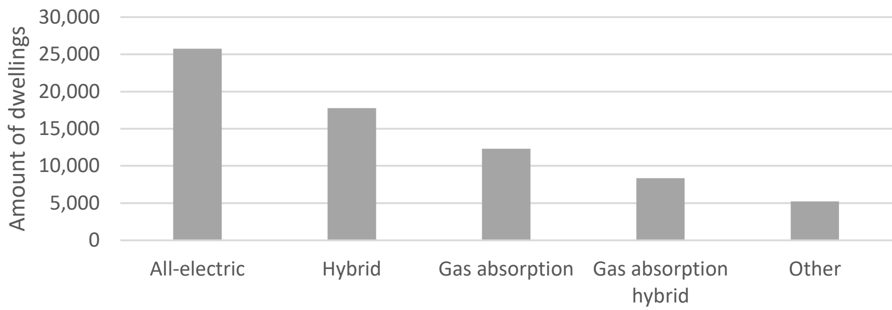

FIG. 4.2 Number of dwellings per heat pump system

Figure 4.2 shows a group of over 25 thousand dwellings which are equipped with an all-electric heat pump system (1.2%). Second, there are about 18 thousand dwellings with a hybrid system in the dataset (0.8%). Third, there are about 12 thousand dwellings with a gas absorption heat pump (0.6%), and fourth, 8 thousand dwellings with a gas absorption heat pump combined with an electric heating system (0.4%). The last group, "Other" (0.2%), is small and due to lack of specification will not be further analyzed. To create a frame of reference, the characteristics of dwellings with an HR107 gas heating system with a combined hot tap water function have also been stated. There are 1,521,734 such dwellings with an HR107 boiler, representing 70.6% of the dwellings in the dataset. Besides the dwellings with a heat pump (3.2%), the other 26.2% of the dwellings in the dataset typically have external heating, an older type of gas boiler, combined systems, or other innovative systems, like CHP systems. These other heating systems are not analyzed in this paper.

4.3.2 Characteristics and quality of dwellings with heat pumps

The first dataset (Table 4.1) is used to describe the characteristics and quality of dwellings with different types of heat pump, consisting of the building type and size, the average building quality expressed in the energy label value, the theoretical primary fossil energy consumption (EP2) and average energy label, the year it was built, the heating system, the distribution system, solar energy systems, ventilation systems and the quality of the outer shell expressed as heat demand in kWh/m2. These are presented in Table 4.3.

TABLE 4.3 Dwelling characteristics to heat pump type

	All-electric	Hybrid	Gas absorption	Gas absorption hybrid	Gas boiler HR107
Number of dwellings	25,743	17,786	12,308	8,371	1,521,734
Building type and size					
Single-family	55%	25%	9%	12%	50%
Multi-family	45%	75%	91%	88%	50%
Single-family size in m^2	96	104	103	102	94
Multi-family size in m^2	58	70	72	72	71
Average building quality					
Energy label value (EP2) in kWh/m^2	55	150	188	132	196
Average energy label	A++	A	B	A	C
Year built					
Built < 2000	20%	39%	61%	58%	87%
Built => 2000	80%	61%	39%	42%	13%
Heating system					
Individual	94%	35%	18%	36%	82%
Collective	6%	65%	82%	64%	18%
Heating distribution system					
Underfloor heating	75%	54%	44%	37%	2%
Radiators	23%	46%	55%	63%	97%
Solar energy systems					
Solar power (PV)	71%	29%	24%	24%	12%
Solar power (PV) m^2	23.6	9.3	5.2	5.9	10.4
Solar heating	2%	14%	18%	2%	2%
Solar heating m^2	4.2	2.0	4.9	5.6	5.4
Ventilation system					
Ventilation system natural	1%	3%	3%	5%	34%
Ventilation system mech. exhaust.	31%	68%	69%	73%	60%
Ventilation system mech. inlet/exhaust	67%	28%	28%	22%	5%
Quality of outer shell					
Heat demand of shell in kWh/m^2	54	73	71	73	122

Building type and size: Dwellings with all-electric heat pumps are often (55%) found in single-family dwellings, but are also in multi-family buildings (45%). Hybrid heat pump solutions and gas absorption heat pumps are mostly found in multi-family buildings. On average the all-electric heat pumps are placed in smaller dwellings.

Average building quality: The average building quality expressed in the energy label value (EP2) and the average energy label show that dwellings with all-electric heat pumps are better quality. As explained later, on average, the outer shell of these dwellings are better quality and they have large areas of photovoltaic panels. Also, dwellings with hybrid heat pumps and gas absorption heat pumps have a higher average building quality than dwellings with a standard HR107 gas boiler.

Retrofit or new construction: It is not possible to directly determine if a system is installed during the construction of the dwelling or as a retrofit, although an estimation can be made by assuming that in dwellings built before 2000, the heat pump was installed during a retrofit, while in dwellings built in, or after, 2000 heat pumps were installed during construction. Using this estimation, most heat pump systems were found to be installed during the construction of the dwelling, but also a significant group was retrofitted with a heat pump system.

Heating systems: Most all-electric heat pump systems are installed as individual systems for a single dwelling (94%). Hybrid and gas absorption solutions are mostly installed as a central system, covering multiple dwellings. This is in line with the dominant installation in multi-family buildings.

Heating distribution systems: Heating distribution systems with underfloor heating are dominant in dwellings with electric heat pumps. A large gap is shown between this and dwellings with regular HR107 gas boilers, where only 2% has underfloor heating. In the database, no distinction is made between high or low-temperature radiators.

Solar energy systems: Dwellings with all-electric heat pumps are frequently accompanied by photovoltaic panels (79%), with 23.6 m^2, on average. Also, dwellings with hybrid or gas absorption heat pumps have higher rates of PV panels, as opposed to dwellings with an HR107 gas boiler (12%). Solar heating systems to heat water are not a dominant design solution, although they are found to be placed more often when combined with hybrid or gas absorption heat pump systems.

Ventilation systems: Typically, dwellings with an HR107 gas boiler have a natural ventilation system (34%) or a mechanical exhaust system (64%). Dwellings with hybrid or gas absorption heat pumps typically have mechanical exhaust systems or systems with both a mechanical inlet and exhaust. These systems are able to recapture energy from the outflowing ventilation air. Dwellings with all-electric heat pumps have these balanced ventilation systems in 67% of the cases, where the system is sometimes directly coupled with the heat pump, increasing its performance.

Quality of the outer shell: The quality of the outer shell is expressed as the average heat demand in kWh/m2. Dwellings with an all-electric heat pump show a lower heat demand than dwellings with hybrid or gas absorption heat pumps, which means better insulated. However, all dwellings, on average, have a lower energy demand, meaning that the quality of the building shell is better than dwellings with a traditional HR107 gas boiler.

4.3.3 Energy consumption of dwellings with heat pumps

In this paragraph the average electricity and gas consumption in 2020 of these groups of dwellings are shown with more detailed insights, split into five building parameters.

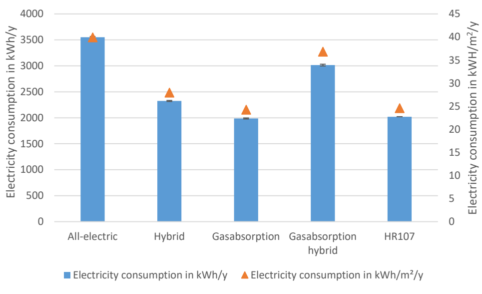

FIG. 4.3 Average electricity consumption per dwelling and per m^2 to heat pump type

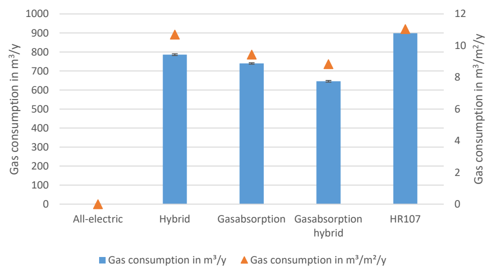

FIG. 4.4 Average gas consumption per dwelling and per m^2 to heat pump type

Figure 4.3 shows the average electricity consumption of dwellings with the different heat pump systems, with the HR107 gas boiler as a reference. Dwellings with an HR107 gas boiler use, on average, 2021 kWh of electricity, or 25 kWh/m2. Dwellings with all-electric heat pumps, on average, use 3553 kWh, or 40 kWh/m2, which is, on average, 76% higher than for dwellings with an HR107 gas boiler. As outlined in the previous paragraph, dwellings with all-electric heat pumps have a significantly higher average building quality than dwellings with an HR107 gas boiler. Dwellings with hybrid or gas absorption hybrid heat pumps show a 15% to 50% higher average electricity consumption as opposed to dwellings with an HR107 gas boiler. Dwellings with a gas absorption heat pump have, on average, the same electricity consumption as dwellings with an HR107 gas boiler, which seems logical, because both systems are gas based and do not influence electricity consumption to a large extend.

TOC

Figure 4.4 shows the average gas consumption of the different heat pump systems, again with dwellings with an HR107 gas boiler as a reference. An average dwelling with an HR107 gas boiler uses 899 m^3 gas, or 11 m^3/m2. Dwellings with all-electric heat pumps have no gas consumption. Dwellings with hybrid heat pumps have an average gas consumption which is 13% lower, while gas absorption heat pumps show 18% lower gas consumption, and gas absorption heat pumps including an electric system show, on average, 28% lower gas consumption. Again, as outlined in the previous paragraph, this includes a higher average building quality for dwellings with heat pumps.

TABLE 4.4 Average electricity and gas consumption of dwellings with heat pumps

Type heat pump	Dwellings		Electricity in kWh/y			Gas in m^3/y		
	Total	Valid	Mean	SEM	St. Dev.	Mean	SEM	St. Dev.
All-electric	25,743	15,033	3,553	13	1,540	0	0	0
Hybrid	17,789	12,727	2,324	10	1,144	786	5	447
Gasabsorption	12,308	10,139	1,987	10	1,048	740	4	336
Gasabs. hybrid	8,371	7,527	3,015	17	1,454	646	4	297
HR107	1,521,734	1,446,419	2,021	1	1,080	899	0	442

Table 4.4 gives the number of dwellings per heat pump system used for this analysis, the standard error of the mean (SEM), and the standard deviation. The standard error of the mean is significantly low because of the large sample size, but the standard deviation shows a large spread, which indicates that large differences in energy consumption are present on an individual dwelling level. These differences on an individual dwellings level can be partly explained because dwelling characteristics are different, but more importantly, the occupant characteristics and behavior are also different for individual dwellings, leading to differences in electricity and gas consumption.

Figure 4.5 shows the differences in average electricity consumption for dwellings with an all-electric heat pump system, split into the five building parameters.

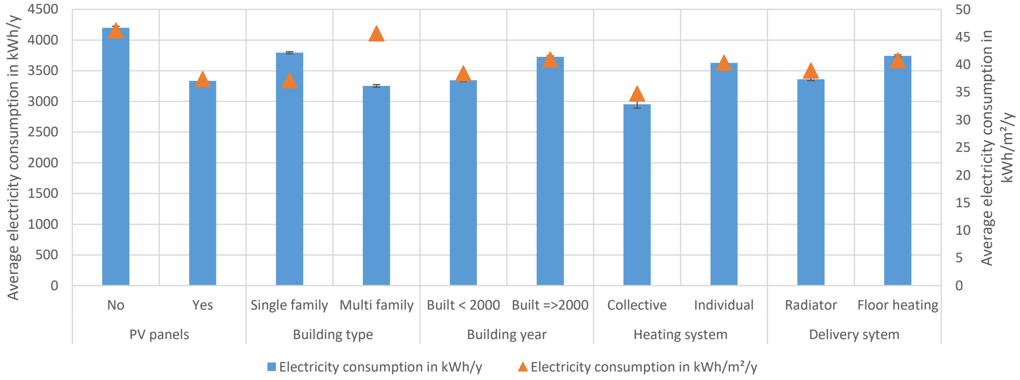

FIG. 4.5 Average electricity consumption of dwellings with all-electric heat pumps to building parameter

Dwellings with all-electric heat pumps with PV panels have, on average, 866 kWh lower electricity consumption than dwellings without PV panels. Single-family dwellings, as opposed to multi-family dwellings, have, on average, 541 kWh higher electricity consumption, mainly due to a larger building size (96 over 58 m^2). Multi-family dwellings have a higher electricity consumption per m^2. PV panels are more likely to be placed on single-family dwellings, thus lowering the average electricity consumption per m^2. Dwellings built before 2000, have a slightly lower electricity consumption, also per m^2, than dwellings built after 2000. Dwellings with a central all-electric heat pump system servicing multiple dwellings (although only 6% of the dataset) have a lower average electricity consumption than heat pumps servicing a single dwelling. Dwellings with underfloor heating show slightly higher electricity consumption than dwellings with radiators.

Figures 4.6 and 4.7 show the average electricity and gas consumption of dwellings with a hybrid, gas absorption, or gas absorption hybrid heat pump system, using dwellings with an HR107 gas boiler as a reference, split into the five different building parameters.

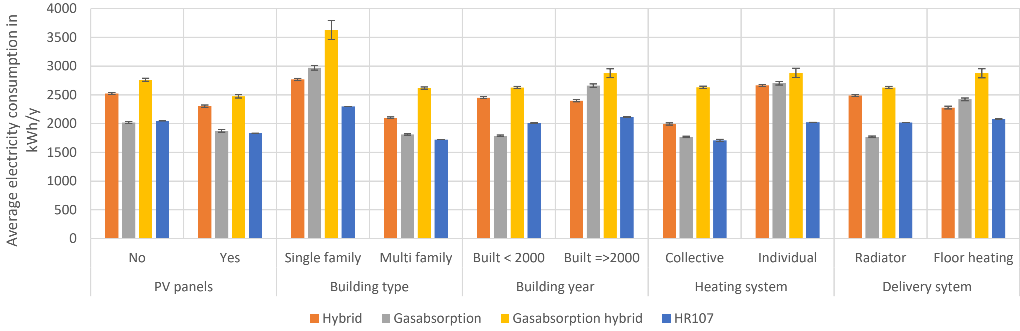

FIG. 4.6 Average electricity consumption of dwellings by heat pump system by building parameter

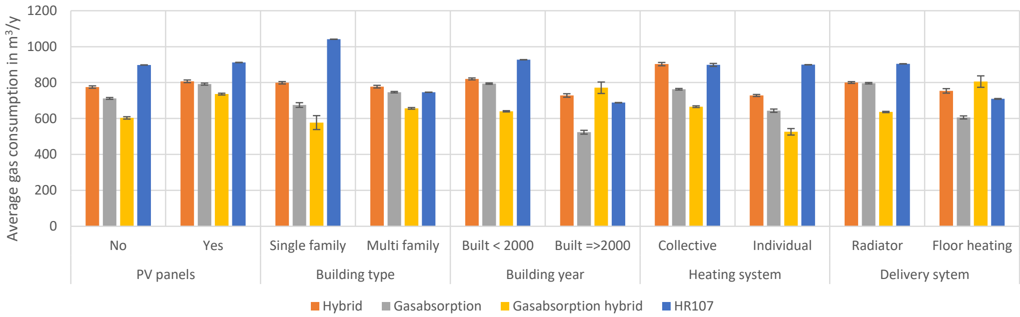

FIG. 4.7 Average gas consumption of dwellings with heat pump system by building parameter

These graphs show that dwellings with PV panels have a lower, but still significant, electricity consumption. Multi-family dwellings have a lower energy consumption than single-family dwellings. Dwellings built before 2000 have a lower electricity consumption, but a higher gas consumption for the different heat pump types. Dwellings with collective heating systems, on average, have a lower electricity consumption, but a higher gas consumption. And finally, the graph shows small differences in gas and electricity consumption between dwellings with radiators and underfloor heating.

4.4 Limitations

Several limitations apply to this research. One limitation is that the research only examines dwellings with tenants from non-profit housing associations. An extension of this research could make the research results applicable to privately owned dwellings as well. A second limitation is that this research shows average building characteristics and the average energy consumption of the current non-profit housing stock with heat pumps. This is not necessarily the average quality of future dwellings which are built or renovated with a heat pump system. Therefore it should be argued that extrapolating these results to the future includes a large uncertainty. A third limitation is that this research covered a large sample size of dwellings with heat pumps, but lacks detailed information about the heat pumps installed; for example: the installed type, COP, power or layout of the heat pump system, etc. Detailed case studies could reveal if certain types, or configurations, of heat pump systems increase the performance. The study was not detailed enough to reveal those benefits.

4.5 Discussion

Despite the limitations, the research does deliver added value as opposed to other studies and the Dutch context. The research provides an overview of the energy consumption of dwellings with heat pumps owned by Dutch non-profit housing associations and delivers added value, due to the analysis of the large dataset with several different heat pump systems, the detailed discussion of building characteristics, and insights on actual energy consumption. The research reports the average electricity and gas consumption of dwellings with different heat pump systems and different building characteristics, as opposed to dwellings with a traditional HR107 gas boiler. This research is one of the first studies that presents insight into the actual energy consumption of dwellings with heat pumps on such a large scale. Other researchers can benefit from the research approach and the results presented as an outline to examine the energy performance of dwellings with heat pumps in other regions, therewith contributing to a well-founded knowledge base in light of the global energy transition in the built environment. The study also delivers added value within the Dutch context. The Dutch built environment is moving towards a CO_2 neutral energy system by 2050. In the Dutch Climate Agreement (2019) a neighborhood-oriented approach was chosen to determine future CO_2 neutral heat sources for every neighborhood. Converting the energy system to all-electric heat pumps is one of the strategies. Dwellings owned by non-profit housing associations are present in these neighborhoods, as one-third of Dutch dwellings is owned by Dutch non-profit housing associations. The research shows that dwellings with all-electric heat pumps show a 75% higher electricity consumption compared to dwellings with a traditional HR107 gas boiler. This takes into account a significant increase in the quality of the dwelling, as mentioned in Table 4.3. The increase of the electricity demand would place a significant strain on the power grid. Moreover, the increase in PV panels on these dwellings will also increase the demand on the power grid through the difference between production and consumption in the summer-winter cycle. This means that with a large-scale adoption of all-electric heat pumps and PV panels, the capacity of the electricity grid will need to be increased. This should be covered by this neighborhood approach. Although heat pumps are mostly installed in newly constructed dwellings, the results did not show a lower performance in dwellings that were renovated with an all-electric heat pump. Hybrid heat pumps or gas absorption heat pumps are a proposed temporary solution to decrease gas consumption and related CO_2 emissions in the period up to 2050, without the need to strongly increase the building quality of a dwelling, and more specifically, the thermal quality of the outer shell. The research shows that dwellings with hybrid or gas absorption heat pumps have lower gas consumption ranging between 13% to 28%, compared to dwellings with a standard HR107 heating gas boiler, and higher average electricity consumption of up to 50%, with an increase in the average building quality. The gas savings reported by Lu et al. (2020) and Famiglietti et al. (2021) are higher than the reported difference in gas consumption in this research. The differences in energy consumption cannot be attributed solely to the differences in the type of heating system. As shown in Table 4.3, the characteristics of the dwellings also differ between the types of heating system. And, from previous studies, it is known that there is a relation between the characteristics of a dwelling and type of occupants, which, of course, has an influence on the energy consumption (van den Brom, Meijer, & Visscher, 2018). Further, this research did not have enough detailed data to inspect aspects like the commissioning and maintenance of the heat pumps. Studies have shown that wrong commissioning and lack of maintenance can have a significant impact on a building’s energy consumption (Burman, Mumovic, & Kimpian, 2014; Gleeson, 2016). Further research is recommended to give more insight into the energy performance of more specific types of hybrid and gas absorption heat pump systems.

4.6 Conclusion

The research concludes that achieving energy efficiency in the built environment requires extensive efforts in the renovation and adaptation of the housing stock. A promising design solution is the heat pump. The energy performance of dwellings with different types of heat pump in Dutch non-profit housing stock has been examined to gain insights into their performance. The characteristics and the average actual energy consumption of these dwellings have been determined and compared to dwellings with a traditional HR107 condensing gas boiler.
In 2021, 3.2% of the dwellings owned by non-profit housing associations operated with a heat pump, consisting of all-electric heat pump systems (1.2%), hybrid systems (0.8%), gas absorption heat pumps (0.6%), gas absorption hybrid systems (0.4%) and other configurations (0.2%). Dwellings with all-electric heat pumps have an average higher building quality with more PV panels, no gas consumption, and a higher electricity consumption, than dwellings with hybrid or gas absorption heat pumps, which have an average higher building quality, lower gas consumption, and higher electricity consumption than dwellings with a traditional HR107 gas boiler. Further research is recommended to determine the energy performance of dwellings with specific heat pump configurations in light of the energy transition in the built environment.

Disclosure statement

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5 Benchmarking energy performance

Indicators and models for Dutch housing associations

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ABSTRACT

Benchmarking is a method that can be used to measure progress and to create awareness about the performance of organizations. Benchmarking the housing stock energy performance of Dutch housing associations can be used to measure and assess progress towards the decarbonization of the housing stock. A new national climate agreement was signed in 2019 and in 2021 a new method to determine the theoretical energy performance of dwellings came into force in the Netherlands. To be able to benchmark the energy performance, a set of indicators is created that adequately represents the performance of Dutch housing associations according to the changed policies. A process involving key stakeholders is presented here to identify, assess and combine possible indicators. These were then integrated into four integrated models which led to a final benchmark model. A model was chosen which consists of three indicators covering the energy performance of Dutch housing associations. The process and arguments which led to this final model are presented. While applicable within the Dutch context, the method and research results provide generalizable insights for the creation of energy performance benchmarks for building stocks.

PRACTICE RELEVANCE

This paper provides both researchers and policymakers with a practical approach to monitor and benchmark the energy performance of dwellings owned by organizations. An analysis of the Dutch policy context is presented. Examples of possible benchmark indicators are described and evaluated. A method is created to assess indicators and it is shown how to integrate indicators in different benchmark models. The final model consists of three indicators: (1) the average theoretical primary fossil energy consumption (energy label value), (2) the difference between the theoretical heating demand (quality building envelope) and the theoretical maximum heating demand of dwellings, and (3) the average actual CO_2 emissions from gas consumption. Researchers and policymakers from other countries can adapt both the process and the final benchmark model to create similar benchmark models across housing stocks.

KEYWORDS Non-profit housing associations, energy performance, benchmark model.

5.1 Introduction

The United Nations agreed to keep global warming below 2 °C and continue efforts to limit it to 1.5 °C (UNFCCC, 2015). Subsequent UN conferences of the parties (COP) agreed to limit the effects of climate change, up to the Glasgow Climate Pact (UNFCCC, 2021). With worldwide CO_2 emissions of over 10Gt per year (IEA, 2020), the built environment is an important factor. Decarbonizing the energy system in the built environment is a major challenge. This challenge is adopted at a European level, among others through the Energy Performance of Buildings Directive (EPBD) (European Commission, 2018) and adopted at national levels into national policies.

In 2021, Dutch national policy on the sustainable development of the Dutch built environment entered a new phase. A new national climate agreement was signed in 2019 (*National Climate Agreement*, 2019) and a new method to determine the theoretical energy performance of dwellings came into force in 2021 (NEN, 2020). These changes (among others) influence how Dutch non-profit housing associations measure the energy performance of their building stock.

Dutch non-profit housing associations (hereafter called housing associations) own 2.4 million dwellings, organized in 286 housing associations in 2021. This means one-third of the Dutch housing stock is owned by social housing associations (Autoriteit Woningcorporaties, 2020). Other European countries with a large share of social housing are Austria 24%, Denmark 21%, Sweden 17%, UK 17%, France 16%, Norway 14%, and Finland 11% (Housing Europe, 2021). Therefore, the non-profit housing stock plays an important role in helping to fulfil the Paris Climate Agreement.

Benchmarking is a method to measure progress and to create awareness about the performance of organizations in relation to goals. Benchmarking can be defined as: "a continuous analysis of strategies, functions, processes, products or services, performances, etc. compared within or between best-in-class organizations by obtaining information through appropriate data collection method, with the intention of assessing an organization's current standards and thereby carry out self-improvement by implementing changes to scale or exceed those standards" (Anand & Kodali, 2008). This paper examines the process of making a model to benchmark the energy performance of the housing stock of Dutch non-profit housing associations.

5.1.1 Benchmarking the energy performance of dwellings

The Paris Climate Agreement requires actions to reduce global warming worldwide, including in the built environment. The sustainable development of the housing stock is a challenge for many countries and is the subject of several papers which discuss the sustainable development of the housing stock, e.g. Bulgaria, Serbia, Hungary, Czech Republic (Csoknyai et al., 2016), Sweden (Hjortling et al., 2017), Switzerland (Streicher et al., 2018), Ireland (Ahern & Norton, 2019), and The Netherlands (van der Bent, Visscher, et al., 2021). These papers describe changes of (parts of) the housing stock using many different descriptive parameters, without the aim to benchmark the progress.

Several papers seek to find appropriate conditions for establishing accurate models to benchmark the energy performance. Jiang et al. (2014) highlight the importance of establishing accurate and efficient databases to have a sound basis to assess and monitor the improvement of the energy performance of several types of Chinese buildings. They stress the need for clear definitions and discuss differences in indicators to be used in benchmarks. They argue for indicators that include both technical and non-technical measures. Moreover, besides the energy performance unit of $kWh/m^2/yr$ used for assessing the overall energy performance, the unit of $kg\ CO_2/m^2/yr$ could be used for assessing the CO_2 emissions of buildings.

However, Jiang et al. (2014) do not extrapolate their research to an organizational level and do not address the possibility of a performance gap between theoretical and actual energy consumption. This performance gap can be defined as the difference between the theoretical modelling of energy consumption through the EPBD and the actual energy consumption of dwellings, and is acknowledged throughout several papers covering multiple countries (Sunikka-Blank & Galvin, 2012; Saunders, 2015; Summerfield et al., 2019; Cozza et al., 2020). Reasons for the performance gap are an inadequate assumption of the actual indoor temperature, the influence of user behaviour on actual consumption, and differences between the theoretical calculation and the actual building quality of dwellings. Aranda et al. (2018) found that the energy performance gap for social housing is even larger than energy performance gaps found for other dwellings.

Duvier et al. (2018) argue that it can be difficult to build and use high-quality datasets. They considered the UK social housing sector and argue that utilizing the potential is difficult due to the constant changes of regulations which makes it difficult to develop long-term strategies. However, Steadman et al. (2020) give an example of large-scale available data within the UK to monitor and benchmark the energy performance of buildings. Ding and Liu (2020) compared several data-driven methods to benchmark the energy performance of individual dwellings. They highlight the need for high-quality data and the need for robust benchmark models. They address that different indicators could lead to a different ranking of subjects, and recommend policymakers to consider multiple benchmarking methods or to select a method, while being aware of what they actually measure. Although they do not apply this to housing associations, but on the level of individual dwellings.

Roth et al. (2020) examined the possibilities of using open data to benchmark building energy consumption in cities. They conclude benchmarking by itself will not lead to energy savings, but benchmarking the energy consumption of dwellings can help to develop effective policies to lower actual energy consumption. Benchmarking the average energy performance of the housing stock of housing organizations could lead to similar results. Laaroussi et al. (2020) realize that the large amount of energy used by residential buildings means that the renovation of the building stock is one of the key strategies to reach energy performance targets. As a part of a European H2020 project, they analyzed the situation in Spain, France, Italy, Slovenia, and Austria and used a weighted method as an analytic approach to evaluate the main indicators of collected data. Bordass (2020) analyzed in his research different metrics for benchmarking the energy performance of buildings. He argues benchmarks should not only focus on a single most important indicator, but a more diverse range of indicators could help users of benchmarks to take the correct actions. Too few indicators may lead to wrong decision-making. Furthermore, too many indicators leads to fogginess and also to wrong decision-making. Although applied to individual dwellings this is applicable for benchmarking the energy performance of large sets of dwellings as well.

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Several lessons arise from this literature:

- Benchmarking the energy performance can help to make effective interventions to realize energy savings (Laaroussi et al., 2020; Roth et al., 2020).
- Different metrics should be examined (Bordass, 2020), e.g. kWh/m^2/yr and kg CO_2/m^2/yr (Jiang et al. (2014).
- Measuring only the energy label indicator through the EPBD could be inaccurate due to the energy performance gap (Sunikka-Blank & Galvin, 2012; Saunders, 2015; Summerfield et al., 2019; Cozza et al., 2020).
- High-quality datasets should be used as a basis for measuring and benchmarking (Jiang et al., 2014; Duvier et al., 2018; Steadman et al., 2020).
- Using a weighted method as an analytic approach can contribute to the selection of main indicators (Laaroussi et al., 2020).
- Examining multiple benchmark models to select a robust method is recommended (Ding & Liu, 2020).
- A benchmark with too few indicators, but also with too many indicators may lead to wrong decision making (Bordass, 2020).

5.1.2 Dutch context: Benchmarking and housing associations

The definition of benchmarking by Anand and Kodali (2008) indicates benchmarking the energy performance of dwellings could be useful on an organization level as well. Aedes, the Dutch umbrella organization of housing associations located in The Hague, organizes a benchmark between housing associations since 2014, covering topics like overhead costs, maintenance, tenant appreciation, availability and affordability, and energy performance (Aedes, 2020). The benchmark helps to enhance the knowledge and factual basis about the development of the Dutch built environment owned by non-profit housing associations. Until 2020, the benchmark for the energy performance consisted of two indicators, (1) the energy label value: the average Energy Index Nader Voorschrift (EI NV) and (2) the average actual CO_2 emissions from the heating demand through gas consumption and district heating. Due to changes in policy these indicators need to be adjusted.

Social housing in the Netherlands has its origin in the industrial revolution when the *Vereeniging ten behoeve der Arbeidersklasse te Amsterdam* (Association for the benefit of the working class in Amsterdam) was established in 1852 (Boissevain, 1865). The housing Act of 1901 provided the means for state funding for social housing organizations, which as a result grew in number and size. A policy change in 1995, the so-called *"bruttering"* (Netherlands & Schorer, 2004), made social housing organizations financially independent and focused their role as social entrepreneurs. In 2020, one-third of the Netherlands' housing stock was owned by social housing associations. (Autoriteit Woningcorporaties, 2020). The social housing stock of 2.4 million dwellings is organized in 286 housing associations. Housing associations are able to make decisions on how to manage their housing stock but are regulated by strong central law (Woningwet, 2018). For example, laws govern the allocation of tenants, maximum rents, and the sustainable transformation of dwellings. Housing associations in the Netherlands cover a broad range of organisations. Some are small (<1.000 dwellings), while others are large (>80,000 dwellings). Some operate mainly in urban environments, while other housing associations own assets in more rural areas. Also, differences occur in the financial position of Dutch non-profit housing associations. Housing associations also have different types of dwellings. Some have relatively new dwellings, for example, in the province of Flevoland, which is largely a polder that was developed in the second half of the 20th century. Other housing associations own old dwellings in historical city centers. Also, differences occur in the quality of the dwellings regarding the energy performance. Some housing associations improved the energy performance of their stock extensively, while others have a stock with a lower energy performance, as benchmarked in the Dutch context up to 2020 (Aedes, 2020).

Policies aimed at increasing the energy performance of dwellings of non-profit housing associations originate from the Energy Agreement (Sociaal Economische Raad, 2013). Until 2020, the aim was to achieve an average energy label B in 2020 as directed from the Energy Performance of Building Directive (EPBD), as analyzed in van der Bent, Visscher, et al. (2021).

In 2021, national policy on the sustainable development of the Dutch built environment entered a new phase. A new national climate agreement was signed in 2019 (National Climate Agreement, 2019) and a new method to determine the theoretical energy performance of dwellings came into force in 2021, the NTA8800 (NEN, 2020). These changing policies affect the measuring of the energy performance, and consequently the benchmarking of the energy performance of the housing stock of Dutch non-profit housing associations. These policies are further discussed in phase 1 of the results section.

5.1.3 Research question

No scientific research was found regarding the process of creating a benchmark for the energy performance of the housings stock of housing organizations. Creating a benchmark model is relevant both in the Dutch context and for the international community, helping to move to a sustainable built environment. Researchers and policymakers from other countries can benefit both from the following process as well from the final benchmark model to create similar benchmark models across their housing stock. Dutch non-profit housing associations aim to benchmark the energy performance of the non-profit housing stock, given the changes in policy derived from the National Climate agreement 2019 (*National Climate Agreement*, 2019) and the enforcement of the NTA8800 (NEN, 2020) in 2021.

The aim of the present research is to find a set of indicators that adequately represents the performance of Dutch housing associations according to the changed policies. The research question is therefore: Which set of indicators can be used to benchmark the energy performance of Dutch housing associations and what can we learn from the process to find these indicators?

5.2 Research method

The research method used is a combination of desk research with action research where the principal researcher participated in group sessions with experts from Dutch housing associations. The expert group consisted of eighteen employees from housing associations and two employees of Aedes, the umbrella organization of housing associations. The expert group guided the existing benchmark until 2020 and now guides the adjustment of the benchmark model beyond 2021. The group was a mix representing both small and large housing associations, from different parts of the Netherlands, operating in different parts of the non-profit housing stock, both rural and in cities. Staff members in this group typically have several to many years (10+) of working experience in the field of sustainable development of housing associations and typically have job descriptions related to the strategic advisory of sustainable development or the actual planning of sustainable projects at housing associations. Based on availability they attended sessions following phase 2 to 4 as described below, usually 12 to 15 attendees. Decisions were made on shared agreement after discussion sessions following the phases. Two different advisory groups of Aedes comprising directors of housing associations and the general board of Aedes, also comprising directors of housing associations, were involved in the selection of the final model. The advisory groups and the general board are part of the decision making structure of Aedes, the umbrella organization of Dutch housing associations.

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Seven phases are distinguished in this research: policy review, identifying available data, assessment of indicators, integration in benchmark models, selection of benchmark model, data collection, and benchmark results. These phases were not predetermined, but suggested throughout the process by the principal researcher and acknowledged by the expert group. The phases took place between September 2020 and December 2021 as specified in Table 5.1.

TABLE 5.1 Research phases and participation

Phase	Group	Period
1: Policy review	Expert group	2020: Sept
2: Identify available data	Expert group	2020: Sept.
3: Assessment of indicators	Expert group	2020: Oct.
4: Integration in benchmark models	Expert group	2020: Nov.
5: Selection of benchmark model	Two directors groups & general board Aedes	2021: Jan. & Apr.
6: Data collection	Principal researcher	2021: Jun-Aug.
7: Benchmark results	Principal researcher	2021: Sept-Dec

Phase 1 consists of a policy review, to identify relevant incentives for housing associations. Phase 2 consists of desk research where available benchmark indicators were identified from available data sources. After this phase, a group session with expert staff members from housing associations was organized, where they discussed the policy review and confirmed the list of available indicators. Phase 3 consists of an assessment of the available indicators using a weighted multi-criteria approach with five assessment criteria to narrow down the identified options in phase two to a smaller list of viable options. The assessment of the available indicators ended with a group session of the expert group confirming the assessment of the available indicators. Phase 4 consists of a desk assessment and expert group discussion about four integrated models with indicators to measure the sustainable development of Dutch housing associations. The expert group confirmed the four selected models and proposed a final model. Phase 5 consists of a group discussion with two different advisory groups of directors of housing associations. They analyzed and judged the four selected models. The general board of Aedes, also comprising directors of housing associations, affirmed the selected final model. Phase 6 consists of the data collection used for benchmarking and phase 7 describes shortly the results of the benchmark.

5.3 Results

The results of this research are described according to the phases in the research method section.

5.3.1 Phase 1: Policy review

The first phase consisted of a policy review. The aim was to understand the policy context relevant for benchmarking the energy performance of housing associations.

In the summer of 2019, a new Climate Agreement (National Climate Agreement, 2019) was agreed between the Dutch Government, Dutch companies, and organizations, to mitigate climate change in agreement with European goals. The Climate Agreement is enforced with legislation and further specified agreements with businesses and sector organizations. For the Dutch non-profit housing sector, several policies apply. A generic goal was formulated to lower CO2 emissions from the built environment. This is framed as the fossil fuel (natural gas) consumption used by the built environment (primarily for space heating and water heating). This is enforced with several policies discussed below. These policies are different from those resulting from the Climate Agreement in 2013 (Sociaal Economische Raad, 2013), where it was agreed that the housing stock of housing associations should obtain an average energy label B in 2020, based on the theoretical energy performance of buildings calculation. Newly proposed policies from the Climate Agreement 2019 do not enforce a goal expressed as energy label. These proposed policies relevant to housing associations are the neighborhood-oriented approach, subsidies to accelerate the rate of the renovation, and the proposed introduction of a theoretical maximum heating demand for dwellings.

The neighborhood-oriented approach is a policy that is driven by municipalities. It aims to enhance a sustainable energy system by coordinating actions of (local) authorities, energy infrastructure companies, local companies, inhabitants, and also housing associations. Regional and local development plans are written to combine the availability of heat, the quality of the energy infrastructure, and the energy demand from buildings and companies. With one-third of the Dutch housing stock owned by non-profit housing associations, they are an important stakeholder in this neighborhood-oriented approach. Policy aiming to accelerate the renovation pace of housing associations consists of two main subsidies. A subsidy for district heating solutions and a subsidy to increase renovations by bundling demand and coupling it to innovative steady supplies. The new policy introducing a theoretical maximum heating demand for dwellings in 2050 aims to lower the energy demand of dwellings by improving the quality of the building envelope.

These policies are successors of the old policy where housing associations aimed at improving the energy performance of dwellings to an average energy label B. These new policies form a wider approach with different incentives to improve the energetic quality of the non-profit housing stock. These incentives are mainly aimed at the energy performance of dwellings, with an aim to decrease of energy consumption during the operation phase of dwellings.

Following European regulations from the Energy Performance of Buildings Directive (EPBD), an improved calculation method for the theoretical energy performance of buildings is enforced in the Netherlands from 2021, via the NTA8800 (NEN, 2020). This improved calculation method has some major changes as opposed to its predecessor the NEN7120 NV, as examined by van der Bent, Visscher, et al. (2021). Previously, the energy label had a dimensionless value: the theoretical energy index (a calculation of the theoretical energy use, divided by a combination of floor area and building envelope area). The new energy label value is still based on a theoretical energy consumption, but divided only by the floor area. Therefore it can be expressed in the dimension of kWh/m2/yr. Also, the calculation of the theoretical energy consumption is improved and updated regarding characteristics of building installations and building physics.

5.3.2 Phase 2: Data available for benchmarking

In the second phase, available indicators for benchmarking the sustainable development of Dutch non-profit housing associations were identified by the principal researcher in consultation with the expert group. High-quality datasets are recommended as a basis for measuring and benchmarking (Jiang et al., 2014; Duvier et al., 2018; Steadman et al., 2020). Different metrics should be examined (Bordass, 2020), where the units kWh/m^2/yr and kg CO_2/m^2/yr are specifically mentioned by Jiang et al. (2014). A combination of desk research, expert knowledge from the principal researcher, and expert knowledge from the expert group led to the identification of three main data sources which are available to benchmark the sustainable development of Dutch non-profit housing associations. These are the SHAERE database, the dVi database, and data from the Central Bureau of Statistics

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(CBS). Creating new data sources was not considered feasible due to high overhead costs to collect new data.

A SHAERE database

The SHAERE database is maintained by Aedes. Data on building characteristics and energy performance of the individual dwellings of voluntarily participating housing associations are collected annually as a basis for the existing benchmark. In 2021 the structure of the database was adapted to the implementation of the NTA8800. The database is filled with data that is exported from software to administrate the energy performance of dwellings. This software is called VABI Assets Energy. Every housing association with this software is able to export their dwellings' data with descriptive parameters of each of their dwellings. Over 90 percent of housing associations use this software. However, some mostly smaller housing associations do not, mainly due to the cost, hence they are not able to deliver this data. The exports are gathered in a central data management environment. Main indicators are the theoretical primary fossil energy consumption, energy label, heating demand, maximum theoretical heating demand, type of heating systems, type of ventilation systems, insulation components of the outer shell, and installed solar systems.

B dVi

The dVi is a different central database, among others managed by the Dutch Ministry of Internal Affairs. It collects many indicators about housing associations, one being the energy index (energy label value up to 2020) of every dwelling of social housing associations. This is only a single indicator, without other clarifying indicators about the quality of the dwelling. Every housing association is obliged by law to deliver this data.

C CBS

The Central Bureau of Statistics (CBS) collects the actual energy consumption of individual dwellings, consisting of gas consumption and electricity consumption, which are available under an anonymization procedure. The anonymization assures no ethical issues arise during the collection and handling of data. Energy consumption for district heating is not available at the CBS, but some housing associations are able to provide these data separately.

From these sources, a list of potential indicators was extracted to measure the development of the energy performance of the housing stock of Dutch housing associations. A proposal was made by the principal researcher to the expert group which discussed and agreed that these twelve indicators are options to consider measuring the development of Dutch non-profit housing associations. The potential indicators are listed in Table 5.2.

TABLE 5.2 Possible indicators describing the energy performance of dwellings

Possible indicator	Unit	Source	Description
1. Average theoretical primary fossil energy consumption	kWh/m2/yr	SHAERE	Energy label value after 2020 under the NTA8800. Based on a theoretical energy consumption divided by floor area.
2. Average theoretical energy-index	number	dVi	Energy label value up to 2020.
3. Average number of label steps in energy label	number	SHAERE	Average number of energy label steps after 2020 under the NTA8800.
4. Average theoretical heating demand	kWh/m2/yr	SHAERE	Theoretical unit of measurement of the heating demand of dwellings.
5. Average difference heating demand and maximum heating demand	kWh/m2/yr	SHAERE	Average difference between the heating demand of dwellings (insulation quality) and the maximum heating demand based on the layout and topology.
6. Percentage dwellings complying with maximum heating demand	Percentage	SHAERE	Percentage of dwellings below the maximum heating demand of the dwelling based on its layout and topology.
7. Percentage of dwellings gas-free	Percentage	SHAERE	Percentage of dwellings without a gas-fired heating system.
8. Percentage of dwellings with PV panels	Percentage	SHAERE	Percentage of dwellings with PV panels, and therewith contributing to the production of clean electricity.
9. Indicator mix of building characteristics	Undefined	SHAERE	Undefined combination of building characteristics, however not yet operationalized.
10. Average actual energy consumption (gas + electricity and district heating)	kWh/m2/yr	CBS	Combined average actual energy consumption on a dwelling level per m^2 of the three main energy carriers in the Netherland, gas, electricity, and district heating.
11. Average actual CO2 emission (gas + electricity and district heating)	kgCO2/m2/yr	CBS	Combined average actual CO2 emissions on a dwelling level per m^2 of the three main energy carriers in the Netherland, gas, electricity, and district heating.
12. Average actual CO2 emission (gas)	kgCO2/m2/yr	CBS	Average actual CO2 emissions on a dwelling level per m^2 of gas consumption. CO2 emission within the building.

5.3.3 Phase 3: Indicators most suitable for benchmarking

In the third phase, the indicators from the list were assessed on suitability by scoring the indicators on five assessment criteria by the principal researcher in consultation with the expert group (see below). Using a weighted method as an analytic approach can contribute to the selection of main indicators (Laaroussi et al., 2020). The aim of this phase was to narrow down the identified options in phase two to a smaller list of viable options. The criteria to assess the identified options were determined by the principal researcher and validated by the expert group. The five criteria aim to ensure indicators are effectual (available and comparable), are communicable (recognizable), and relate to policy (both on national level and as perceived by housing associations). The five criteria are:

A Availability of the data
B Comparability of the data
C recognisability of the indicator
D Relation to national policy
E Relation to housing association policy

Each possible indicator was scored with a number ranging from -2 (totally non-compliant) to +2 (totally compliant). A weighting factor of 1 was given to the criteria, availability, comparability, and recognisability, and a weighting factor of 2 was given to the criteria: the relation to national policy and the relation to housing association policy, because these last two are regarded as more important by the expert group. This led to the following scoring table as shown in Table 5.3.

TABLE 5.3 Assessment of indicators with scoring table

Weighting factor assessment criteria	1	1	1	2	2		
	Availability	Comparability	Recognizability	National policy	H. a. policy	Total	Selected next phase
Building indicator							
1. Average theoretical primary fossil energy consumption	1	1	1	2	2	11	x
2. Average theoretical energy-index	-2	-2	1	-1	0	-5	
3. Average number of label steps in energy label	1	1	1	-1	-1	-1	
Insulation indicators							
4. Average theoretical heating demand	1	0	1	-1	-1	-2	
5. Average difference heating demand and maximum heating demand	1	1	1	2	1	9	x
6. Percentage of dwellings complying to maximum heating demand	1	1	1	1	1	7	x
Installation indicators							
7. Percentage of dwellings gas-free	1	2	2	1	1	9	x
8. Percentage of dwellings with PV panels	1	2	2	1	1	9	x
9. Indicator mix of building characteristics	1	0	0	0	0	1	
Effect indicator							
10. Average actual energy consumption (gas + electricity + district heat)	-1	0	1	0	1	2	
11. Average actual CO_2 emissions (gas + electricity + district heat)	-1	0	1	1	2	6	x
12. Average actual CO_2 emissions (gas)	0	0	1	2	1	7	x

It was then decided in consultation with the expert group to consider seven indicators scoring above five (see Table 5.3). Five indicators scoring below five are not considered in the next phase. The most salient trade-offs from the assessment of the indicators are described below:

- **Indicator 1:** The average primary fossil energy consumption (value of energy label) scores highest in the assessment. This indicator is available and comparable for housing associations that can generate SHAERE exports and is in line with national and housing association policy. Having an energy label is mandatory for every dwelling.

- **Indicator 2:** The average theoretical energy-index from the dVi scores low. In 2021, the energy label value in the dVi is still the energy index based on the old policy up to 2020 (NEN, 2014). The indicator that will be included from 2022 is not yet known, nor is it available for benchmarking in 2021.

- **Indicator 3:** The average number of label steps does not score well because this does not play an important role in policy.

- **Indicators 4, 5, 6:** The average difference between heating demand (quality building envelope) and the maximum heating demand scores positive on all assessment criteria. It is available, comparable, recognizable, and relates to both national and housing association policies. This can be expressed as indicator 5 the average difference between the heating demand (quality building envelope) and the maximum heating demand in kWh/m^2 or indicator 6 in the percentage of the dwellings that meet the maximum heating demand on a dwelling level.

- **Indicator 7:** The percentage of gas-free dwellings scores well on comparability and recognisability, and is also indirectly linked to policy.

- **Indicator 8:** The percentage of dwellings with PV panels scores well on comparability and recognisability, and is in line with policy in a broad social sense.

- **Indicator 9:** A mix of housing indicators scores low because it is not in line with comparability and recognizability, and has no direct link with policy.

- **Indicator 10:** The actual consumption in kWh of gas, electricity, and district heating is not directly in line with policy. The availability of actual district heating consumption is problematic, because these are not available by the Dutch Central Bureau of Statistics, but must be collected separately from housing associations.

- **Indicator 11:** The actual CO_2 emission from gas, electricity, and district heating is less in line with national policy where gas is attributed to the built environment and CO_2 emissions from electricity and district heating are attributed to the industrial sector. The availability of actual heat consumption is less good, because these are not available by the Dutch Central Bureau of Statistics, but must be collected separately from housing associations.

- **Indicator 12:** The actual CO_2 emission from gas consumption alone is more in line with the national objectives from the Climate Agreement for the built environment. This indicator scores better on availability because the actual gas consumption is available at the Dutch Central Bureau of Statistics.

5.3.4 Phase 4: Integration in benchmark models

In the fourth phase, the available and ranked indicators were integrated by the principal researcher in consultation with the expert group in different benchmark models consisting of one or several indicators. Examining multiple benchmark models to select a robust model is recommended by Ding & Liu (2020). This was done to be able to assess relations between indicators. The integrated models all have a different bandwidth of benchmarking, ranging from a small model (housing associations are benchmarked on a single indicator) to a wide model (housing associations are benchmarked on six indicators). The different combinations of indicators were determined by the principal researcher and validated by the expert group. The combinations are shown in Table 5.4. We gave the four benchmark models a name with a description, explaining the nature of the combination of indicators.

1. The basic model — Focusing on a single indicator
2. The real estate model — Focusing on real estate
3. The policy performance model — Focusing on policy
4. The wide model — Focusing on a broad spectrum

TABLE 5.4 Schematization of the four proposed benchmark models

	Basic model	Real estate model	Policy performance model	Wide model (/ = or)
1. Average theoretical primary fossil energy consumption	x	x	x	x
5. Percentage of dwellings complying to maximum heating demand		x		/
6. Average difference heating demand and maximum heating demand			x	/
7. Percentage of dwellings gas-free		x		x
8. Percentage of dwellings with PV panels		x		x
11. Average actual CO2 emissions (gas + electricity + district heat)				x
12. Average actual CO2 emissions (gas)			x	x

In the expert group, the advantages and disadvantages of these benchmark models were discussed. These are described as:

1 The basic model

- *Advantages:* Having one indicator makes benchmarking the energy performance transparent. The average value of the energy label scores highest in the assessment, lies within the direct sphere of influence of housing associations, and is also recognizable and communicable.
- *Disadvantages:* In the Climate Agreement 2019 improving the energy label value is not a single dominant policy and therefore leads to a non-optimal focus. Also, an assessment of the performance based on a single indicator can be interpreted as limited (Bordass, 2020).

2 The real estate model

- *Advantages:* It gives housing associations space to make their own real estate strategy visible in the energy performance assessment. This then applies to the commitment to making dwellings gas-free, the installation of PV panels, and the quality of the building envelope of dwellings.
- *Disadvantages:* The indicators gas-free, share of PV panels and quality of the building envelope can be seen as input for the primary fossil energy demand (the energy label) and from a benchmark perspective it is better to benchmark double indicators only in the top indicator. There is also a policy goal for the maximum heating demand, but not for the share of PV panels, and not for the share of natural gas-free homes.

3 The policy performance model

- *Advantages:* This combination of indicators is best in line with policy objectives: having an energy label, improving dwellings to the maximum heat demand, and the Climate Agreement target to reduce CO_2 emissions from the built environment by reducing CO_2 emissions from gas consumption.
- *Disadvantages:* The actual CO_2 emissions from gas consumption are an outcome of policy, but do not lie within the entire sphere of influence of a corporation. For example, the behaviour of the resident and the price of natural gas also influence gas consumption.

4 The wide model

- *Advantages:* This model makes many nuances of the sustainability performance transparent by the various indicators.
- *Disadvantages:* From a benchmark perspective, a large number of indicators is less desirable and ambiguous (Bordass, 2020). As in the real estate variant, this applies

to the indicator share of natural gas-free and share of PV panels. Finally, as in the policy variant, the actual CO_2 emissions from natural gas consumption do not lie within the entire sphere of influence of the corporation, but this applies even less to the actual CO_2 emissions from electricity and heat. Actual electricity use has an even stronger resident component (household consumption) and the responsibility for CO_2 emissions from electricity generation is a responsibility of the industrial sector in the Dutch Climate Agreement

5.3.5 Phase 5: Selecting the final model

The fifth phase consists of a group discussion of two advisory groups of housing association directors. They analyzed and judged the four proposed models and agreed with the proposal of the expert group to select the policy performance model as the final model. The combination of three indicators in the policy performance model most accurately reflects efforts of housing associations to improve the average energy performance of their housings stocks in accordance with the current policies. The general board of Aedes, the umbrella organization of housing associations, affirmed the selected policy performance model. Therefore the selected benchmark model consists of three indicators:

1. The average theoretical primary fossil energy consumption,
2. the average difference between the theoretical heating demand (quality building envelope) and the theoretical maximum heating demand, and
3. the average actual CO2 emissions from gas consumption.

5.3.6 Phase 6: Data collection

Data were collected in June and July 2021, commissioned by Aedes, and executed by the principal researcher. Housing associations voluntarily delivered a standardized data export with indicators of the energetic quality of their dwellings, together forming the SHAERE database. 246 housing associations participated with over 2 million dwellings, covering 95% of the Dutch non-profit housing sector. This data source delivered data for indicators 1 and 2. In August 2021, the dwellings were anonymously connected to actual energy consumption data in an analysis environment at the Dutch Central Bureau of Statistics (CBS) to be able to deliver data for indicator 3. The anonymization assured no ethical issues arose during the collection and handling of data.

5.3.7 Phase 7: Benchmark results

Figures 5-1, 5-2, and 5-3 give a visual representation of the ranking of the housing associations according to the three indicators of the selected benchmark model. A more extensive description of the benchmark results was published by Aedes as part of a wider benchmark of the Dutch non-profit housing sector (Aedes, 2021). No absolute benchmark values are stated for the different indicators. In this wider benchmark housing associations are scored with an A, B, or C, respectively one-third of the population per indicator, accompanied by a more detailed dataset with secondary indicators to enhance learning opportunities from the benchmark results.

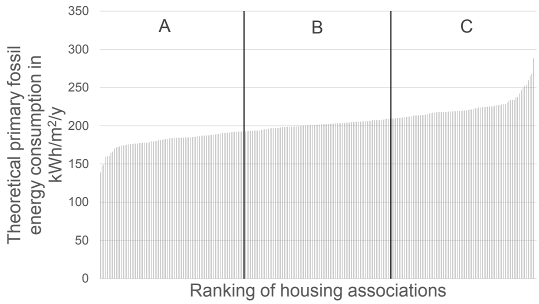

FIG. 5.1 Housing associations ranked by average theoretical primary fossil energy consumption

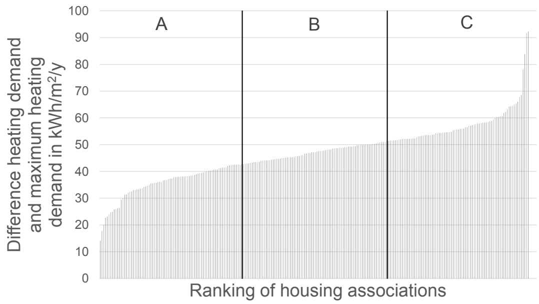

FIG. 5.2 Housing associations ranked by average difference between theoretical heating demand and maximum theoretical heating demand

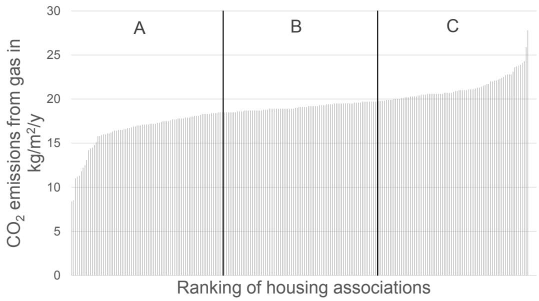

FIG. 5.3 Housing associations ranked by average actual CO_2 emissions from gas

5.4 Discussion

This research addressed the research question: Which set of indicators can be used to benchmark the energy performance of Dutch housing associations and what can we learn from the process to find these indicators? After an extensive process, three indicators were selected that cover the most important policy aspects for the sustainable change of the housing stock of non-profit housing associations. The process was divided into several phases, which helped to arrive at a well-founded benchmark model. During the process several aspects from literature were applied. Different metrics (Bordass, 2020) were examined and the units kWh/m^2/yr and kg CO_2/m^2/yr were applied in the benchmark, complying with Jiang et al. (2014). High-quality datasets were found and used as a basis for measuring and benchmarking (Jiang et al., 2014; Duvier et al., 2018; Steadman et al., 2020). A weighted method as an analytic approach contributed to the selection of main indicators (Laaroussi et al., 2020), and we found that exploring multiple benchmark models could support decision making to a final model (Ding & Liu, 2020).

Several limitations arose. The analysis is country-specific, which means it is only applicable for Dutch non-profit housing associations within the current Dutch policy context. However, the process used to create a benchmark model is generic. A policy analysis, selections of indicators, assessment of indicators, the integration into models, the selection of the final model, data collection, and delivering results are applicable to a wide variety of similar questions in other countries that seek energy performance measurement and benchmarking of the built environment.

A second limitation is the Dutch specific policy context: where the built environment focus is on the quality of dwellings and the emissions of CO_2 related to the energy consumption within the dwelling. For example, no clear goals or targets are formulated regarding the use of materials in retrofitting dwellings (although these exist for new construction). Moreover, no data is available describing the sustainable use of materials for every housing association. This limits the measurement of the sustainable performance to energy consumption. Other countries may have a different policy context with a wider interpretation of sustainable performance.

A third limitation within the Dutch policy context is the presence of the energy performance gap, widely researched for both the Dutch context (Majcen et al., 2013; Filippidou et al., 2019; van der Bent, van den Brom, et al., 2021) and European context (Laurent et al., 2013; Summerfield et al., 2019). Theoretical indicators measuring the energy performance of dwellings, derived from the EPBD, all have a performance gap: the theoretical energy consumption deviates strongly from actual energy consumption. In the Dutch benchmark model, this is covered to some extent by having three indicators. Two are theoretical, but the third is based on the actual energy consumption of fossil fuel – natural gas (translated to CO_2 emissions). This ensures housing associations also have an incentive to lower actual gas consumption and related CO_2 emissions. Other countries measuring and benchmarking sustainable performance should be aware of this performance gap as well.

Finally, Anand and Kodali (2008) state that benchmarks should be understood as a repetitive process. The results of benchmarking should lead to improvement in organizations, so the effectiveness of the benchmark model needs to be reviewed and updated periodically. During our research we were not able to close this loop for time reasons, but a suggestion for improvement would be to include this in future research.

5.5 Conclusion

A process was created for formulating an energy performance benchmark for Dutch housing associations. A similar process can be used by other researchers aiming at benchmarking the energy performance between organizations within their policy context. The final policy performance model to measure and benchmark the sustainable performance of Dutch housing associations consists of three indicators closely related to governing policies regarding the sustainable improvement of the Dutch non-profit housing sector: The average theoretical primary fossil energy consumption, the average difference between the theoretical heating demand (quality building envelope) and the maximum theoretical heating demand, and the average actual CO2 emissions from gas consumption. The first indicator is related to the current policy regarding the energy labeling of dwellings, derived from the EPBD, the NTA8800. The second indicator relates to the policy to decrease the average theoretical heat demand of dwellings. The third indicator is related to the goal for the Dutch built environment to lower actual CO2 emissions. The model was then used to collect data and benchmark the energy performance of dwellings of housing associations. This research contributes to the wider literature by creating a model for benchmarking the energy performance of dwellings within the relevant policy context. This will be increasingly relevant for policymakers and landlords who need to respond to the UN Paris Agreement by reducing GHG emissions.

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Author contributions

The first author was responsible for conceptualization, data collection, methodology, analysis, and writing. The second author was responsible for funding, review, and editing. The third and fourth authors contributed in review and editing.

Competing interests

The authors have no competing interests to declare.

Data availability

Data used in the research project is not publically available, due to restrictions of ownership.

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6 Conclusions, limitations, and recommendations

6.1 Introduction

The main aim of the thesis is to assess and understand the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock. This was done by performing four related studies.

- **Study 1: Monitoring energy performance improvement:** *insights from Dutch housing association dwellings*
- **Study 2: The energy performance of dwellings of Dutch non-profit housing associations:** *modelling actual energy consumption*
- **Study 3: The energy consumption of dwellings with heat pumps of Dutch non-profit housing associations**
- **Study 4: Benchmarking energy performance:** *indicators and models for Dutch housing associations*

In the following paragraphs, the key questions of the different studies are answered, an overall conclusion is stated, limitations are specified and the research ends with several recommendations.

6.2 Research questions

In the following paragraphs, the answers to the key research questions of the studies are discussed.

6.2.1 Monitoring energy performance improvement

In the study "Monitoring energy performance improvement: insights from Dutch housing association dwellings", the improvement of the Dutch non-profit housing stock was analysed. The following research questions are answered:

- **RQ 1:** How did the energetic quality of the Dutch non-profit housing stock develop between 2017 and 2020?

It was found that the energy performance of dwellings of Dutch non-profit housing associations improved steadily between 2017 and 2020 from an average Energy Index of 1.73 to an average Energy Index of 1.51 in 2020, according to the energy performance calculation (NEN, 2014), based on the Energy Performance of Buildings Directive (European Commission, 2010). More specifically, the research examined changes in the general characteristics of the Dutch non-profit housing stock, changes in the level of insulation, changes in heating and hot water systems, changes in ventilation systems, changes in solar systems, and changes in cooling systems. General characteristics like size and type do not change much between 2017 and 2020. The average insulation quality of the floor, façade, roof, glazing, and doors increased steadily over the years. The research shows a steady growth of HR107 condensing gas boilers as the main system for heating and hot tap water to 79.8% of the non-profit housing stock in 2020. Future-proof heating systems, like heat pumps and district heat are steadily growing occupying respectively 2.6 and 8.0% in 2020. The research shows an increase in ventilation systems, 5.2% with a mechanical outflow and 1.5% with both mechanical inflow and outflow. PV panels show strong growth, with an increase of 7.1% of the housing stock between 2017 and 2020, while cooling systems are slowly adopted from 0.5% in 2017 to 1.0% of the housing stock in 2020.

- **RQ2:** What is the effect of changes of the stock (construction and demolition) and changes within the stock (renovations) on the energy performance of the Dutch non-profit housing stock from 2017 to 2020?

  The effect of changes of the stock (construction and demolition) to the improvement of the average energy performance is modest (15.6%). The improvement of the average sectoral energy performance happens for 85.4% within the existing stock, mostly with traditional improvements like changing heating installations and adding insulation. Innovative solutions like photovoltaic solar systems, combined heat and power systems, biomass systems, heat pumps, and external heating, are responsible for a relatively small part of the sectoral improvement (15.6%).

- **RQ 3:** How do characteristics of non-profit housing associations explain the progress of the energy performance of the non-profit housing sector from 2017 to 2020?

  The following characteristics were examined: the size of the housing association, the location of the housing association, the degree of urbanity of the assets of the housing association, and the financial strength of the housing association. The research shows that large urban housing associations drive the improvement of the average sectoral energy performance. These housing associations own a large share of the stock, have on average a lower energetic quality, but also make more progress between 2017 and 2020.

- **RQ 4:** Did the Dutch non-profit housing sector meet its agreed goal on the average energy performance in 2020?

  The research of Filippidou et al. (2017) shows that the annual improvement of the energy-index followed a linear line between 2010 and 2015. The goal in 2020 was an average EI=1.25. In 2015 the determination method of the energy-index changed (NEN, 2014). Also, the related goal changed to an average EI of 1.40 for housing associations in 2020 (Blok, 2016).

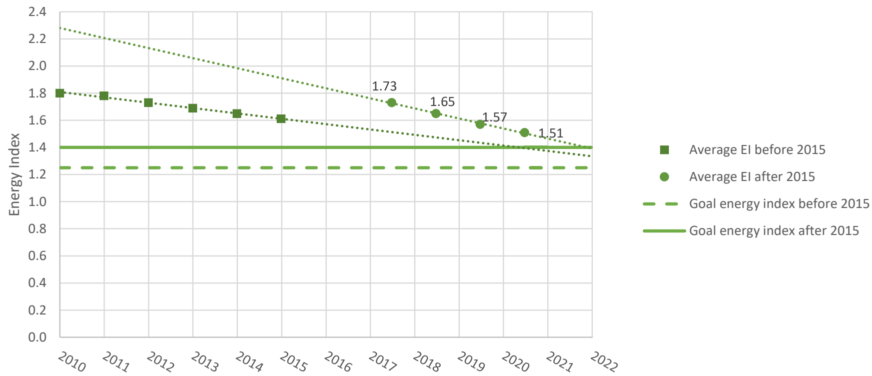

FIG. 6.1 Progress average energy-index Dutch non-profit housing sector

With an average energy-index of 1.51 halfway through 2020 and a linear extrapolation, the goal of EI=1.40 is not achieved in the year 2020 but can be achieved at the end of 2021 (Figure 6.1).

6.2.2 Modelling actual energy consumption

In the study "The energy performance of dwellings of Dutch non-profit housing associations: modelling actual energy consumption", different models to determine actual energy savings from renovations were examined. The goal of the study was to investigate the extent to which empirical models provide more accurate estimations of actual energy consumption when compared to a theoretical building energy model, in order to estimate the average actual energy savings of renovations. More accurate estimations are defined as: (A) average estimations on cross-sections of the non-profit housing sector closer to average actual energy consumption, (B) a higher correlation between estimated and actual consumption, and (C) a positive qualitative interpretation of estimated energy savings of renovations from a reference dwelling. Dwellings owned by Dutch non-profit housing associations were used to demonstrate the potential of empirical models. The following research questions were answered:

- **RQ 5:** To what extent do a linear regression model, a non-linear regression model, a machine learning model (GBM) and a theoretical building energy model differ in terms of their predictions of the actual energy consumption of dwellings?

A large performance gap was found between the theoretical building energy estimations and actual energy consumption for the dwellings owned by Dutch non-profit housing associations. This is in accordance with previous studies (Cozza et al., 2020; Filippidou et al., 2019; Majcen et al., 2013; Summerfield et al., 2019). In the research, three empirical models to predict the actual energy consumption of dwellings were examined: a linear regression model, a non-linear regression model, and a machine learning model (Gradient Boosting Model or GBM), and compared them to the actual energy consumption. Following the stated definition of more accurate estimations, the research shows that on cross-sectoral levels, all three empirical models have significantly higher accuracy than the theoretical building energy model. The empirical models also have higher correlations between estimated and actual consumption.

— **RQ 6:** To what extent do a linear regression model, a non-linear regression model, a machine learning model (GBM) and a theoretical building energy model predict the energy consumption of dwellings when individual renovation measures are analyzed?

A case study of the three different empirical models revealed that the order of magnitude of the estimations of gas and electricity consumption is significantly more accurate than the theoretical building energy model, but differences in the estimations for several renovation measures question the accuracy of these empirical models on a detailed level, especially for newly-introduced systems like heat pumps. Looking at the three different empirical models it is concluded that they have their own pros and cons. Linear regression models are simple and fast and estimate sectoral cross-sections very well but are not useful in analysing the effects of detailed renovation measures. A non-linear model can estimate sectoral cross-sections and detailed renovations and uses the structure of actual consumption physics but is only able to use given relations between building features and will therefore not pick up on other relations which could improve the estimations of the effects of renovations. The non-linear model is easier to interpret, which could be a reason to prefer such a model above the other models. A Gradient Boosting Model is able to detect all kinds of relations between building features. It can find correlations and interactions that even specialists in the field are not aware of. However, the model does not use the structure of actual energy consumption physics to its advantage. Therefore, it is more difficult to interpret the results and if some renovation measures (e.g. electrical heat pumps) occur less frequently in the dataset this can result in outcomes that are unrealistic. This could cause doubt by the engineers/specialists using the model and they will interpret the results as less reliable.

6.2.3 The energy performance of dwellings with heat pumps

the study “The energy performance of dwellings with heat pumps of Dutch non-profit housing associations” is one of the first studies that present insights into the actual energy consumption of dwellings with heat pumps on a large scale. A dataset of 69,422 dwellings was analyzed and the following research questions were answered:

- **RQ 7:** To what extent are dwellings with different heat pump systems present in the Dutch non-profit housing sector?

  The research results show that 3.2% of the dwellings of non-profit housing associations have a heat pump, consisting of all-electric heat pump systems (1.2%), hybrid systems (0.8%), gas absorption heat pumps (0.6%), gas absorption hybrid systems (0.4%) and other configurations (0.2%).

- **RQ 8:** What are the characteristics of dwellings with different heat pump systems compared to dwellings with a traditional condensing gas boiler (HR107)?

  Then the differences in building characteristics of dwellings with heat pumps as opposed to dwellings with HR107 gas boilers were examined. The research regards: the building type and size, average building quality expressed in the energy label, the building year, individual or collective heating systems, the distribution system, the presence of solar systems, ventilation systems and the quality of the outer shell. Table 6.1 describes the differences. It is concluded that the building quality of dwellings with all-electric heat pumps systems is higher than dwellings with hybrid or gas absorption heat pumps, which have a better building quality than dwellings with a traditional HR107 gas boiler.

TABLE 6.1 Dwelling characteristics to heat pump type

	All-electric	Hybrid	Gas absorption	Gas absorption hybrid	Gas boiler HR107
Number of dwellings	25,743	17,786	12,308	8,371	1,521,734
Building type and size					
Single-family	55%	25%	9%	12%	50%
Multi-family	45%	75%	91%	88%	50%
Single-family size in m^2	96	104	103	102	94
Multi-family size in m^2	58	70	72	72	71
Average building quality					
Energy label value (EP2) in kWh/m^2	55	150	188	132	196
Average energy label	A++	A	B	A	C
Building year					
Built < 2000	20%	39%	61%	58%	87%
Built => 2000	80%	61%	39%	42%	13%
Heating system					
Individual	94%	35%	18%	36%	82%
Collective	6%	65%	82%	64%	18%
Heating distribution system					
Floor heating	75%	54%	44%	37%	2%
Radiators	23%	46%	55%	63%	97%
Solar energy systems					
Solar power (PV)	71%	29%	24%	24%	12%
Solar power (PV) m^2	23.6	9.3	5.2	5.9	10.4
Solar heating	2%	14%	18%	2%	2%
Solar heating m^2	4.2	2.0	4.9	5.6	5.4
Ventilation system					
Ventilation system natural	1%	3%	3%	5%	34%
Ventilation system mech. exhaust.	31%	68%	69%	73%	60%
Ventilation system mech. inlet/ exhaust	67%	28%	28%	22%	5%
Quality outer shell					
Heat demand shell in kWh/m^2	54	73	71	73	122

- **RQ 9:** What is the actual average energy consumption of dwellings with heat pumps compared to dwellings with a traditional condensing gas boiler (HR107)?

The average electricity and gas consumption of dwellings with different heat pump systems were examined as opposed to dwellings with a traditional HR107 gas boiler. Figure 6.2. and Figure 6.3. show the average gas and electricity consumption of dwellings with different heat pump systems as opposed to dwellings with a traditional HR107 condensing gas boiler.

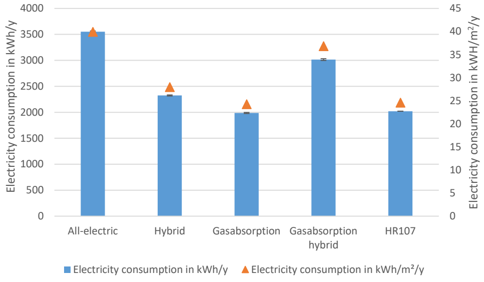

FIG. 6.2 Average electricity consumption per dwelling and per m² to heat pump type

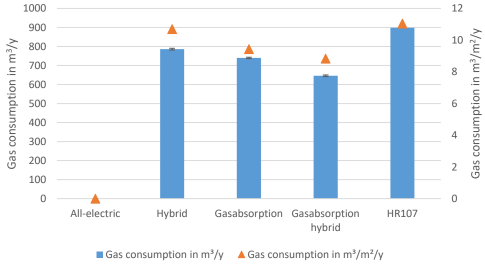

FIG. 6.3 Average gas consumption per dwelling and per m² to heat pump type

The research shows that dwellings with all-electric heat pumps show a 75% higher electricity consumption compared to dwellings with a traditional HR107 gas boiler. This takes into account a significant increase of the dwelling quality as mentioned in research question 8. Hybrid heat pumps or gas absorption heat pumps are a proposed temporary solution to decrease gas consumption and related CO_2 emissions in the period to 2050, without the need to strongly increase the building quality of a dwelling, and more specifically, the thermal quality of the outer shell. This research shows that dwellings with hybrid or gas absorption heat pumps have a lower gas consumption of in a range between 13 to 28% compared to dwellings with a standard HR107 heating gas boiler and higher average electricity consumption up to 50%, with an increase of the average building quality. The differences in energy consumption cannot be attributed solely to the differences in the heating system. As shown in research question 8, also the characteristics of dwellings differ amongst the heating systems. From previous studies, it is known that there is also a relation between the characteristics of a dwelling and the type of occupants which has, of course, an influence on the energy consumption (van den Brom, Meijer, & Visscher, 2018). Further, this research didn't have detailed enough data to inspect aspects like the commissioning and maintenance of the heat pumps. Studies have shown that wrong commissioning and lack of maintenance can have a significant impact on a building's energy consumption (Burman, Mumovic, & Kimpian, 2014). The study recommends further research to give more insights into the energy performance of more specific types of hybrid and gas absorption heat pump systems.

6.2.4 Benchmarking the energy performance of housing associations

The final study is “Benchmarking energy performance: indicators and models for Dutch housing associations”. Benchmarking is a method that can be used to measure progress and to create awareness about the performance of organizations. Benchmarking the energy performance of the housing stocks of Dutch housing associations aims to measure the progress and create awareness towards reaching decarbonization goals in the housing stock. The main challenge is to find a set of indicators that adequately represents the performance of housing associations according to current policies and is feasible to execute in practice. While applicable within the Dutch context, the method and research results of this paper deliver generalizable insights to create benchmarks about the energy performance in building stocks. The creation of the model used for benchmarking was commissioned by Aedes, the umbrella organization of housing associations, and was created in cooperation with Aedes and an export group of staff members of Dutch housing associations. The following research questions were answered:

- **RQ 10:** How to benchmark the energy performance of Dutch non-profit housing associations in relation to the policy context beyond 2020?

The study describes the process to create a model to benchmark the energy performance of Dutch non-profit housing associations. In a structured process, seven steps were taken to find a grounded benchmark model: 1. Policy review, 2. Identification of indicators, 3. Assessment of indicators., 4. Integration into benchmark models, 5. Selection of benchmark model, 6. Data collection and 7. Benchmark results. The research covers the process and arguments during this structured process. Other researchers aiming at benchmarking the energy performance between organizations within their policy context, can adopt and adapt this structured approach. In this study, a model was chosen which consists of three indicators covering the energy performance of Dutch non-profit housing associations. The final policy performance model to measure and benchmark the sustainable performance of Dutch non-profit housing associations consists of three indicators closely related to governing policies regarding the sustainable improvement of the Dutch non-profit housing sector:

TOC

1. The average theoretical primary fossil energy consumption,
2. The average distance to the maximum theoretical heat demand (Insulation Standard)
3. The average actual CO_2 emissions from gas consumption

The first indicator is related to the current policy regarding the energy labelling of dwellings, derived from the EPBD, from 2021 following the NTA8800. The second indicator relates to the new policy (Insulation Standard) expressed in the average theoretical quality level of the outer shell of dwellings. The third indicator is related to the goal for the Dutch built environment to lower actual CO2 emissions by the burning of gas in dwellings. A similar process can be used by other researchers aiming at benchmarking the energy performance between organizations within their policy context.

6.3 Overall conclusion

The main research question of the thesis is: How to assess and understand the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock? The studies performed in this thesis show that in order to assess the energy performance of non-profit housing associations a systematic data collection method is vital. The studies are based on the SHAERE database with the energy performance characteristics of over two million dwellings collected annually and the actual energy consumption of those dwellings available in an anonymized environment at the Dutch Central Bureau of Statistics (CBS). To assess the data different analytical methods help to deliver insights. In this research, a monitoring system, advanced modelling techniques, statistical analysis of data, and a benchmark model are used. These techniques help to gain valuable insights to understand the improvement of the energy performance of dwellings of non-profit housing associations.

The research concludes that monitoring the improvement of the energy performance of Dutch non-profit housing associations helps to understand which measures are taken and which potential is left to renovate or to replace with new construction. The research concludes that the energy performance of dwellings of Dutch non-profit housing associations improved steadily between 2017 and 2020. The research concludes that the effect of changes of the stock (construction and demolition) to the improvement of the average energy performance is modest (15.6%). The improvement of the average sectoral theoretical energy performance happens for 85.4% within the existing stock, mostly with traditional improvements like changing heating installations and adding insulation. It was found that large urban housing associations drive the improvement of the average sectoral energy performance. The research concludes that the sectoral goal of an average energy-index of 1.40 in 2020 will not be achieved in the year 2020 but can be achieved at the end of 2021.

The research concludes that modelling the actual energy consumption helps to understand the effectiveness of renovation measures in lowering actual energy consumption and related CO_2 emissions. The research found a large performance gap between theoretical and actual energy consumption underlining the need for actual energy consumption modelling. However, the research concludes that modelling the actual energy consumption of dwellings is challenging. Actual energy consumption was modelled using three different models, a linear regression, a non-linear regression, and a GBM machine learning model. Looking at the three different empirical models it is concluded that they have their own pros and cons. Linear regression models are simple and fast and estimate sectoral cross-sections very well but are not useful in analysing the effects of detailed renovation measures. A non-linear model can estimate sectoral cross-sections and detailed renovations and uses the structure of actual consumption physics but is only able to use given relations between building features and will therefore not pick up on other relations which could improve the estimations of the effects of renovations. The non-linear model is easier to interpret, which could be a reason to prefer such a model above the other models. A Gradient Boosting Model is able to detect all kinds of relations between building features. It can find correlations and interactions that even specialists in the field are not aware of. However, the model does not use the structure of actual energy consumption physics to its advantage. Therefore, it is more difficult to interpret the results and if some renovation measures (e.g. electrical heat pumps) occur less frequently in the dataset this can result in outcomes that are unrealistic. The research concludes that combining theoretical models with empirical calibrations (grey box models) could also be used to enhance the accuracy of the theoretical building energy models.

The research concludes that a statistical analysis to assess the energy performance of dwellings with heat pumps helps to understand the potential of heat pump systems in the future Dutch non-profit housing stock. In the research, the characteristics and the average actual energy consumption of dwellings with heat pumps are determined and compared to dwellings with a traditional HR107 condensing gas boiler. 3.2% of the dwellings of non-profit housing associations operates with a heat pump, consisting of all-electric heat pump systems

(1.2%), hybrid systems (0.8%), gas absorption heat pumps (0.6%), gas absorption hybrid systems (0.4%) and other configurations (0.2%). Dwellings with all-electric heat pumps have an average higher building quality with more PV panels, no gas consumption, and higher electricity consumption, as opposed to dwellings with hybrid or gas absorption heat pumps, which have an average higher building quality, lower gas consumption, and higher electricity consumption as opposed to dwellings with a traditional HR107 gas boiler.

The research concludes that a model to benchmark the energy performance of Dutch non-profit housing associations can be created by following a structured approach. It helps to support housing associations to analyse and compare the energy performance of their housing stock in agreement with active policies. A similar approach can be used by other researchers aiming at benchmarking the energy performance between organizations within their policy context. The final policy performance model to measure and benchmark the sustainable performance of Dutch non-profit housing associations consists of three indicators closely related to governing policies regarding the sustainable improvement of the Dutch non-profit housing sector:

1. The average theoretical primary fossil energy consumption,
2. the average distance to the maximum theoretical heating demand, and
3. the average actual CO2 emissions from gas consumption.

The first indicator is related to the current policy regarding the energy labelling of dwellings, derived from the EPBD, the NTA8800. The second indicator relates to the policy to decrease the average theoretical heat demand of dwellings. The third indicator is related to the goal for the Dutch built environment to lower actual CO_2 emissions.

6.4 Limitations

There are limitations to this research. These are discussed accordingly.

Limitation 1

Research results are restricted by data availability

There are limitations in the availability and quality of data. A large dataset was collected with the energy performance characteristics of over two million dwellings annually. This made it possible to assess the energy performance of the non-profit housing stock and to study the relation with actual consumption. However, energy consumption data about dwellings with district heating systems were not available at the CBS and those dwellings were therefore excluded in the study on modelling actual energy consumption. The quality of the data for newly introduced systems, like heat pumps, was also limited. This research covered a large sample size of dwellings with heat pumps, but lacks detailed information on the installed heat pumps, for example, the installed type, COP, power, or configuration of the heat pump system. This limits the extent to which conclusions can be drawn about the actual energy performance of dwellings with those systems. Detailed case studies could reveal if certain types or configurations of heat pumps could increase their performance significantly. Our study was not detailed enough to reveal those benefits.

Limitation 2

There are constraints in covering the performance gap

Covering the performance gap between theoretical energy consumption models and actual energy consumption of dwellings would increase the ability of housing associations to estimate the actual energy savings from renovations. Several studies have shown that the estimation of the theoretical energy consumption within the energy-index can deviate strongly from actual energy consumption and could lead to the systematic overestimation of potential energy savings. The realized savings in actual energy consumption are lower than expected, and thus also lower saved CO_2 emissions (Sunikka-Blank & Galvin, 2012; Laurent et al., 2013; Saunders, 2015; Galvin & Sunikka-Blank, 2016; Summerfield et al., 2019). In accordance with previous research (Santin, 2010; Majcen et al., 2016; Filippidou et al., 2019), this research shows the performance gap is present in the Dutch non-profit housing sector between 2017 and 2020 as well. However, closing the performance gap proved to be challenging. A constraint is the use of different modelling techniques. In the research, a linear, non-linear, and gradient boosting model were examined. However, other modelling techniques (Amasyali & El-Gohary, 2018), (X. Li & Yao, 2021) are available, and also different choices can be made within the linear, non-linear and gradient boosting model, to improve the quality of the estimations. The modelling of confidence intervals is challenging and was not included in this research. Also, the applicability of the estimations generated by the models proved to be challenging. The detailed case study revealed that the estimations of the different empirical models lack accuracy for certain renovation measures and therefore the estimations are not mature enough to be used over the theoretical building energy model, although the theoretical building model shows a large performance gap and therefore also has its limitations. Closing the performance gap between theoretical and actual energy consumption needs continuous efforts, to improve the accuracy of predictions of actual energy savings by constructing new dwellings and renovating the existing housing stock.

Limitation 3

There are constraints through the policy context

A limitation of the study is that it has country-specific elements, mainly aimed at Dutch non-profit housing associations within the Dutch policy context. This applies to the benchmark model found in the thesis. Dutch policy on the sustainable development of the built environment mainly focuses on the quality of dwellings and the emissions of CO_2 related to the energy consumption within the dwelling. For example, no clear goals or targets are formulated regarding the use of materials in retrofitting dwellings, although those can be found regarding new construction of dwellings. Moreover, no data is available describing the sustainable use of materials. This leads to the limitation that the measurement of the sustainable performance is limited to indicators closely related to the energy performance of dwellings, as found in the final benchmark model. However, the different phases used to create a benchmark model are generic. A policy analysis, selection of indicators, assessment of indicators, the integration into models, the selection of the final model, data collection, and delivering results are applicable to a wide variety of similar questions in other countries where the search for the measurement and benchmarking of the energy performance within the built environment is present. Other researchers aiming at benchmarking the energy performance between organizations within their policy context, can adopt and adapt this structured approach.

Limitation 4

Extrapolating research results to the future has limitations

A limitation of this research is that it has limits in extrapolating results to the future. For example, this thesis shows the average building characteristics and energy consumption of the current non-profit housing stock with heat pumps. This is not necessarily the average quality of future dwellings which are built or renovated with a heat pump system. Therefore it should be argued that extrapolating this to the future includes a large boundary of uncertainty and it underlines the need for continuous monitoring systems as a basis to assess the effectiveness of changes in the non-profit housing stock towards a sustainable built environment.

6.5 Recommendations

Following the conclusions and limitations, the thesis concludes with recommendations for further scientific research, recommendations for policymakers, and practical recommendations for housing associations.

6.5.1 Recommendations for further scientific research

Recommendation 1

Continue the monitoring of the energy performance of dwellings

The housing stock of over two million dwellings of non-profit housing associations is large and without a detailed monitoring process, it is not possible to value and evaluate the efforts of housing associations in the change towards a sustainable building stock. Future policies benefit from continuous monitoring of the energetic quality of the building stock, like the SHAERE monitoring system. The monitoring system shows which measures currently have, or don’t have, a substantial impact, therewith enabling the adaptation of strategies to speed up the improvement of the building stock. Aedes, the umbrella organization of non-profit housing associations, facilitates a continuation of this monitoring system. A continuation of the dissemination of research results among the scientific community after 2021 ensures other researchers are able to benefit from future insights as well.

Recommendation 2

Improve the modelling of the actual energy consumption of dwellings to accurately measure the effect of renovations

The performance gap between modelled energy consumption and actual energy consumption is large. This research aimed to cover the performance gap by modelling actual energy consumption through three different models, a linear regression, a non-linear regression, and a GBM machine learning model. However, this proved to be challenging. The research provides the following recommendations for further research. First, improve the quality of the dataset as a basis for the actual consumption model. Since the quality of the data is decisive for the quality of the model, the research recommends a more detailed collection of data on dwellings with heat pumps to improve the predictions of the actual energy consumption of these dwellings. This is also recommended for dwellings using district heating systems because these could not be included in this research. If other researchers would like to build empirical energy consumption models, they should use large datasets to average out the influence of occupant behaviour. Second, the research recommends further examining the possibilities of both the non-linear and Gradient Boosting Model, or a combination of these two. These models perform more accurately than the linear regression model because they are able to model relations between building characteristics when they estimate the actual energy consumption. The structure of the non-linear model and the flexibility of the GBM model both have their advantages and a combination could take advantage of them both. Adding confidence intervals to estimations is challenging, but would help to interpret the quality of the estimations, and is therefore recommended. Third, evaluating new models on their capability of closing the performance gap (and therewith to better estimate the actual consumption of dwellings) should be done both on a stock level with sectoral crosssections and for individual renovation measures. This research shows that closing the performance gap for sectoral crosssections can be achieved with a linear, non-linear and a Gradient Boosting model. However, the evaluation of individual renovation measures showed larger discrepancies in the estimations of actual energy consumption. These evaluations of individual renovation measures are vital to understanding the robustness of the model, and therefore its practical applicability. Fourth, combining theoretical models with empirical calibrations (grey box models) could be used to enhance the accuracy of the theoretical building energy models. Promising examples are given by Hörner and Lichtmeß (2017) and van den Brom (2020). Including behavioural parameters in the empirical models could be useful in order to understand the origin of the performance gap in greater detail. It would also increase the accuracy of estimations of specific dwellings where these parameters are known, for example for privately owned dwellings.

Recommendation 3

Determine the energy performance of dwellings with specific heat pump configurations in light of the energy transition in the built environment

Our research covered a large sample size of dwellings with heat pumps, but lacks detailed information of the installed heat pumps, for example, the installed type, COP, power, or layout of the heat pump system. Detailed case studies could reveal if certain types or configurations of heat pump systems increase the performance. This study was not detailed enough to reveal those benefits, so it is recommended to determine the energy performance of dwellings with specific heat pump configurations in light of the energy transition in the built environment.

6.5.2 Recommendations for policymakers

Recommendation 4

Support detailed monitoring systems

The research recommends that policymakers should support detailed national monitoring systems, like the SHAERE database. Future policies benefit from continuous monitoring of the energetic quality of the whole building stock. Monitoring systems are a basis to determine which measures currently are applied, therewith enabling the adaptation of strategies to speed up the improvement of the building stock. An example of this could be the replacement rate of gas-heated dwellings towards a housing stock heated with external heating or electric heat pumps as pursued in the Dutch policy context. Detailed monitoring systems are also a basis to create empirical building energy models.

Recommendation 5

Support efforts to improve building energy models using actual energy consumption data

The research recommends that policymakers increase efforts to improve building energy models using actual energy consumption data. Theoretical energy building models have a large performance gap between the modelled and actual energy consumption, which leads to the ineffective renovation of dwellings, where energy savings are not actually realised. Improving the modelling of the energy consumption using actual energy consumption data is the key solution to reduce the energy performance gap and therewith to accurately predict the actual energy savings from different types of renovations. Policymakers should be aware of the performance gap and could speed up the mitigation of the performance gap by supporting efforts to improve building energy models using actual energy consumption data.

6.5.3 Recommendations for housing associations

Recommendation 6

Continue to renovate the building stock, but be aware of the actual energy consumption of dwellings

The thesis recommends housing associations to continue to renovate the building stock, but to be aware of the actual energy consumption of dwellings. The performance gap between the theoretical and the actual energy performance could lead to inadequate estimations of energy savings of renovation measures. Therefore it is recommended to analyze the actual energy consumption of local housing stocks to ensure renovations lead to actual energy savings and related CO_2 emissions.

Recommendation 7

Start/continue to benchmark and learn from each other

Benchmarking is a method to measure progress and to create awareness about the performance of organizations in relation to goals. Benchmarking can be defined as: “a continuous analysis of strategies, functions, processes, products or services, performances, etc. compared within or between best-in-class organizations by obtaining information through appropriate data collection method, with the intention of assessing an organization's current standards and thereby carry out self-improvement by implementing changes to scale or exceed those standards" (Anand & Kodali, 2008). The thesis recommends housing associations in Europe to start or maintain benchmarks to analyse performance and to learn from each other. The model to benchmark the energy performance of Dutch non-profit housing associations can be used as an example. The structured approach can be used by other researchers aiming at benchmarking the energy performance between organizations within their policy context.

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Herman van der Bent, 2022

Curriculum Vitæ

Herman van der Bent was born in Ommen, The Netherlands in 1986. He accomplished a bachelor Civil Engineering at the University of Twente, The Netherlands, from 2005 to 2009 and accomplished the master Construction Management and Engineering at the University of Twente, The Netherlands, from 2009 to 2012. After concluding his studies he accomplished a traineeship at the province of South-Holland and worked as a data-analyst at Aedes, the umbrella organization of Dutch non-profit housing associations. From 2018 to 2022 he accomplished this doctoral thesis at the University of Technology in Delft.

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Towards a future sustainable housing stock

Assessment of the energy performance of dwellings of non-profit housing associations

Herman van der Bent

This thesis examines the energy performance of dwellings of Dutch non-profit housing associations towards a future sustainable housing stock. Improving the energy performance of dwellings aims to improve the quality of dwellings and therewith to lower the actual energy consumption. Lowering the actual energy consumption of dwellings contributes to the battle against climate change. This thesis addresses four studies. Study 1 assesses the energy performance progress of over two million dwellings of Dutch non-profit housing associations between 2017 and 2020. It gives insights into the development of the housing stock, the effect of changes of and within the stock, the effect of characteristics of housing associations and it relates the improvement of the energy performance to the sectoral goal. Study 2 assesses advanced models to improve estimations of actual energy consumption of dwellings and therewith to better estimate the effect of renovation measures on actual energy savings. Study 3 assesses the energy performance of dwellings with heat pumps. It gives insights into the energy performance of dwellings with heat pumps as a promising renovation measure towards a future sustainable housing stock. Study 4 assesses the process to create a model to benchmark the energy performance in a changing policy context. The four studies contribute to the understanding of the improvement of the energy performance of dwellings of non-profit housing associations towards a future sustainable housing stock.

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