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Feasibility of energy reduction targets under climate change: The case of the residential heating energy sector of the Netherlands

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Abstract

In order to achieve meaningful climate protection targets at the global scale, each country is called to set national energy policies aimed at reducing energy consumption and carbon emissions. By calculating the monthly heating energy demand of dwellings in the Netherlands, our case study country, we contrast the results with the corresponding aspired national targets. Considering different future population scenarios, renovation measures and temperature variations, we show that a near zero energy demand in 2050 could only be reached with very ambitious renovation measures. While the goal of reducing the energy demand of the building sector by 50% until 2030 compared to 1990 seems feasible for most provinces and months in the minimum scenario, it is impossible in our scenario with more pessimistic yet still realistic assumptions regarding future developments. Compared to the current value, the annual renovation rate per province would need to be at least doubled in order to reach the 2030 target independent of reasonable climatic and population changes in the future. Our findings also underline the importance of policy measures as the annual renovation rate is a key influencing factor regarding the reduction of the heating energy demand in dwellings.

Keywords: climate change, heating energy demand, reduction targets, residential building stock, renovation, the Netherlands

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1. Introduction

In order to meet global climate targets, the building sector needs to reduce energy consumption by 60% worldwide by 2050 [1]. However, to increase the chances of successful and far-reaching measures on a national level, reliable estimates regarding the future energy demand are required. We take the Netherlands as a case study and assess the nation's ability to achieve given national heating energy saving targets. The Netherlands are a small country with 17 mio. inhabitants but belong to the 25 countries

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worldwide with the largest CO_2 emissions. Thus, the country can make a considerable contribution to climate mitigation. Furthermore, the Netherlands could be representative for regions such as Belgium, Great-Britain, Luxembourg and huge parts of France that have the same maritime temperate climate [2] and similar population projections for the future [3].

To avoid adding one more example to the large number of published assessments in this field, we went through the literature, categorized existing studies and chose on this basis an appropriate approach for our case study. Publications considering the impact of climate change and other future changes on the energy demand of buildings are shown in Table 1 which is partly based on Li et al. [4] and Yang et al. [5] who reviewed existing papers regarding the impacts of climate change on energy use in the housing sector.

Concerning the modeling approach, we find statistical models (S) which relate heat energy consumption with driving forces like temperature on the basis of observed, historical data. Here the difficulty lies in the correct statistical distinction between the weather influence and the other independent variables (insulation etc.) due to the restriction to historical data which may not contain all relevant combinations of these variables. This can cause problems for the application of the statistical model in the scenario calculations. In contrast, mechanistic approaches rely on the representation of the physical processes of heat transfer which are all well known. The achievable level of detail in these models depends on the availability of detailed building properties. Therefore, these detailed models (MD) are applied mainly in small scale studies (see Table 1). The application on more aggregated mechanistic models of intermediate complexity (MI) might be advantageous in data sparse situations compared to MD-models where unknown parameters are simply fixed to a roughly estimated value. The spatial scale of the considered studies is typically either global (G), national (N), or regional/local (L) and related to the model type as mentioned above. Most studies calculate the energy demand annually (a) which may induce complications in case of the presence of non-linear relationships between weather variables and heat flows - here a monthly temporal scale (m) would be more appropriate. The studies vary widely in the consideration of relevant influencing factors and their trends, including climatic changes, thermal renovation measures, and population changes. Table 1 shows that only a few studies consider all factors simultaneously. Regarding the building sector, most studies deal with the residential (R) or the commercial (C) sector, few with both. Some studies consider a comprehensive stock of buildings, while others only use a limited number of prototype buildings and their respective distribution over the whole housing stock leading to a more coarse grained representation of the relevant parameters.

For our case study country, a statistical model is not possible as sufficiently long-term historical time series are not available to determine and discriminate the influence of the different driving factors. Therefore, a mechanistic approach is needed. The available Dutch housing typology covers the whole country and comprises 18 dwelling types by year of construction, size, and insulation standard of the main dwelling components. It does not allow for an application of a data demanding model (MD) that normally requires parameters like the exact location of windows and doors to model the energy demand of a specific building. However, using the heat flux components as defined in the national building standards for the modeling of the monthly heating energy demand of dwellings together with regional population and climate data, the available housing typology allows for the establishment of an intermediate complexity model (MI) with a monthly (m) and local/regional (L) resolution for the residential sector. By using the monthly resolution, we consider possible non-linear effects which would be masked by an annual time resolution. The data situation enables us to consider temperature projections, population trends, and future renovation measures on a regional level. Our study simulates for the first time the combined effect of these factors on the monthly space heating energy demand of the housing stock of each Dutch province.

Table 1: List of papers that deal with the impact of climate change on the future energy demand or consumption of buildings. We give an overview over the modeling approach they use, which scale they analyse and which future influencing variables they consider. S=Statistical models, MD=Data demanding models, MI=Intermediate complexity models, R=Residential, C=Commercial, a=Annual, m=Monthly, G=Global, N=National, L= Regional/ Local, Compreh.=Comprehensive.

Paper	Modeling approach	Sector	Temporal scale	Spatial scale	Climatic changes	Renovation measures	Population changes	Compreh. stock
Aguiar et al. [6]	MD	R+C	m	N+L	x	-	-	-
Jenkins et al. [7]	MD	C	a	L	x	-	-	-
Zmeureanu and Renaud [8]	S	R	a	L	x	-	-	-
Lam et al. [9]	MD	C	a	L	x	-	-	-
Dolinar et al. [10]	MD	R	a	L	x	-	-	-
Wan et al. [11]	MD	C	a	L	x	-	-	-
Wang et al. [12]	MD	R	a	L	x	x	-	-
Scott et al. [13]	MD	C	a	L	x	x	-	-
Gaterell and McEvoy [14]	MD	R	a	L	x	x	-	-
Wan et al. [15]	MD	C	a	L	x	x	-	-
Chow and Levermore [16]	MI	C	a	L	x	-	-	x
Collins et al. [17]	MD	R	a	L	x	-	-	x
Isaac and vanVurren [18]	MI	R	a	G+N	x	-	x	-
Frank [19]	MD	R+C	a	L	x	x	-	-
Zhou et al. [20]	MI	R+C	a	N	x	-	x	x
Belzer et al. [21]	S	C	a	N+L	x	x	x	x
Olonscheck et al. [22]	MI	R	a	N	x	x	x	x
Yu et al. [23]	MI	R+C	a	N+L	x	x	x	x
This study	MI	R	m	N+L	x	x	x	x

Belzer et al. [21] and Yu et al. [23] who did similarly comprehensive studies (Table 1), only analyze the heating energy demand on an annual level. There are some studies for the Netherlands that deal with energy use in the building stock which are discussed in Section 4. Only one of these Dutch studies took future changes in climate and the housing stock into consideration. We limit the analysis to the calculation of the useful heating energy demand which is defined as the energy that a heating system must theoretically supply to a building. This useful heating energy demand does not say anything about how efficient this demand is supplied. Moroever, as cooling has only a share of 6% in the energy consumption of the Netherlands at the moment, we focus on the calculation of the future heating energy demand.

National targets of the Dutch government aim to achieve an energy neutral building stock in 2050 [24] which is somewhat more ambitious than the EU target of 80% reduction in energy consumption of buildings by that same year [25]. By 2030, the energy consumption of the Dutch building sector should be reduced by half when compared to 1990 [26]. For two reasonable future scenarios, we calculate whether it is possible to decrease the heating energy demand of the Dutch housing stock to these two aspired levels and give recommendations regarding the required annual renovation rate per province in order to achieve these goals. Furthermore, we are able to determine which influencing factor - population development, temperature changes or annual renovation rate - has the strongest effect on the future heating energy demand which might be policy relevant.

In Section 2, we introduce the used housing stock data and the method to determine its quantitative (number of dwellings) and qualitative (renovation measures) change over time. Moreover, we present the equations used to calculate the heating energy demand of dwellings. The results are described in Section 3. The discussion in Section 4 is followed by a conclusion and an outlook in Section 5.

2. Data and Methods

The Netherlands are characterized by some differences regarding the share of different dwelling types per province, the future population development on a regional level and the projected change of the outdoor temperature (Table 2, Table A & B in the appendix). While this future temperature is varied per province and per month, the mean amount of energy of incoming sun rays [in W/m^2] was assumed to be constant over time. There are about 7.2 million dwellings in the Netherlands of which roughly 26% are situated in freestanding and semi-detached houses and about 40% in row houses [27].

Table 2: Population and projected population changes between 1991-2000 and 2051-2060 according to the forecast and the lower and upper 95% forecast interval in the different provinces as well as share of dwellings in freestanding buildings in the total number of dwellings in 2012 [27] and projected temperature changes between 1991-2000 and 2031-2040 resp. 2051-2060 according to the RCP scenarios 8.5 and 2.6 [28].

	Population in mio. in 2012	Population changes btw. 1991-2000 and 2051-2060 in % according to			Share of dwellings in freestanding buildings in %	Projected annual mean temperature changes in K compared to 1991-2000			
		the lower 95% forecast interval	the population forecast	the upper 95% forecast interval		2031-2040 (RCP8.5)	2051-2060 (RCP8.5)	2031-2040 (RCP2.6)	2051-2060 (RCP2.6)
Groningen	0.58	-2.30	4.21	11.57	24.4	1.41	2.12	0.88	0.94
Friesland	0.65	0.68	7.38	14.97	31.7	1.38	2.06	0.85	0.92
Drenthe	0.49	-3.24	3.20	10.49	29.7	1.40	2.11	0.87	0.92
Overijssel	1.14	5.16	12.17	20.09	19.6	1.36	2.09	0.86	0.93
Flevoland	0.40	72.55	84.05	97.05	8.9	1.34	2.04	0.84	0.92
Gelderland	2.02	1.94	8.73	16.41	18.7	1.33	2.10	0.88	0.95
Utrecht	1.25	22.00	30.12	39.31	6.9	1.31	2.07	0.88	0.94
Noord-Holland	2.72	12.96	20.48	29.00	8.1	1.33	2.01	0.84	0.91
Zuid-Holland	3.56	9.10	16.37	24.59	5.3	1.28	2.02	0.86	0.89
Zeeland	0.38	-5.09	1.23	8.39	23.4	1.22	2.01	0.86	0.89
Noord-Brabant	2.47	5.64	12.67	20.63	17.9	1.29	2.08	0.91	0.95 s
Limburg	1.12	-12.78	-6.97	-0.40	19.5	1.29	2.13	0.96	0.99
The Netherlands	16.8	-4.10	14.19	36.27	14.1	1.33	2.07	0.87	0.93

For the analysis we used data from the Dutch Building Typology 'Exemplary apartments 2011' of Agentschap NL, which is part of the Ministry of Economy, Agriculture and Innovation [29]. The insulation standard of the main dwelling components is expressed by heat transmission values (U-values). These change in the case of a renovation. Past data on population, housing stock and the number of new and demolished dwellings on national and province level were derived from Federal Statistical Office data [27].

2.1. Calculation of the heating energy demand

Motivated by the available data and building regulations we decided to use a MI. The monthly heating energy demand Q_h of each dwelling is calculated with the statistical software R [30] on the basis of the Dutch NEN standard 7120:2011 if not stated differently, given equation (1). It considers heat losses via transmission and ventilation and heat gains from internal heat sources and the sun multiplied by an utilisation factor. Figure 1 provides an overview on the main heat fluxes.

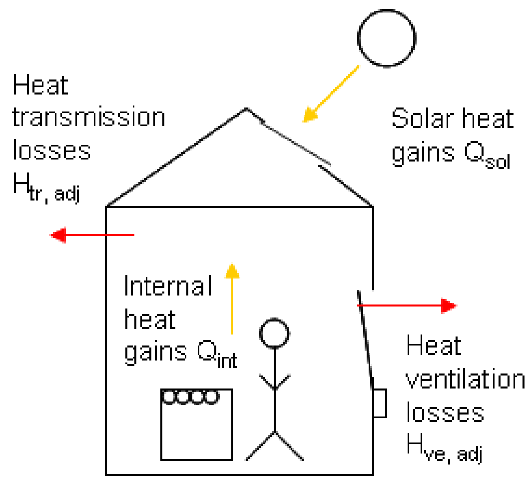

Figure 1: Heat fluxes that determine the heat balance of a building.

The most important equations are described below. The full details can be found in the appendix.

$$Q_h = (Q_{H,ht} - \eta_{H,gn} \cdot Q_{H,gn}) \; [MJ/month] \quad (1)$$

where
$Q_{H,ht}$ = Total heat losses [MJ],
$\eta_{H,gn}$ = Utilisation factor for heat gains [-],
$Q_{H,gn}$ = Total heat gains [MJ].

2.1.1. Calculation of heat losses

Total heat losses of a dwelling are affected by changing outdoor temperatures and vary in the course of the year due to the different length of months. We calculated them according to equation (2).

Total heat losses $Q_{H,ht}$ were calculated by:

$$Q_{H,ht} = (H_{tr,adj} + H_{ve,adj}) \cdot f_{int,set,H,adj} \cdot a_{H,red,night} \cdot (\theta_{int,set,H} - \theta_e) \cdot t \tag{2}$$

where
$H_{tr,adj}$ = Heat transfer coefficient for transmission [W/K],
$H_{ve,adj}$ = Heat transfer coefficient for ventilation [W/K],
$f_{int,set,H,adj}$ = Correction factor for levelling the temperature in a dwelling [-] (for details see appendix),
$a_{H,red,night}$ = Reduction factor for night setback of the temperature [-] (for details see appendix),
$\theta_{int,set,H}$ = Indoor temperature = 20 [°C],
θ_e = Outdoor temperature [°C],
t = Value for the length of the considered month = 2.6784 in every second month starting with January; 2.5920 in every second month starting with April; 2.4192 in February [Ms].

The heat transfer coefficient for transmission $H_{tr,adj}$ was calculated over the dwelling components i (roof, wall, basement, windows) by equation (3). It is mainly dependent on the surface and the U-value of a component and differs per dwelling type.

$$H_{tr,adj} = \sum_{i=1}^{4} (A_{T,i} \cdot (U_i + \Delta U_{for,i})) \tag{3}$$

where
$A_{T,i}$ = Surface of the considered component [m^2],
U_i = Heat transition coefficient [U-value] of a dwelling component [$W/m^2 \cdot K$],
$\Delta_{U_{for,i}}$ = Value for the consideration of thermal bridges = $-0.15 \cdot (U_i - 0.4)$ [$W/m^2 \cdot K$].

The heat transfer coefficient for ventilation $H_{ve,adj}$ was calculated by:

$$H_{ve,adj} = \frac{\rho_a \cdot c_a}{1000} \cdot q_{ve,mn} \tag{4}$$

where
ρ_a = Density of air = 1.205 [kg/m^3],
c_a = Specific heat capacity of air = 1008 [$J/kg \cdot K$],
$q_{ve,mn}$ = Time and temperature weighted air volume supply and return flow [dm^3/s] (for details see appendix).

Due to a lack of information, we assumed a mean specific internal heat capacity of 'traditional, mixed heavy' and 'mixed light' dwelling types. $q_{ve,mn}$ mainly considers the air volume flow resulting from the ventilation system. It differs per dwelling type. The detailed calculation can be found in the appendix.

2.1.2. Calculation of heat gains

Total heat gains within one month are approximated by equation (5). They consist of internal heat gains which are represented via a constant factor dependent on the base area and solar heat gains that differ e.g. per size of the component i.

Total heat gains $Q_{H,gn}$ were calculated by:

$$Q_{H,gn} = Q_{int} + Q_{sol} \tag{5}$$

where
Q_{int} = Internal heat gains [MJ],
Q_{sol} = Solar heat gains [MJ].

Internal heat gains Q_{int} were calculated by:

$$Q_{int} = (230 + 1.8A_g) \cdot t \tag{6}$$

Solar heat gains Q_{sol} were calculated by:

$$Q_{sol} = \sum_{k=1}^{4} (\phi_{sol,k} \cdot t) \tag{7}$$

where
$\phi_{sol,k}$ = Heat flow caused by incoming sun rays [W] (for details see appendix).

The utilisation factor for heat gains $\eta_{H,gn}$ depends on the heat balance ratio γ_H between total heat gains $Q_{H,gn}$ and losses $Q_{H,ht}$ as well as on a numerical parameter a_H that is up to the inertia of the building.

As:

$$\gamma_H \neq 1 \; and \; \gamma_H > 0 : \quad \eta_{H,gn} = \frac{1 - \gamma_H^{a_H}}{1 - \gamma_H^{a_{H+1}}} \tag{8}$$

where
a_H = Numerical parameter depending on the time constant = $1 + \frac{\tau_H}{15}$.

Based on these equations we calculated the total heating energy demand of dwellings in the Netherlands and its provinces for not yet renovated and renovated dwellings.

2.2. Projection of the future number of dwellings

For determining the future annual housing stock on the national level, we applied the population forecast as well as the 95% forecast intervals given by the Federal Statistical Office [27] since these represent a reasonable large range of possibilities (until 2060: nationwide population increase to 21.5 mio., 17.7 mio. or decrease to 14.6 mio. from a value of 16.8 mio. in 2012). Population forecasts on a regional level were only available for the period 2013-2040. For the missing years until 2060 population data for the provinces are assumed to be proportional to these population forecasts on the national level in such a way that a certain percentage increase or decrease on the national level between two years is also assumed for each province. For the period 2013-2060 the number of dwellings both on the national and regional level was assumed to be proportional to the population numbers.

Each year a certain number of new dwellings is added to the existing stock of dwellings. We extrapolated the trend of the available data for the number of new dwellings on the national and local level from 1988-2012 and it was determined that a logarithmic extrapolation fitted best. New dwellings were assigned to different dwelling types according to their past shares meaning that we assumed the percentage proportion between e.g. new freestanding and new row houses to remain the same in the future. The total number of demolished dwellings was derived by subtracting the number of new dwellings from the total stock in a respective year. Due to a lack of information, we presumed that only dwellings aged 50 years or older in the considered year are at disposal for demolishing [15, 19, 31, 32].

2.3. Projection of the future energetic standard of dwellings

The renovation standard of a building was assumed to improve over time. We presumed that in each considered year only those dwellings that are 50 years or older and that are not yet demolished are substantially renovated. This means that the roof, wall, basement and windows are improved. The applied renovation rate per year is 1% which equals the current annual rate [33, 34] and 3% which we see as a reasonable, but challenging desirable value. For future new dwellings we used U-values given in the Dutch regulation 'Bouwbesluit' [35] and assume a tightening to passive house standards from 2021 on, as required by the European Union (Directive 2010/31/EU of the European parliament and of the council). Regarding energetic improvements of dwellings, we considered those U-values for different dwelling components given in the typology from 2011 onwards and those required in Germany since 2010 (EnEV 2009) starting from 2021 as they are even stricter than those required in the typology (Table 3). Thus, if a building is renovated from 2021 onwards, the energetic standard is better than that for dwellings renovated between 2011 and 2020 but worse than that for new dwellings from 2021 onwards. Under the assumption that all required U-values in the ordinances valid at the respective time are followed, the extent of energetic improvement of dwellings was determined.

Table 3: U-values [in $W/(m^2K)$] according to regulations for renovation of as well as new dwellings over time by component.

Dwelling component	U-values new dwellings from 2011 on (Bouwbesluit 2012)	U-values new dwellings from 2021 on (EU Directive)	U-values renovated dwellings from 2011 on (typology)	U-values renovated dwellings from 2021 on (German EnEV 2009)
Roof	0.286	0.1	0.36	0.24
Wall	0.286	0.15	0.36	0.24
Basement	0.286	0.12	0.36	0.3
Window	1.1	0.8	1.8	1.3

2.4. Projection of temperatures

We applied data on the mean monthly temperature from the World Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX)

[36]. We selected the downscaling Rossby Centre Regional Climate Model (RCA4) and the global driving model ICHEC-EC-EARTH as this combination allowed us to use results of the two extreme future Representative Concentration Pathways (RCPs) [28, 37] with a radiative forcing of 2.6 W/m^2 and 8.5 W/m^2 in the year 2100. The climate data has a spatial resolution of about 12.5km. We made use of the delta approach, that means we calculated the temperature differences between 1991 and 2000 and each considered future decade in the projections of the regional climate model. These delta values have than been added to the empirical baseline, which was taken from the gridded observational E-OBS data (resolution 0.22°) provided by the European Climate Assessment & Data (ECA&D) [38]. Both data sets have been aggregated to the province level of the Netherlands.

2.5. Considered scenarios for the heating energy demand

We combined the population forecasts and assumptions regarding the annual renovation rate into a maximum scenario with a high population, a low renovation rate of only 1% and outdoor air temperatures according to RCP2.6 (which causes the future heating energy demand to be high) as well as a minimum scenario with a low population, a high renovation rate of 3% and a temperature according to RCP climate scenario 8.5 (that leads to a comparatively low heating energy demand). For the majority of months, the RCP climate scenario 8.5 projects higher average temperature values for future time periods compared to RCP2.6 but not for all. However, for reason of consistency, we used the RCP8.5 scenario for the minimum and the RCP2.6 for the maximum scenario.

3. Results

After a reproduction of the historical heating energy demand, we display per province the simulated future reductions in the heating energy demand as well as the corresponding absolute values for the period 2051-2060. We also show whether the national energy reduction target for 2030 is achievable. Moreover, we calculate how high the annual renovation rates would need to be per province in order to reach this goal. With a sensitivity analysis, we determine the impact of the considered influencing factors on the future heating energy demand.

3.1. Reproduction of the historical heating energy demand

We compare the calculated monthly heating energy demand summed over a year with the annual heating energy consumption of Dutch households for room conditioning (Source: Marijke Menkveld, ENC, Personal communication: 17.11.2014) for the period 1995-2012 (Figure 2).

This past heating energy demand was calculated with the same R script that we used for calculating the future heating energy demand using the building typology, annual data on the total number of dwellings as well as annual data of the outdoor temperature.

The lower simulated heating energy demand in the first few years can be explained by not having accounted for changes in the renovation status of dwellings before 2012 due to a lack of corresponding information. The building typology provides data on the present state of dwellings in the Netherlands. A backwards calculation of the renovation status and thus a consideration of past renovation measures would have caused the graph of the calculated energy demand to start at a higher point in 1995, as a higher number of dwellings with an inferior energetically standard at that time actually caused more energy consumption than dwellings with an average energetic standard of the 2011 stock.

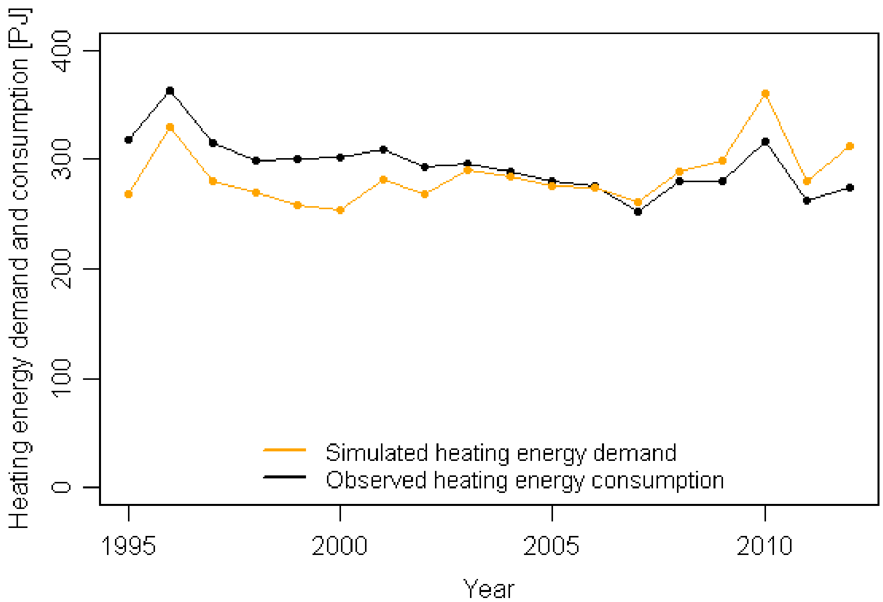

Figure 2: Calculated heating energy demand and observed heating energy consumption according to the Dutch Statistical Office [27].

The deviation between the graphs may be caused by different factors that have not been considered in our calculations:

- Rising energy prices over the considered time period could have caused a decrease in energy consumption over time that we were not able to consider,
- empty dwellings, second residences, and holiday flats that are not constantly inhabited and thus heated may cause the heating energy demand to be lower in reality than what we calculated,
- the specific characteristic of the urban building density can also cause our values to deviate from the observed consumption as we assumed that all dwellings are in buildings that are located in a model surrounding unaffected by other houses, vegetation etc.

Despite the differences, there is a good correlation between the two graphs. Colder years like 1996 and 2010 were characterized by both a higher simulated heating energy demand (orange graph) and a higher observed heating energy consumption (black graph), while warmer years such as 2007 and 2011 had both a lower heating energy demand and consumption.

3.2. Estimation of the future energy demand

Based on the assumptions regarding the U-values in Table 3, a reduction of the total annual heating energy demand of Dutch dwellings to nearly zero by 2050 is not possible (Figure 3). Even increasing the annual renovation rate to more than 3%, which is very ambitious, would only marginally further reduce the heating energy demand in the middle of the century.

This is because the renovation standard for dwellings from 2021 onwards is still too poor for a sufficient reduction in the energy demand (as a large number of low-energy houses still demand a large amount of heating energy). However, with some extra effort, especially those provinces with a current low heating energy demand are able to approach the 'near zero' mark. These include Zeeland and Flevoland especially, but also Drenthe, Groningen, and Friesland. Due to the already very low heating energy demand in September, it seems possible to achieve the 2050 target in this month in all provinces. Thus, in the future, very little heating will be necessary in the Dutch provinces in September.

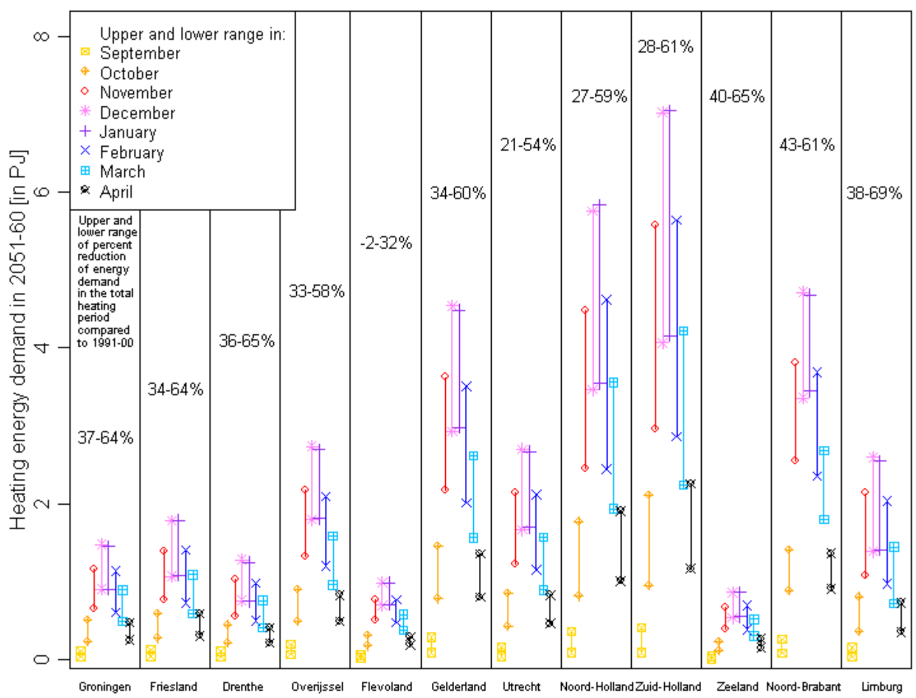

Figure 3: Heating energy demand in 2051-2060 for the different provinces and heating months. Note: The upper dot for each province shows the value for the maximum scenario with a high population, a 1% renovation rate per year and a low temperature increase. Lower dot: Low population, 3% renovation rate, and high temperature increase. Additionally, we displayed the upper and lower range of the percent reduction of the energy demand in the total heating period compared to 1991-2000.

In Figure 3, we additionally display the upper and lower range of the percentage reduction of the heating energy demand in the total heating period when comparing 2051-2060 with the baseline period 1991-2000. The largest decreases are found for Limburg, Drenthe, and Zeeland with more than 64% in the minimum scenario. Provinces such as Utrecht, Noord-Holland, and Zuid-Holland are able to reduce their heating energy demand only by less than 30% in the maximum scenario in the considered period.

For reason of completeness, we also show the results for Flevoland (increase of 2% to decrease of 32% in the maximum and minimum scenario) for this part of the analysis as it shows that the province is less important for our analysis as the heating energy demand will anyhow be very low by the middle of the century (3% of the national heating energy demand in 2051-2060 in the maximum scenario). While for all the other provinces, our assumption regarding a comparable age distribution seems to be valid, there are few old dwellings in Flevoland as it was mainly created by land reclamation in 1986, meaning that our calculated value for 2050 is too high.

As the goal for 2050 ('near zero') is quite fuzzy and for the above mentioned reasons not achievable, we take a closer look at the target for 2030 (Table 4). We compare the period 1991-2000 (representative baseline for 1990) with 2031-2040 (representative for the 2030 reduction target). In both scenarios, the largest future reductions can be expected in September.

When comparing the summed heating energy demand between the baseline and 2031-2040 over the eight heating months, in the maximum scenario ('lowest heating energy demand reductions'), the highest reductions will occur in Limburg and Zeeland (-28%) and Drenthe (-24%). However, in none of these provinces, the goal of reducing the energy demand by 50% by 2030 will be reached (Table 4, left). Utrecht will only be able to decrease its heating energy demand by 7%. The decrease calculated for the whole country will be around 6%.

Table 4: Heating energy demand reductions in the maximum (left) and minimum (right) scenario for the different provinces when comparing 2031-2040 with the period 1991-2000. Note: The provinces with the lowest reduction per month are marked in red, those with the highest in green. Results for Flevoland are not shown in this table.

	Maximum scenario: High population,1% renovation/yr; RCP2.6								Minimum scenario: Low population, 3% renovation/yr, RCP8.5							
	J	F	M	A	S	O	N	D	J	F	M	A	S	O	N	D
Groningen	-16	-34	-26	-25	-61	-37	-21	-17	-56	-66	-57	-60	-82	-67	-53	-52
Friesland	-13	-31	-24	-22	-60	-36	-18	-14	-54	-64	-55	-59	-82	-67	-52	-51
Drenthe	-15	-34	-25	-24	-61	-36	-19	-16	-55	-66	-56	-59	-82	-66	-52	-52
Overijssel	-9	-30	-19	-19	-62	-33	-13	-10	-50	-62	-51	-55	-81	-64	-47	-47
Gelderland	-12	-30	-21	-22	-66	-36	-15	-12	-52	-63	-53	-57	-83	-65	-49	-49
Utrecht	4	-17	-8	-7	-61	-25	0	4	-44	-57	-45	-50	-80	-59	-40	-41
Noord-Holland	-4	-23	-16	-15	-62	-32	-10	-5	-49	-60	-51	-55	-83	-64	-47	-46
Zuid-Holland	-7	-25	-17	-16	-66	-33	-9	-6	-51	-61	-52	-56	-84	-65	-47	-48
Zeeland	-21	-34	-29	-27	-74	-43	-22	-19	-57	-65	-57	-62	-86	-70	-54	-54
Noord-Brabant	-10	-27	-19	-18	-66	-33	-11	-9	-51	-62	-52	-56	-83	-64	-48	-49
Limburg	-22	-37	-29	-28	-70	-42	-21	-20	-59	-67	-59	-62	-86	-69	-54	-56
The Netherlands	4	-17	-7	-6	-57	-23	1	1	-55	-65	-56	-60	-84	-68	-52	-53

In our minimum scenario ('strongest heating energy demand reductions'), the energy demand reductions will be more than 50% in most provinces and month (Table 4, right). Overijssel, Gelderland, Utrecht, Noord-Holland, Zuid-Holland and Noord-

Brabant miss the goal in several months. On the national level, the governmental target of reducing the energy demand by at least half would be achievable.

3.3. Determination of the necessary annual renovation rates

The required annual renovation rates to reduce the energy demand by half until 2030 can be seen in Figure 4 for each province in the maximum scenario.

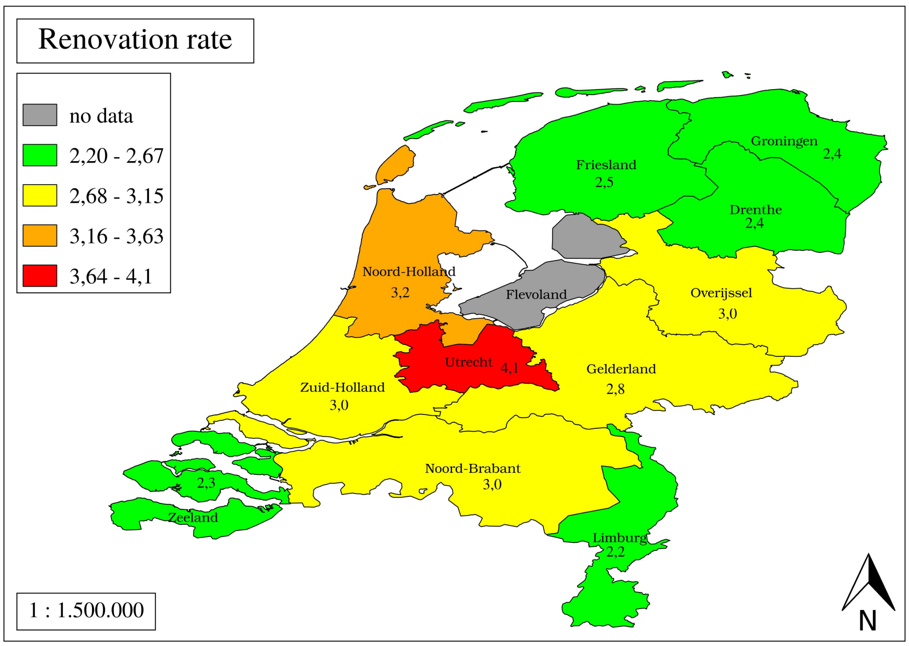

Figure 4: Necessary annual renovation rates per province to reduce the energy demand by half given the maximum scenario when comparing the time periods 1991-2000 and 2031-2040. Results for Flevoland are not shown in this map.

The provinces with a high projection for the 2051-2060 population such as Utrecht and Noord-Holland have the highest required renovation rates of 4.1% and 3.2% while those with a projected relatively strong population decrease in the national population forecast up to the middle of the century such as Limburg, Zeeland, Drenthe and Groningen have lower rates of 2.2% to 2.4%.

In general, the values regarding the necessary renovation rate per province may be a bit higher in reality due to the fact that the cooling energy demand is expected to rise in the future and the national reduction targets are meant for both heating and cooling energy use.

3.4. Most important influencing factors on the future energy demand

Based on a sensitivity analysis, we determine which of the three influencing factors future population development, projected temperature changes and renovation rates has the largest impact on the future heating energy demand of the housing stock. Per province we vary specific influencing factors while keeping the others constant (Table

5). In addition to our extreme scenarios, we consider a scenario with no renovation and one with 2% renovation per year.

Considering the same renovation rate and the same development of the stock of dwellings (which is strongly dependent on the forecasted population), there are clear differences in the heating energy demand in 2051-2060 between the two considered climate scenarios (at least 10% difference). In Groningen, for climate scenario RCP2.6 and a 3% annual renovation rate, the difference between a high and a low future population is e.g. 0.1 PJ in 2051-2060 (0.7 PJ or 0.6 PJ). Exceptions are Friesland, Drenthe, Overijssel, Utrecht, Noord-Holland, Zeeland and Limburg where a lower decrease in the heating energy demand occurs for some scenarios if climate scenario RCP8.5 is considered instead of RCP2.6. In five provinces however, RCP8.5 even shows more than 15% reductions compared to RCP2.6 for some scenarios.

Table 5: Sensitivity analysis for the heating energy demand [in PJ] of the different provinces (except Flevoland) in 2051-2060 (average over the heating months). The values show the future heating energy demand for cases where all factors are held ccnstant while one is varied each time, e.g. the climate scenario. Note: The first value in each field shows the result for a high population, the second that for a low population.

Groningen Q_h [PJ]	Climate scenario		Friesland Q_h [PJ]	Climate scenario		Drenthe Q_h [PJ]	Climate scenario	
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5
0%	1.4/1.2	1.2/1.0	0%	1.7/1.4	1.5/1.3	0%	1.2/1.0	1.0/0.9
1%	0.9/0.7	0.8/0.6	1%	1.1/0.9	1.0/0.8	1%	0.8/0.6	0.7/0.6
2%	0.7/0.6	0.6/0.5	2%	0.9/0.7	0.8/0.7	2%	0.6/0.5	0.6/0.5
3%	0.7/0.6	0.6/0.5	3%	0.8/0.7	0.7/0.6	3%	0.6/0.5	0.5/0.4
Overijssel Q_h [PJ]	Climate scenario		Gelderland Q_h [PJ]	Climate scenario		Utrecht Q_h [PJ]	Climate scenario	
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5
0%	2.5/2.1	2.2/1.9	0%	4.1/3.5	3.6/3.1	0%	2.4/2.1	2.1/1.8
1%	1.7/1.4	1.4/1.2	1%	2.7/2.3	2.4/2.0	1%	1.6/1.3	1.4/1.2
2%	1.4/1.2	1.2/1.1	2%	2.3/2.0	2.0/1.7	2%	1.3/1.2	1.2/1.0
3%	1.3/1.2	1.1/1.0	3%	2.1/1.9	1.8/1.7	3%	1.2/1.1	1.1/0.9
Noord-Holland Q_h [PJ]	Climate scenario		Zuid-Holland Q_h [PJ]	Climate scenario		Zeeland Q_h [PJ]	Climate scenario	
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5
0%	5.2/4.5	4.6/4.0	0%	6.3/5.4	5.6/4.8	0%	0.8/0.7	0.7/0.6
1%	3.5/2.9	3.1/2.5	1%	4.3/3.5	3.7/3.0	1%	0.5/0.4	0.5/0.4
2%	2.8/2.4	2.9/2.1	2%	3.3/2.9	2.9/2.5	2%	0.4/0.4	0.4/0.3
3%	2.6/2.2	2.3/2.0	3%	3.0/2.6	2.7/2.3	3%	0.4/0.3	0.3/0.3
Noord-Brabant Q_h [PJ]	Climate scenario		Limburg Q_h [PJ]	Climate scenario				
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5			
0%	5.2/4.5	4.6/3.9	0%	2.3/2.0	2.0/1.8			
1%	3.5/2.8	3.1/2.5	1%	1.6/1.3	1.4/1.4			
2%	2.7/2.4	2.4/2.1	2%	1.1/1.0	1.0/0.9			
3%	2.5/2.2	2.2/1.9	3%	1.0/0.9	0.9/0.8			

The number of dwellings also affects the heating energy demand in the period 2051-2060. For almost all scenarios, a low stock of dwellings causes a heating energy demand reduction of more than 10% compared to a high stock (exceptions with lower reductions in some scenarios can be found for Drenthe, Overijssel, Gelderland, Utrecht, Zeeland, and Limburg). In some scenarios for the provinces Groningen, Friesland, Drenthe, Noord-Brabant, Noord-Holland, and Zeeland, the reduction is even more than 20%. In Noord-Brabant, for climate scenario RCP2.6 and a renovation rate of 1%, the heating energy demand is 3.5 PJ for a high population or 2.8 PJ for a low population in 2051-2060.

A large impact can be also seen for an increase of the renovation rate per year to 2%, which describes a policy option as the current level is about 1%. This would reduce the heating energy demand in Groningen, Friesland, Drenthe, Gelderland, Zuid-Holland, Noord-Brabant and Limburg by at least 13%.

Although a 1% renovation rate and a low population may lead to a similar heating energy demand in 2051-2060 as a 2% annual renovation rate and a high population for some provinces, striving for a 2% renovation rate per year is desirable as future changes in the population are difficult to influence. Table 5 also clearly shows that the current rate of about 1% renovation per year causes the heating energy demand in 2051-2060 to be at least 30% lower in each province (except Zeeland and Limburg) than in the scenarios with no renovation.

4. Discussion

Considering future changes in population and temperature, we calculate the heating energy demand of Dutch dwellings up to the middle of the century and determine the annual renovation rates that are necessary in order to reach national targets for this sector. We find that renovation activities have the strongest impact but projected building stock and temperature changes also significantly influence the future heating energy demand.

We approach this topic on both the national and regional as well as an annual and a monthly scale and find reductions in the heating energy demand of 21-43% in the maximum scenario and 54-69% in the minimum scenario (neglecting Flevoland) when comparing 2051-2060 with the period 1991-2000. As far as we know, there is just one study on the energy demand of dwellings in the Netherlands that considers future climatic changes. For three example residential buildings, van der Spoel and van den Ham [39] studied the pure impact of future temperature changes on the heating and cooling energy demand. As they neglect future renovation measures, they found lower future heating energy demand reductions of 11%-27% between 1990 and 2050 and stronger cooling energy demand increases of 43%-200%, but from a much lower level compared to the heating energy demand. Other authors analyzed the energy use in the Dutch building sector without taking future climatic changes into consideration. Tambach et al. [40] examined policy instruments for energy savings in the existing building stock and Noailly and Batrakova [41] explored the effect of public policies on technological innovations in the housing sector. Both the study of Taleghani et al. [42] and our study underline that the energy demand of a building is not only depending on its size, but also the energetic standard which is normally correlated to the year of construction.

Our study is aimed at determining the feasibility of national targets regarding energy demand reductions in the building sector. Majcen et al. [43] found that the theoretical energy demand which is the basis for the efficiency label of a building does not correspond with the actual energy use. While energy-efficient dwellings consume more than predicted, those with a low energy label consume less. This implies that improving a building from a bad to a good energetic standard reduces the energy consumption less than expected which may result in a failure of achieving reduction targets. The difference between the energy demand and the energy consumption that was found by Majcen et al. [43] is mainly due to social factors such as the heating behaviour of inhabitants. Although, the energy consumption is influenced by these individual aspects, the energy use in Dutch dwellings is strongly influenced by building characteristics. Guerra Santin et al. [44] showed that the latter have a ten times larger influence on the energy use than the behavior of the occupants. This is in line with our findings regarding the relevance of energetic improvements in the building sector. We show that every Dutch province needs at least to double its annual renovation rate in order to reach the national target of reducing the energy demand of dwellings by half. Overijssel, Noord-Holland, Zuid-Holland, and Noord-Brabant have to triple and Utrecht even has to quadruple this rate to meet the target.

A comparison with Table 1 shows that our study allows for a comprehensive analysis of the future heating energy demand of residential buildings under climate change. Less than half of the listed publications consider more than one of these factors: comprehensive stock of buildings, population changes, or future renovation measures. Moreover, only one of the listed publications presents future results for the energy use on a monthly basis and none provides recommendations regarding the amount of necessary renovation measures in order to reach national targets. Our study fills this gap and thus forms a sound and reliable basis of argumentation for decision makers.

Comparing our results regarding the heating energy demand development and sensitivity of the Dutch residential building sector with that of studies for other countries is difficult due to differences in the modeling approaches, the considered scenarios as well as future changes in population and climate. However, reductions that are similar to ours have been calculated by Aguiar et al. [6] who discovered heating energy demand decreases of 34-60% for residential buildings in Portugal between 1961-1990 and 2070-2099 and Frank [19] who calculated reductions of 33-44% for Switzerland in 2050-2100 compared to the same reference period. Taking different energy efficiency measures such as wall or roof insulation into account, Gaterell and McEvoy [14] calculated heating energy demand reductions in UK houses of 9-39% in the low emission scenario up to 2050 and 17-53% in the high emission scenario, which is also close to our results. The aforementioned publications are all based on very detailed and data demanding models (MD), but do not consider population changes or a comprehensive stock of buildings. Strong reductions in warmer regions that are similar to our results should not be misinterpreted. On the one hand, the authors often only analyse example buildings instead of a comprehensive building stock or do not consider future population changes (Table 1), on the other hand, heating often only plays a minor role in the considered countries such as in Hong Kong [9] and Australia [12]. Chow and Levermore [16] conducted a study for different office buildings in three cities in the UK up to the 2080s and underlined that the focus should be on renovating existing houses as the rate of new buildings per year is too low for a sufficient reduction in energy demand for room conditioning. The large importance of renovation measures was also shown in our study and that of Olonscheck et al. [22] who also used simplified, intermediate complexity models (MI).

We used an U-value of 0.286 for roof, wall and basement as we consider the values for new buildings from 2011 onwards and neglect another tightening of the U-values to 0.222 between 2011 and 2021. Such a consideration would have made the calculation effort very large. However, in order to check, whether using an U-value of 0.222 instead of 0.286 has a significant impact on the result, we calculated the heating energy demand using an U-value of 0.222 for all new dwellings erected between 2011 and 2021 (when the better U-values are anyhow assumed). The difference to our original result was in all scenarios and for all provinces neglectable (less than 1%).

Some aspects had to be neglected in our study. We assume a constant desired indoor temperature although in reality not all dwellings are heated uniformly to this temperature as physical characteristics, personal attitudes, and lifestyles also play a role regarding how much and how strongly people warm their dwellings. As Chappells and Shove [45] point to the fact that the comfort zone of people could extend in the future due to familiarization with greater variety which may reduce the energy demand for heating and cooling. Moreover, a dwelling typology is only a simplified representation of the Dutch building stock. Especially, passive houses and plus energy houses that will gain in importance in the future were not considered due to a lack of adequate trend data. While Frank [19] found that the heating season will be 53 days shorter, we do not study changes in the length of the heating period but only look at changes in the amount of heating energy that is required per month. However, we could show that by the middle of the century, heating will play a small role for Dutch residential buildings in September.

Hekkenberg et al. [46] found an increasingly positive trend in the electricity demand for the summer months which could be an indication for future summer electricity demand peaks in the Netherlands. Thus, although we do not focus on the future developments in the cooling energy demand as it does not play a significant role in most middle European countries at the moment [17, 22], it is important to keep in mind that this may change in the coming decades due to more frequent and longer lasting heat waves. Klein et al. [47] already showed that the electricity sector of the Netherlands is quite susceptible to climatic changes which is partly caused by the projected rise in the share of air conditioners. However, as our method is based on monthly values regarding the future energy demand, the threshold for cooling of 24°C will not be exceeded until 2060. Thus, for future studies, it would be necessary to focus on daily outdoor temperature values in order to be able to adequately consider times with a cooling energy demand. A follow-up study aims to calculate future cooling energy demand changes of the housing stock in the Netherlands in order to find out whether the country as a whole and its provinces are going to benefit from projected temperature increases or not. For the present study, such an analysis would exceed the scope substantially.

5. Conclusion and outlook

Retrofitting buildings is a win-win option as it not only helps to mitigate climate change and to lower the dependency on fossil fuels, but it also converts the building stock into one that is better equipped for extreme temperatures that may occur more frequently with climate change.

Whether such a transformation to a low energy demand of the stock of residential buildings is possible, mainly depends on future climatic and demographic changes as well as renovation activities. Our method allows for the consideration of these factors and provides data on the past heating energy demand that correlate quite well with the observed heating energy consumption. Thus, the method is likely also suitable for computing the future heating energy demand of residential buildings. We show that renovation measures have a strong impact on the future heating energy demand. In the majority of provinces a doubling of the current annual rate of 1% would lead to at least 13% less heating energy demand at the middle of the century. However, both the future dwelling stock and the projected temperatures also play a crucial role, but are difficult to influence locally. The presented information on the required annual renovation rates per province which range from 2.2% to 4.1% is robust and supports policy makers in taking the necessary steps on a regional level. Our approach constitutes an important step towards a better understanding of the relation between future temperature changes and the heating energy demand of the residential building sector. Given appropriate input data, the method can be applied for other spatial and temporal scales - something which is left for future work.

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