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

H. S. van der Bent [a], P. I. van den Brom [a], H. J. Visscher [a], A. Meijer [a] and N. Mouter [b]

[a]Architecture and the Built Environment, Delft University of Technology, Delft, Netherlands; [b]Technology Policy and Management, Delft University of Technology, Delft, Netherlands

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.

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Heat pump systems; energy consumption; housing stock; non-profit housing

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 et al., 2021). Over 87% of Dutch non-profit housing stock was heated by gas boiler heating systems in 2020.

CONTACT HS van der Bent h.s.vanderbent@tudelft.nl

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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 are 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 et al., 2021; Wang & He, 2021; Zhuravchak et al., 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.

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 et al., 2012; Roy & Caird, 2013) and lastly, the fine-tuning of the installation also influences its performance (Deng et al., 2019; Gleeson, 2016). A recent study by Kieft et al. (2021) analyses the Technological Innovation System of heat pumps in the 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 et al., 2020). Other researchers propose the use of hybrid heat pumps (Bagarella et al., 2016) or gas absorption heat pumps (Famiglietti et al., 2021). These systems benefit from a higher COP but are also able to generate enough heat in winter conditions. Kieft et al. (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 et al. (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.

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 et al. (2022) 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 in electricity consumption of up to 40%. Biglia et al. (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% in CO_2 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 et al. (2017) analysed the prospective energy consumption and CO_2 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%.

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:

(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.

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 1.

Table 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< 70 kW, 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

This dataset is combined with a second dataset of the actual gas and electricity consumption in the year 2020 (Table 2), available at the address level in an anonymized analysis environment from the Dutch Central Bureau of Statistics (CBS). Figure 1 shows how these two databases have been combined in this research.

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

Table 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

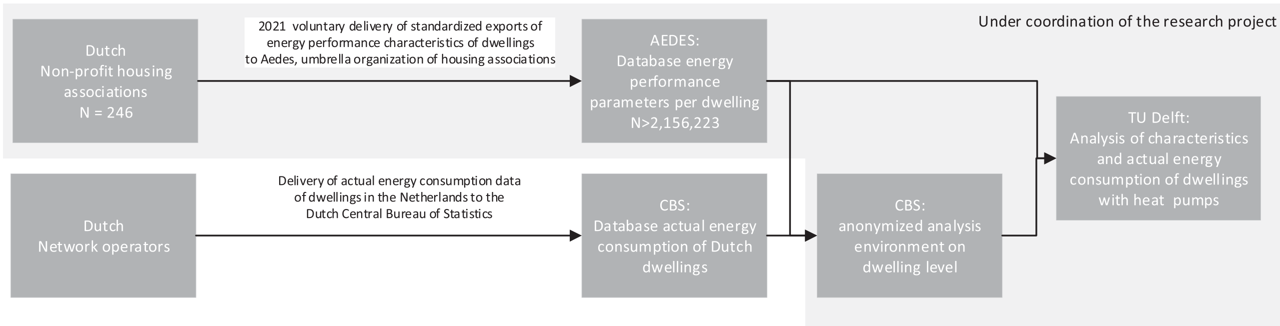

Figure 1. Process of data collection and analysis.

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 years 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 standardized 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 standardized 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.

Results

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 an electric system for heating or hot tap water
(5) Other: Both gas and electric heat pump systems combined with external heating or biomass systems.

Figure 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,

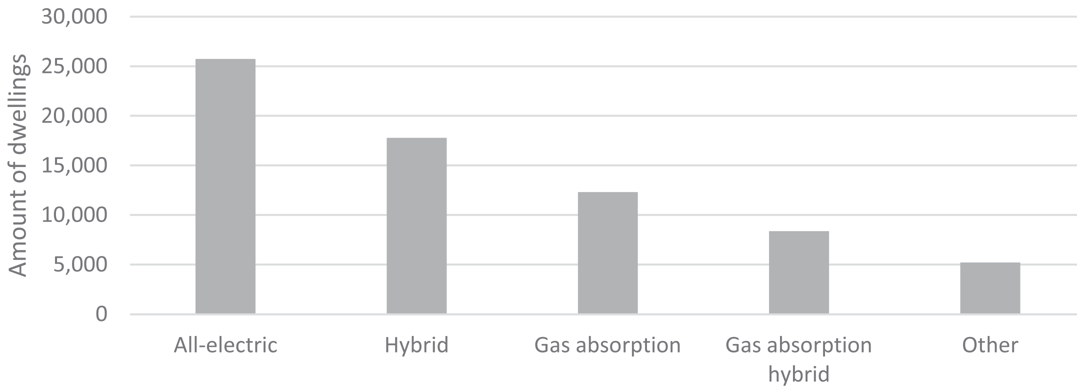

Figure 2. Number of dwellings per heat pump system.

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 analysed. 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 analysed in this paper.

Characteristics and quality of dwellings with heat pumps

The first dataset (Table 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/m^2. These are presented in Table 3.

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 of better quality. As explained later, on average, the outer shell of these dwellings are of 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

Table 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	8371	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

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/m^2.

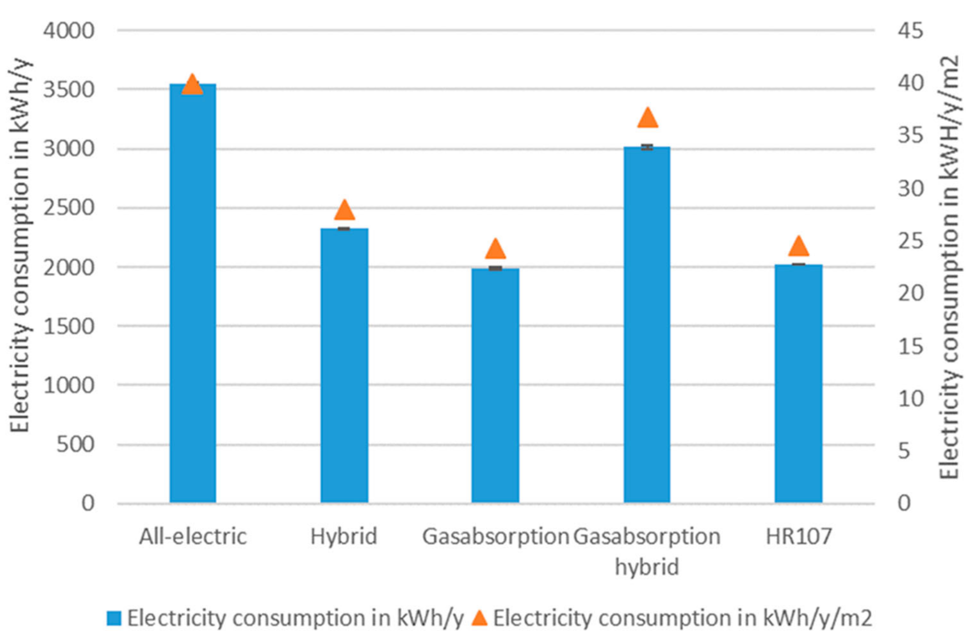

Figure 3. Average electricity consumption per dwelling and per m^2 to heat pump type.

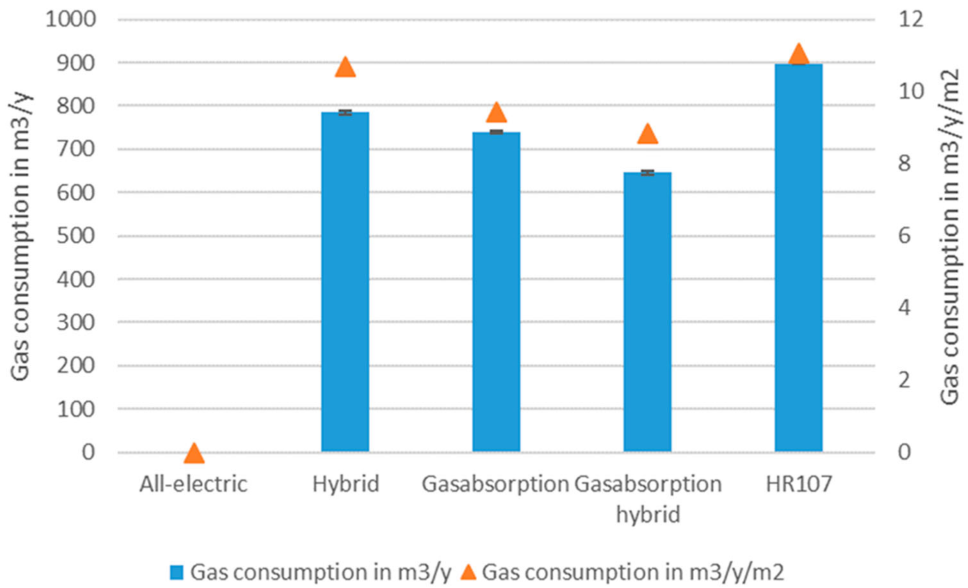

Figure 4. Average gas consumption per dwelling and per m^2 to heat pump type.

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.

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.

Figure 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/m^2. Dwellings with all-electric heat pumps, on average, use 3553 kWh, or 40 kWh/m^2, 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 15–50% 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 extent.

Figure 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/m^2. 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 gives the number of dwellings per heat pump system used for this analysis, the standard error of the

Table 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	3553	13	1540	0	0	0
Hybrid	17,789	12,727	2324	10	1144	786	5	447
Gas absorption	12,308	10,139	1987	10	1048	740	4	336
Gas abs. hybrid	8371	7527	3015	17	1454	646	4	297
HR107	1,521,734	1,446,419	2021	1	1080	899	0	442

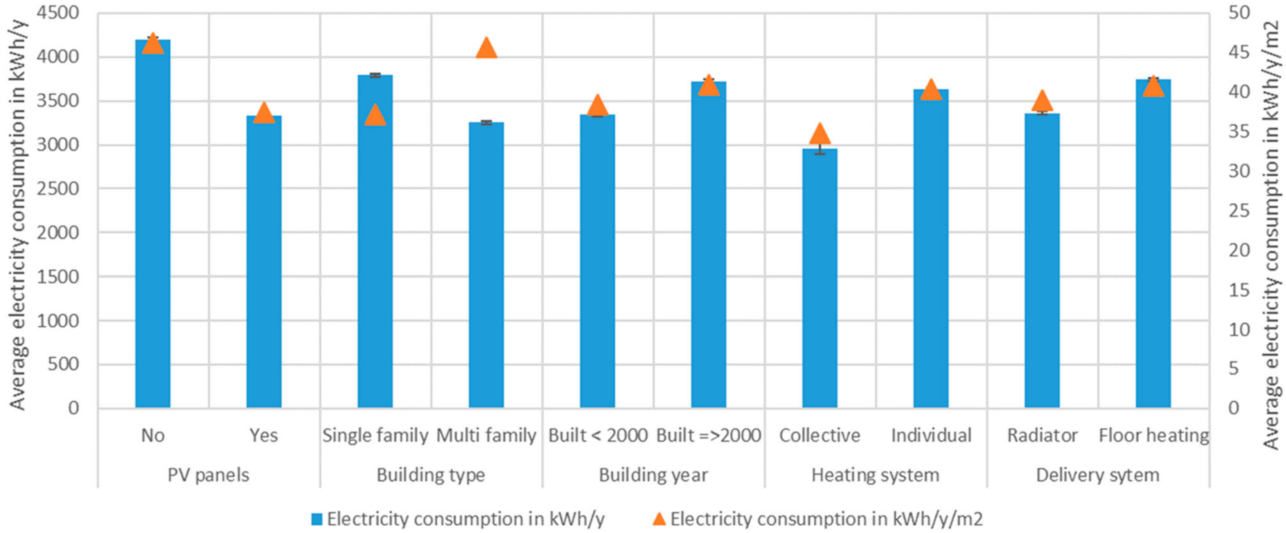

Figure 5. Average electricity consumption of dwellings with all-electric heat pumps to building parameter.

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 dwelling level can be partly explained because dwelling characteristics are different, but more importantly, the occupant characteristics and behaviour are also different for individual dwellings, leading to differences in electricity and gas consumption.

Figure 5 shows the differences in average electricity consumption for dwellings with an all-electric heat pump system, split into the five building parameters.

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 6 and 7 show the average electricity and gas consumption of dwellings with a hybrid, gas absorption,

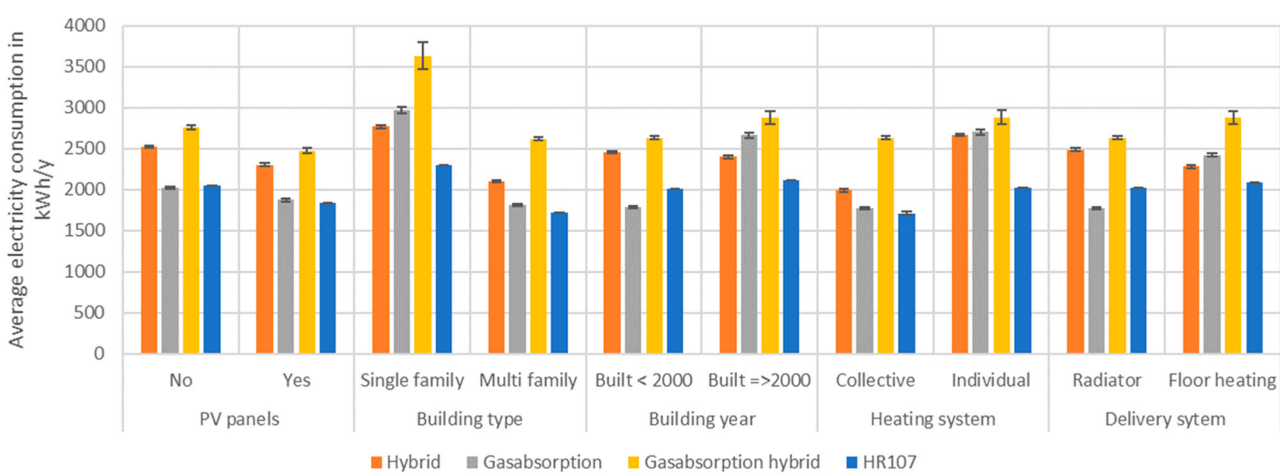

Figure 6. Average electricity consumption of dwellings by heat pump system by building parameter.

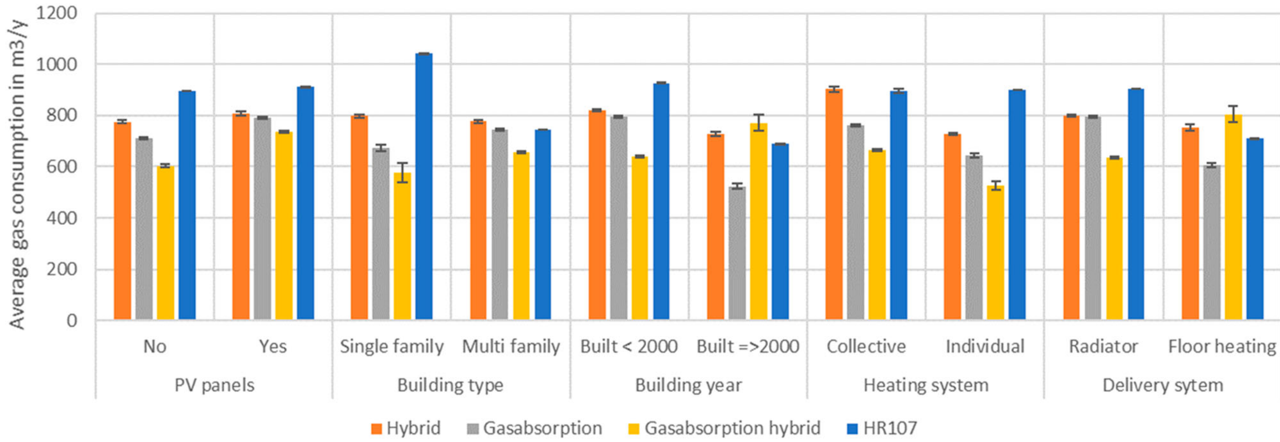

Figure 7. Average gas consumption of dwellings with heat pump system by building parameter.

or gas absorption hybrid heat pump system, using dwellings with an HR107 gas boiler as a reference, split into the five different building parameters.

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.

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.

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 neighbourhood-oriented approach was chosen to determine future CO_2 neutral heat sources for every neighbourhood. 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 neighbourhoods, 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 3. The increase in 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 neighbourhood 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% and 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 the heating system. As shown in Table 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 et al., 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 et al., 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.

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 pumps 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.

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ORCID

H. S. van der Bent http://orcid.org/0000-0002-4019-4298
P. I. van den Brom http://orcid.org/0000-0003-1805-734X
H. J. Visscher http://orcid.org/0000-0003-0929-1812
A. Meijer http://orcid.org/0000-0001-7332-0169
N. Mouter http://orcid.org/0000-0002-0299-5852

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