Applied Geography 154 (2023) 102936

Contents lists available at ScienceDirect

Applied Geography

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

Gendered geography of energy consumption in the Netherlands

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ARTICLE INFO

Handling Editor: Dr. Y.D. Wei

Keywords:
Household energy consumption
Gender inequality
Energy poverty
Energy transition
Spatial analysis

ABSTRACT

Household energy consumption (HEC) significantly impacts global greenhouse gas emissions and can trigger fuel and energy poverty among vulnerable households. Due to environmental policies and geopolitical turmoil limiting the energy supply, HEC needs to be curbed. This urges the identification of most energy-dependent consumers at different locations and the particular life circumstances that trigger such a high level of dependency. A gender perspective can provide insights into the life circumstances of households. Applying a geographically weighted regression model on HEC, including explanatory parameters on gender composition, age, ethnicity, income, home ownership, microclimate, urban morphology and land cover, the results show significant variations in HEC of gender groups in 87% of Dutch residential zones. Women with an immigration background (20%), children younger than 14 years old -presumably single mothers (14%), old buildings in hot climates (10%), or high income (9%) are the most energy-dependent gender groups in a significant portion of residential zones. So are the men in large-size households (18%) and older-than-65-years men in rural areas (8%). The study offers discussions on the results and a series of policy recommendations.

1. Introduction

1.1. Spatial variations of gender groups' energy consumption

Household energy consumption (HEC) has crucial environmental and social importance. The energy sector generates more than two-thirds of global greenhouse gas (GHG) emissions. Energy consumption in buildings, including HEC, accounts for 28% of energy-related GHG (International Energy Agency, 2021). In the United States (U.S.) HEC generated more than 18% of overall energy-related GHG in 2019 (US Energy Information Administration, 2019). In the European Union (EU), households accounted for 17% of total GHG emissions in 2022 (Eurostat, 2022). HEC has a social dimension, too. Various studies show that a significant portion of households faces difficulties affording the energy bills for adequate warming of their homes, which, in extreme cases, causes excessive mortality in winter (Healy, 2003; Liddell et al., 2016). Such energy poverty is related to family type (Walker et al., 2014), gender (O'neill et al., 2006), age (Day & Hitchings, 2009; Wright, F., 2004), income and homeownership (Mulder et al., 2023). Additionally, households are vulnerable to events which can increase household energy expenditures, such as lockdowns aiming to control pandemics (Qarnain et al., 2021) that drastically affect the operation of energy systems globally (Dawn et al., 2022).

HEC is also sensitive to geopolitical events. In Europe, because of the geopolitical turmoil in Ukraine, gas supply from Russia, accounting for 43% of demand in 2020 (Eurostat, 2020a), has become a liability. In addition to short-term plans to find new sources of energy supply, such as LNG and coal, energy demand must be reduced. In July 2022, Ursula von der Leyen, the European Commission president, urged for a 15% reduction in gas consumption in the coming winter (Euronews, 2022a), and experts called to ration energy during winter (Euronews, 2022b). These measures are in addition to the EU's ambitious plans for energy transition before 2030 and 2050, namely RePowerEU (European Commission, 2022a) and European Green Deal Energy (European Commission, 2022b).

Indiscriminate limitation of energy access for all households, e.g. rationing or introducing financial instruments such as carbon tax, can cause injustice, given that not all households have similar options for reducing their consumption. The urges for identifying the most energy-dependent households and the particular life circumstances which trigger such a high level of dependency at different locations. As suggested by various previous studies, a gender perspective can provide insights into such life circumstances of households (Lieu et al., 2020; Permana et al., 2015; Shrestha, Tiwari, Bajracharya, Keitsch, & Rijal,

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https://doi.org/10.1016/j.apgeog.2023.102936
Received 17 October 2022; Received in revised form 13 February 2023; Accepted 13 March 2023
Available online 21 March 2023
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2021; Sovacool et al., 2018). This study offers a statistical model of HEC of gender groups in the residential zones of the Netherlands, controlling for various socioeconomic, climate, land cover, urban morphology and housing factors. It identifies the most energy-intensive gender groups with different ethnicity, income, age and housing status and discloses their spatial distribution across the country. The novelty of this research is using fine-grain data across a vast geography. Using the socioeconomic data and control variables on buildings' geometry and urban microclimate at the neighbourhood scale across the Netherlands, the study provides a detailed and comprehensive database to analyse HEC. Meanwhile, the database covers the whole country, leading to a novel perspective on the heterogeneous geography of gender groups' HEC. The insights into the spatial heterogeneity of gender groups' energy demands have key implications for the development of district-oriented, just energy transition plans - one of the primary goals of the National Climate Agreement of the Netherlands, the Dutch government's policy to reduce GHG emission by 49% in 2030 compared to 1990 in different sectors among them the residential sector (Ministry of Economic Affairs and Climate Policy, 2019). In the following parts of the manuscript, a knowledge gap in previous studies on gender and HEC and the objective and approach of the study are presented. Subsequently, the method and data used in the study and results are presented and discussed. Ultimately, conclusions are drawn, and policy implications are put forward.

1.2. Literature review and knowledge gap: gender and household energy consumption

Energy consumption of gender groups has been widely studied. Shrestha et al. identified three major reasons for HEC variations among gender groups. First is the "social role" of gender groups, i.e. the social constructs that shape different behaviours among gender groups. Second is the "perception and responsibility" of gender groups, referring to varying positions of gender groups in the labour market, e.g. likelihood of male members working more outside of the house and female members being more involved in housework and feeling responsible for the energy security of the households. The third is "preferences and choices", i.e. cultural norms and gender constructs affecting consumption patterns and preferences in purchasing appliances (Shrestha, Tiwari, Bajracharya, Keitsch, & Rijal, 2021). In the following paragraphs, the framework proposed by Shrestha et al. is used to review previous studies on gender and HEC.

Various previous studies approach HEC of gender groups from the perspectives of "social roles" and "perception and responsibility". In a review, Fathallah and Pyakurel showed that various studies had established links between the lifestyle of gender groups and their HEC (Fathallah & Pyakurel, 2020). In a study on the impact of technology on HEC in the U.S., Adua found that energy consumption for space heating was significantly higher in the so-called male-headed households (Adua, 2020). In a study of 22 European countries, Umit et al. found that the presence of females in a family was associated with higher energy efficiency (Umit et al., 2019). In the United Kingdom, Grünewald and Diakonova found that the electricity consumption of a single male outnumbered that of a single female by up to 13% (Grünewald & Diakonova, 2020). A study by Wang et al. on space cooling energy consumption in Zhuhai, China, suggested that males consume 20%–50% more energy than females (Wang, Zhu, et al., 2019). Studying the impact of daily habits on energy consumption among Japanese households, Matsumoto showed that females consumed 0.14 kWh more energy than males, given their pattern of domestic work in late evenings (Matsumoto, 2019). Various researchers have studied gender mainstreaming and energy. Musango et al. studied the energy-gender-poor nexus in Africa and urged energy policies to add such an angle to their perspective (Musango et al., 2020). Lieu et al., through a comparative study on gender mainstreaming in Canada, Kenya and Spain, suggested that the energy transition process is vastly gendered (Lieu et al., 2020). In Kathmandu, Nepal, Shrestha et al. observed unequal participation of gender groups in energy decisions (Shrestha, Tiwari, & Bajracharya, 2021). Ding el al. found evidence of Tibetan women's exclusion from the development and management of energy transition projects (Ding el al., 2019). Daggett conceptualised petro-masculinity, i.e. the historical enforcement of patriarchal capitalism by fossil fuel extraction (Daggett, 2018). Li et al. observed that green energy was more likely to be adopted in Chinese counties with higher levels of gender equality (Li et al., 2019).

Various previous studies approach HEC of gender groups from the perspective of "preferences and choices". In a study on "Is mom energy efficient?" in Bandung city, Indonesia, Permana et al. found that when women were in charge of the energy expenditure of a household, the overall consumption tended to decline (Permana et al., 2015). In a study on energy transition in Groenheuwel informal settlement, South Africa, Musango showed that dwellings with female or male as the head of households varied in types of consumed fuels (Musango, 2022). In a study on the demographics of decarbonising in Nordic regions, Sovacool et al. found that employed, highly-educated, middle-aged men invested more in energy-efficient appliances than women (Sovacool et al., 2018). Nikus and Wayessa found that fuel choice significantly differed across the female- and male-headed households in Ambo Town, Ethiopia (Nikus & Wayessa, 2022). Adusah-Poku et al. found that female-headed households in Ghana were more likely to consume cleaner energy sources than male-headed ones, Ceteris paribus (Adusah-Poku et al., 2022, pp. 1–22), opposite to the observations made by Aryal et al. in Bhutan (Aryal et al., 2019). Soltani et al. showed that male-headed households consumed more liquefied petroleum gas (LPG) than female-headed households in Mashhad, Iran (Soltani et al., 2019). Zou and Luo found that male-headed households consumed less LPG for cooking (Zou & Luo, 2019). Aslam and Ahmad observed that male-headed households consume relatively more electricity but did not find significant evidence of gender variations in gas consumption (Aslam & Ahmad, 2018).

Most of the previous studies on gender and HEC lack a spatial dimension. The studies typically relied on a sample of households and drew conclusions at the individual scale. Consequently, often offering contradicting observations, the studies did not acknowledge that the relations between gender and HEC may differ from one location to another and may not be reduced to a set of spatially homogenous rules. Various researchers have already acknowledged the spatial variations of HEC determinants. Moore and Webb studied spatial variations of energy financial burden for socioeconomic groups across Ohio, U.S. (Moore & Webb, 2022). Wang et al. assessed the spatial variations of HEC in relation to life expectancy in China (Wang, Liu, et al., 2019). Rong et al. analysed the spatial differentiations of HEC emission in Kaifeng, China (Rong et al., 2020). Cartone et al. used spatial statistics to measure sprawl's impact on electricity consumption in Spain (Cartone et al., 2021). Robinson et al. obtained and mapped the spatial variations of energy vulnerability across England (Robinson et al., 2019). A limited number of spatial studies which included gender in their models have shown that highly variant impacts can be expected. Through a comprehensive overview of the factors associated with energy poverty, Robinson disclosed the geographic heterogeneity of gender-sensitive factors in England (Robinson, 2019). A study by Mashhoodi showed that gas dependency among the gender group varied at the country scale (Mashhoodi, 2021a). There, however, is a lack of a comprehensive study on the large-scale geography of gender groups' energy consumption considering all demographic factors such as income, ethnicity, family type, age, and home ownership.

1.3. Objective and approach of this study

Aiming to bridge the knowledge gap in the previous studies on energy consumption of gender groups, i.e. lack of a socio-spatial dimension at a large scale, this study puts forward two research questions:

1. Does HEC vary across the gender groups living in different locations of the Netherlands?
2. If yes, what are the family type, age, income, housing status, and ethnicity of the most energy-intensive gender group in different locations of the country?

Seeking answers to the questions mentioned above, in addition to the data on gender balance in Dutch residential zones, this study includes nine types of socioeconomic data at the Dutch residential zones in 2018:

1. Household size, given its associations with higher numbers of appliances (Surahman et al., 2022), its impact on the use of different energy sources such as gas and electricity (Acharya & Adhikari, 2021), and economies of scale in energy consumption (Selvanathan et al., 2021);
2. Share of low-income inhabitants of the total population, regarding the shortage of resources for investment in energy-efficient appliances (Xu & Chen, 2019), choice of relatively cheaper energy sources and buildings' lower energy efficiency (Ravindra et al., 2019; Yawale et al., 2021), and difficulties with affording energy bills (Wang & Lin, 2022), which affect energy consumption habits;
3. Share of high-income inhabitants of the total population, given its association with possession of more appliances (Zi et al., 2021), relatively higher heft for investment in building efficiency (Trotta, 2018), affording higher energy bills to seek higher thermal comfort (Umit et al., 2019);
4. Share of children younger than 14 years old of the total population, given its increasing impact on energy consumption for water heating (Fuentes et al., 2018), possible increase of energy expenditures among families with children (Simões & Leder, 2022), and the danger of energy poverty (Ye & Koch, 2021);
5. Share of 15–24 years olds of the total population, given age groups' possible engagement in outdoor activities after school hours (Martins et al., 2021) and possible high dependency on electricity (Hu et al., 2020; Jo et al., 2020);
6. Share of the population older than 65 years old of the total population, given the age groups' specific feeling of thermal comfort (Wang, Yu, et al., 2019), the high number of hours spent on leisure and personal care (Vilhelmson et al., 2021), a different attitude towards electricity consumption compared to younger age groups (Cahyani et al., 2022), and vulnerability to fuel poverty (Day & Hitchings, 2009; Wright, F., 2004);
7. Immigration background, given the likelihood of living in dwellings with lower levels of quality (Goldstein et al., 2022) and having a lower-than-average income (CBP, 2019) which can trigger higher energy consumption and danger of energy poverty among ethnic groups (Buylova, 2020; Wang et al., 2021);
8. Tenants, given the different rates of homeownership among ethnic and income groups (Goldstein et al., 2022) and possibly higher levels of electricity and gas consumption in rental dwellings (Burnett & Kiesling, 2022) which can vary based on age and income of households (Lei et al., 2022);
9. Building age, given its robust association with the energy label of buildings (Iraganaboina & Eluru, 2021) which can affect energy consumption for cooling (Yu et al., 2022) and heating (Eum et al., 2018).

Additionally, this study controls for the impacts of seven types of spatial and environmental factors:

1. Building surface-to-volume ratio, given its impact on the thermal transfer between dwellings and their ambient spaces (Moeller & Bauer, 2022; Mushtaha et al., 2021; Leng et al., 2020; Mashhoodi, 2020);
2. Number of cooling and heating degree days, given their impact on energy consumption for heating and cooling of space and water (Adua, 2020; Iraganaboina & Eluru, 2021; Shen et al., 2020);
3. Humidity, as it affects the severeness of felt temperature on heating and cooling days (Liu et al., 2021; Neya et al., 2021; Wolkoff et al., 2021);
4. Wind speed, given its impact on ventilation and thermal transfer between buildings surfaces and outdoor space (Nasrollahi & Ghobadi, 2022; Hadavi & Pasdarshahri, 2021; Neya et al., 2021);
5. Vegetation, given its impact on thermal comfort (Douthat et al., 2020; Sun et al., 2020; Taleghani, 2018);
6. Land surface temperature, given its impact on energy consumption for heating and cooling at different times of the year (Kumari et al., 2021; Litardo et al., 2020; Tian et al., 2021) and its variations across the socioeconomic and gender groups (Mashhoodi, 2021b).

2. Method

The study includes two statistical models. The first model is an ordinary least square linear regression model (OLS), which does not account for the spatial location of the zones. The model measures the global collinearity between the dependent and control variables (equation (1)).

$$HEC_i = \beta_0 + \beta_{WmM} WmM_i + \sum_k \beta_k x_{ik} + \sum_k \gamma_k WmM_i x_{ik} + \sum_k \delta_k z_{im} + \varepsilon_i \quad \text{(equation 1)}$$

where HEC_i, WmM_i are household energy consumption and the percentage of women minus the percentage of men in residential zone i. β_{WmM} represents the coefficients of WmN. β_0 and ε_i respectively show the intercept and random error. x_{ik} and β_k are the measurement of the kth socioeconomic variable at residential zone i and its estimated coefficient. $WmM_i x_{ik}$ and γ_k are the interaction term between WmM_i and the kth socioeconomic variable and its coefficient, and z_{im} and δ_k show the coefficient value of the mth control variable – including microclimate and urban morphology factors, at location i. The second model is a geographically weighted regression (GWR) which models the variations of impacts and estimates location-specific coefficients (equation (2)).

$$HEC_i = \beta_0(\mu_i, \nu_i) + \beta_{WmM}(\mu_i, \nu_i) WmM_i + \sum_k \beta_k(\mu_i, \nu_i) x_{ik} + \sum_k \gamma_k(\mu_i, \nu_i) WmM_i x_{ik} + \sum_k \delta_k(\mu_i, \nu_i) z_{im} + \varepsilon_i \quad \text{(equation 2)}$$

where (μ_i, ν_i) represent the longitude and latitude of the centroid of the ith zone. $\beta_0(\mu_i,\nu_i)$, $\beta_{WmM}(\mu_i,\nu_i)$, $\beta_k(\mu_i,\nu_i)$, $\gamma_k(\mu_i,\nu_i)$, and $\delta_k(\mu_i,\nu_i)$ represent the location-specific intercept and the estimated coefficient of WmM, the kth socioeconomic variable, the interaction terms between WmM and kth socioeconomic variable, and that of control the mth control variable. Equation (3) formulates the estimation of the coefficients of the GWR model (equation (3)):

$$\hat{\beta}(\mu, \nu) = \left(X^T W(\mu, \nu) X\right)^{-1} X^T W(\mu, \nu) y \quad \text{(equation 3)}$$

$\hat{\beta}(\mu, \nu)$ is the unbiased estimate of β. $W(\mu, \nu)$ is an adaptive bisquare spatial weight matrix (equation (4)).

$$W_{ij} = \begin{cases} \left(1 - \frac{{d_{ij}}^2}{\theta}\right)^2, & \text{if } d_{ij} < \theta \\ 0, & \text{otherwise} \end{cases} \quad \text{(equation 4)}$$

W_{ij} represents the weight of zone j in the GWR estimates of the coefficients for zone i. d_{ij} is the straight line length between the centroids of zone i and zone j. θ, the adaptive bandwidth, controls that only a certain number of closets zones of zone i are included in the estimation. The value of θ is the maximum distance that includes a certain number of zones. Using the GWR 4.0 tool (Nakaya et al., 2009), the number of included zones, bandwidth size, is set to minimise the Corrected Akaike Information Criteria (AICc) of the GWR model. Ultimately, to select the best of the two models, OLS and GWR, the performance of the models is compared using four indicators: goodness-of-fit (adjusted R^2), AICc, and magnitude and spatial distribution residuals.

3. Data and case study

3.1. Dependent variable and case study

This study is conducted on one of the most fine-grained administrative boundaries of the Netherlands (Fig. 1a), the so-called Wijken, hereinafter referred to as residential zones, in 2018. The geographic extent of the residential zones is defined by the Netherlands Bureau of Statistics (CBS). The residential zones are one of the most detailed geographic units for which CBS provides open-access data on the residents' energy consumption and socioeconomic characteristics such as income. Excluding the residential zones with district heating, for which the data on consumption is unavailable, or abnormally high or low proportion between gas and electricity consumption, as a proxy for specific arrangements by housing associations or local energy providers (absolute standardised value greater than 2.5), this study includes 2707 residential zones (CBS, 2018a). On average, every residential zone has 2719 dwellings (SD = 3363) and 6013 inhabitants (SD = 7280). The average area of the residential zones is 1207 ha (SD = 1535). The study's dependent variable is per capita household energy consumption (HEC), i.e. total gas and electricity use, in the residential zones in 2018 (Fig. 1b). The spatial pattern of HEC shows that the neighbourhoods with high and low consumption could be distributed across the country and be located adjacent to one another. This is due to the neighbourhood-by-neighbourhood tradition of urban design in the Netherlands, particularly after WWII, which resulted in the presence of neighbourhoods with highly distinguished types of buildings and residents adjacent to one another (Meyer, 1999), creating the diverse pattern of HEC. Fig. 1c uses Anselin Local Moran's I to demonstrate this attribute of Dutch neighbourhoods (Fig. 1c).

3.2. Independent variables: gender and the socioeconomic characteristics of households

The first independent variable of the study is the gender composition of the residential zones, quantified as the difference between the percentage of women and men among the residents registered in a zone according to CBS (CBS, 2018a), hereinafter called *Females (%.)*. On average, women are 1.51% more than men in urban areas. In non-urban areas, men are, on average, 1.57% more than women. (Fig. 2).

In addition to *Females (%)*, the study includes nine socioeconomic characteristics of households. *Household size* is the average number of people in households of a zone. *Low-income* and *High-income* represent the fraction of the zones' population with the Netherlands' lowest 40% or the highest 20% levels of income. *Population age 14 or younger*, *Population age 15–24*, and *Population age 65 or older* are the percentages of the population in the respective age groups. The percentage of the population with at least one foreign parent is represented by the variable called *Immigrants* (%). *Tenants* (%) is the percentage of inhabitants living in a dwelling they do not own. The source of the data is CBS (CBS, 2018a). As a proxy for the energy efficiency of the dwellings *Building age* is included. The variable is the median age of residential buildings in a zone, weighted by the gross floor area of the buildings. The GIS data on building volume is provided by the so-called 3d BAG database (Esri Netherlands, 2016). Table 1 summarizes the descriptive statistics of the independent variables.

3.3. Control variables: building morphology, microclimate and landcover

This study includes eight control variables on building geometry, land cover and climate. *The surface-to-volume ratio, i.e. the buildings' total facade and roof area* divided by the building volume in a block, is computed using the 3D BAG database (Esri Netherlands, 2016). Four variables control for the microclimate of the residential zones. The variables are obtained using the daily records of the 28 meteorological stations of the Royal Netherlands Meteorological Institute, KNMI (KNMI, 2018), and the guidelines for the interpolation of the observed records across the country: Interpolation Methods for the Climate Atlas,

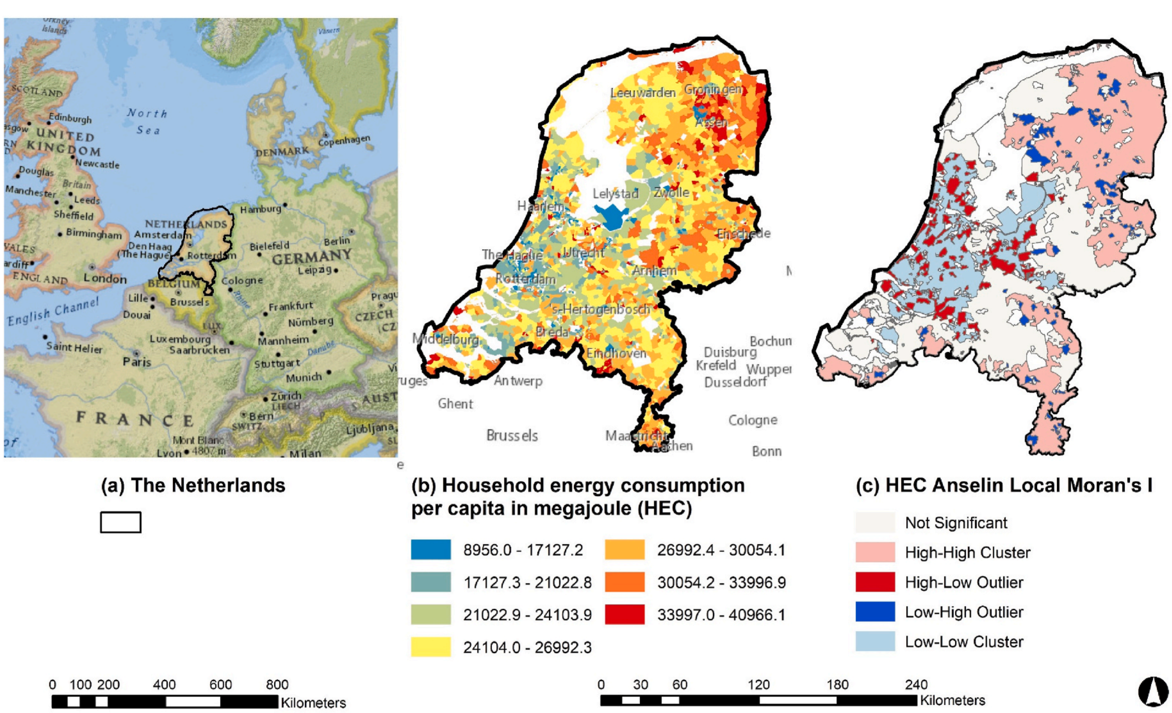

Fig. 1. The study's dependent variable is the average household energy consumption (HEC) per capita in residential zones.

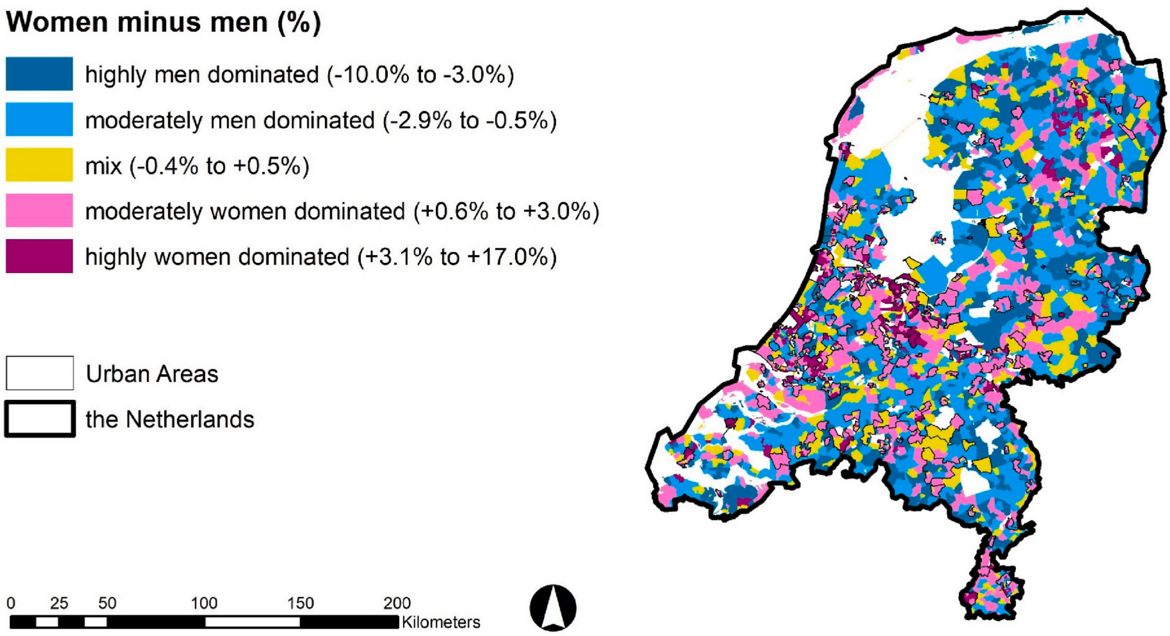

Fig. 2. The study's independent variable is Females (%), the difference between the percentage of women and men registered in a residential zone.

Table 1
Descriptive statistics of the independent variables.

	Mean	Minimum	Maximum	Std. Deviation
Household size	2.282	1.2	3.5	0.3003
Low-income (%)	39.55	19	65	5.041
High-income (%)	20.17	3	55	6.381
Population age 14 or younger (%)	15.61	1	35	3.432
Population age 15–24 (%)	11.93	2	44	2.903
Population age 65 or older (%)	20.09	2	74	5.801
Immigrants (%)	16.29	1	92	12.994
Tenants (%)	32.85	2	100	16.602
Building age	45.18	3.00	375.00	19.11

KNMI technical rapport (Sluiter, 2012). *Humidity (%)* at the height of 1.5 m, retrieved by adaptation of an ordinary kriging interpolation with an exponential variogram of the metrological records. *Wind-speed* at the height of 10 m is estimated using the two-layer model of the planetary boundary layer interpolation (Stepek & Wijnant, 2011) to interpolate the observation of the meteorological stations across the country. To do so, Silva et al. estimation of aerodynamic roughness length (Silva et al., 2007) of the European CORINE landcover database (European Environment Agency, 2018) is used. Two control variables to quantify the annual air temperature at the residential zones are used: *CDD* - the total number of annual degree days with an air temperature requiring energy consumption for space cooling; *HDD* - the total annual degree days with an air temperature which requires energy consumption for space heating. *CDD* and *HDD* are calculated based on three observations at the KNMI metrological stations: the maximum daily temperature (TX), minimum daily temperature (TN), and mean monthly temperature (TM). The three values are interpolated across the residential zones employing universal kriging with logarithmic distance to the shore as an external drift - following the KNMI guideline (Sluiter, 2012). Setting the base temperature for cooling and heating necessities at 22 °C and 15 °C, as suggested for Europe (Spinoni, Vogt, & Barbosa, 2015), *CDD* and *HDD* at the residential zones are obtained as follows (equations (5)–(8)):

$$CDD_i = \begin{cases} 0, if\ T_b \geq T_X \\ \frac{T_X - T_b}{4}, if\ T_M \leq T_b < T_X \\ \frac{T_X - T_b}{2} - \frac{T_b - T_N}{4}, if\ T_N \leq T_b < T_M \\ T_M - T_b, if\ T_b \leq T_N \end{cases} \quad \text{(equation 5)}$$

$$CDD = \sum_{i=1}^{182} CDD_i \quad \text{(equation 6)}$$

$$HDD_i = \begin{cases} T_b - T_M, if\ T_b \geq T_X \\ \frac{T_b - T_N}{2} - \frac{T_X - T_b}{4}, if\ T_M \leq T_b < T_X \\ \frac{T_b - T_N}{4}, if\ T_N \leq T_b < T_M \\ 0, if\ T_b \leq T_N \end{cases} \quad \text{(equation 7)}$$

$$HDD = \sum_{i=1}^{183} HDD_i \quad \text{(equation 8)}$$

where CDD_i represents cooling degrees between April 1st and September 30th, and HDD_i shows heating degrees between October 1st and March 31st.

Landcover properties are retrieved from satellite data. Average monthly values of the Normalized Difference Vegetation Index (*NDVI*), a measurement of the presence of green surfaces, are retrieved from the MODIS/Terra Vegetation Indices Monthly L3 Global 1 km SIN Grid V006 (Earthdata, 2019a, 2019b) to calculate the annual average.

Two control variables represent the land surface temperature (LST) during summer days and nights. To do so, satellite data at four overpassing times are retrieved and used (Earthdata, 2019a, 2019b): MODIS Terra day (10:30 a.m.), MODIS Aqua day (1:30 p.m.), MODIS Terra night (10:30 p.m.), and MODIS Aqua night (1:30 a.m.). The average of the two former satellite images is included as a variable called *LST-day* and that of the two latter as *LST-night*. Table 2 shows the specific dates of the satellite images included in calculations of *LST-day* and *LST-night*.

Table 3 summarizes the descriptive statistics of the control variables of this study.

Table 2
Satellite images included to retrieve LST at days and nights.

Satellite image	LST day		LST night	
Overpassing local time (source)	10:30 a.m. (MODIS/ Terra, MOD11A2)	1:30 p.m. (MODIS/ Aqua, MYD11A2)	10:30 p.m. (MODIS/ Terra, MOD11A2)	1:30 a.m. (MODIS/ Aqua, MYD11A2)
Time period	T01: 26/06/2018–03/07/2018 – T02: 04/07/2018–11/07/2018 – T03: 12/07/2018–19/07/2018 – T04: 20/07/2018–27/07/2018 T05: 28/07/2018–04/08/2018 – T06: 05/08/2018–12/08/2018 – T07: 29/08/2018–05/09/2018 – T08: 06/09/2018–13/09/2018 T09: 14/09/2018–21/09/2018			

Table 3
Descriptive statistics of the control variables.

	Mean	Minimum	Maximum	Std. Deviation
Surface-to-volume ratio	0.26	0.10	0.40	0.04
Humidity (%)	78.11	74.22	84.08	1.77
Wind speed (km/hr)	36.25	21.96	70.96	7.08
HDD	1622.18	1615.38	1625.58	2.07
CDD	96.73	27.30	147.82	28.76
NDVI	0.58	0.17	0.76	0.10
LST day	29.52	23.31	35.05	1.86
LST night	13.59	10.50	17.16	1.33

4. Results

4.1. The results of the OLS and GWR models

In the first step, an OLS model is adopted. The model results show that the Variance Inflation Factor (VIF) of the model's independent, control and interaction terms variables is smaller than 10, the commonly accepted maximum threshold of VIF (James et al., 2013). This shows that the impact of the variables on HEC is independent to an acceptable degree. The significant ($p < 0.01$) Joint Wald Statistic confirms that the overall model is significant. The results show that the Koenker (BP) Statistic is significant at $p < 0.01$ level, possibly due to non-stationary relations or heteroskedasticity – i.e. the error term being a function of dependent variable magnitude. The significant ($p < 0.01$) Jarque-Bera Statistic also confirms that residuals of the OLS model are not normally distributed. The results of the tests provide arguments for the necessity of employing a GWR model for assessing non-stationary relationships embedded in an overall-significant model. The OLS model shows that twenty out of 27 estimated coefficients are significant at the *p-value* < 0.05 levels. In the second step, a GWR model is adopted. Using the GWR4 tool (Nakaya et al., 2009), the bandwidth size of the adaptive bisquare spatial weight matrix is set at 380 zones. The bandwidth is the optimal size to achieve the minimized value of AICc. The GWR model performs better than the OLS model in terms of three measurements. The adjusted R-square of the GWR model is 77% compared to 64.7% of the OLS model. The AICc of the GWR model is substantially smaller than that of the OLS model, 4087.4 compared to 4896.5. Ultimately, the spatial distribution of the residuals of the GWR model is more "random" than that of the OLS model, represented by the closer-to-zero absolute value of the Morans' I test of the model (Table 4). The GWR model's better performance shows a significant spatial variation of gender groups' HEC.

The GWR model also outperforms the OLS model in terms of the magnitude of the residuals. The F-statistics of the ANOVA test on the models' residuals show that the former model generates significantly smaller residuals (Table 5). Given the better performance of the GWR model, hereinafter the model's results are used to explain the associations between gender and HEC.

Table 4
Estimates and diagnoses of the OLS and GWR models.

Variable	OLS model β	OLS model t	OLS model VIF	GWR model β mean	GWR model β SD
Intercept	0.00	0.94		−0.01	0.46
Independent variables					
Women minus men (%)	−0.14	−7.74	2.42	−0.20	0.13
Household size	−0.03	−0.87	7.10	−0.03	0.18
Low-income (%)	0.32	12.60	5.05	0.29	0.13
High-income (%)	0.27	11.59	4.23	0.34	0.12
Population age 14 or younger (%)	−0.28	−12.14	3.95	−0.27	0.13
Population age 15–24 (%)	−0.19	−10.44	2.41	−0.14	0.09
Population age 65 or older (%)	0.19	8.00	4.21	0.20	0.13
Immigrants (%)	−0.06	−2.71	3.42	−0.14	0.15
Tenants (%)	−0.41	−14.36	6.15	−0.28	0.14
Building age	0.31	20.38	1.77	0.28	0.08
Control variables					
Surface to volume ratio	−0.04	−2.49	1.72	−0.04	0.07
Humidity (%)	0.05	1.63	7.36	0.01	0.51
Wind speed (km/hr)	0.01	0.73	2.94	0.09	0.10
HDD	−0.01	−0.62	1.94	−0.12	0.26
CDD	0.22	6.50	8.78	0.30	0.50
NDVI	0.05	2.08	4.12	0.06	0.09
LST day	−0.08	−4.25	2.50	−0.08	0.10
LST night	−0.21	−8.89	4.35	−0.08	0.11
Interaction terms					
Women minus men (%) * Household size	−0.06	−2.04	6.22	−0.12	0.24
Women minus men (%) * Low-income (%)	0.09	3.68	4.34	0.06	0.14
Women minus men (%) * High-income (%)	0.09	4.67	2.72	0.06	0.11
Women minus men (%) * Population age 14 or younger (%)	0.00	−0.13	3.45	0.06	0.23
Women minus men (%) * Population age 15–24 (%)	−0.05	−1.96	4.16	−0.02	0.14
Women minus men (%) * Population age 65 or older (%)	0.01	0.30	3.88	0.00	0.14
Women minus men (%) * Immigrants (%)	0.06	2.97	3.66	0.12	0.16
Women minus men (%) * Tenants (%)	−0.09	−4.61	2.83	−0.08	0.15
Women minus men (%) * Building age	0.12	8.20	1.64	0.14	0.14
R-square	0.650			0.815	
Adjusted R-square	0.647			0.770	
AICc	4896.5			4087.4	
Residual Moran's I	0.1173			−0.0057	
Joint Wald Statistic	NA			380	
Joint Wald Statistic	4514.40*				
Koenker (BP) Statistic	243.90*				
Jarque-Bera Statistic	1323.21*				

β: standardised regression coefficient.
SD: standard deviation
OLS coefficients significant at p-value <0,05 are marked underlined.
* significant at p-value <0,01 are marked underlined.

Table 5
ANOVA test comparing residuals of the OLS and GWR models.

GWR ANOVA Table	SS	DF	MS	F
Global Residuals	946.621	2679		
GWR Improvement	447.102	496.893	0.9	
GWR Residuals	499.519	2182.107	0.229	3.930678

SD: sum-of-squares; DF: degrees of freedom; MS = Mean squares.

4.2. The spatial variation of gender groups' energy consumption

Fig. 3 maps the GWR model's significant interaction coefficients between *Female (%)* and other socioeconomic variables. The zones with pink colour show significant positive coefficients (*p-value* < 0.05), i.e.

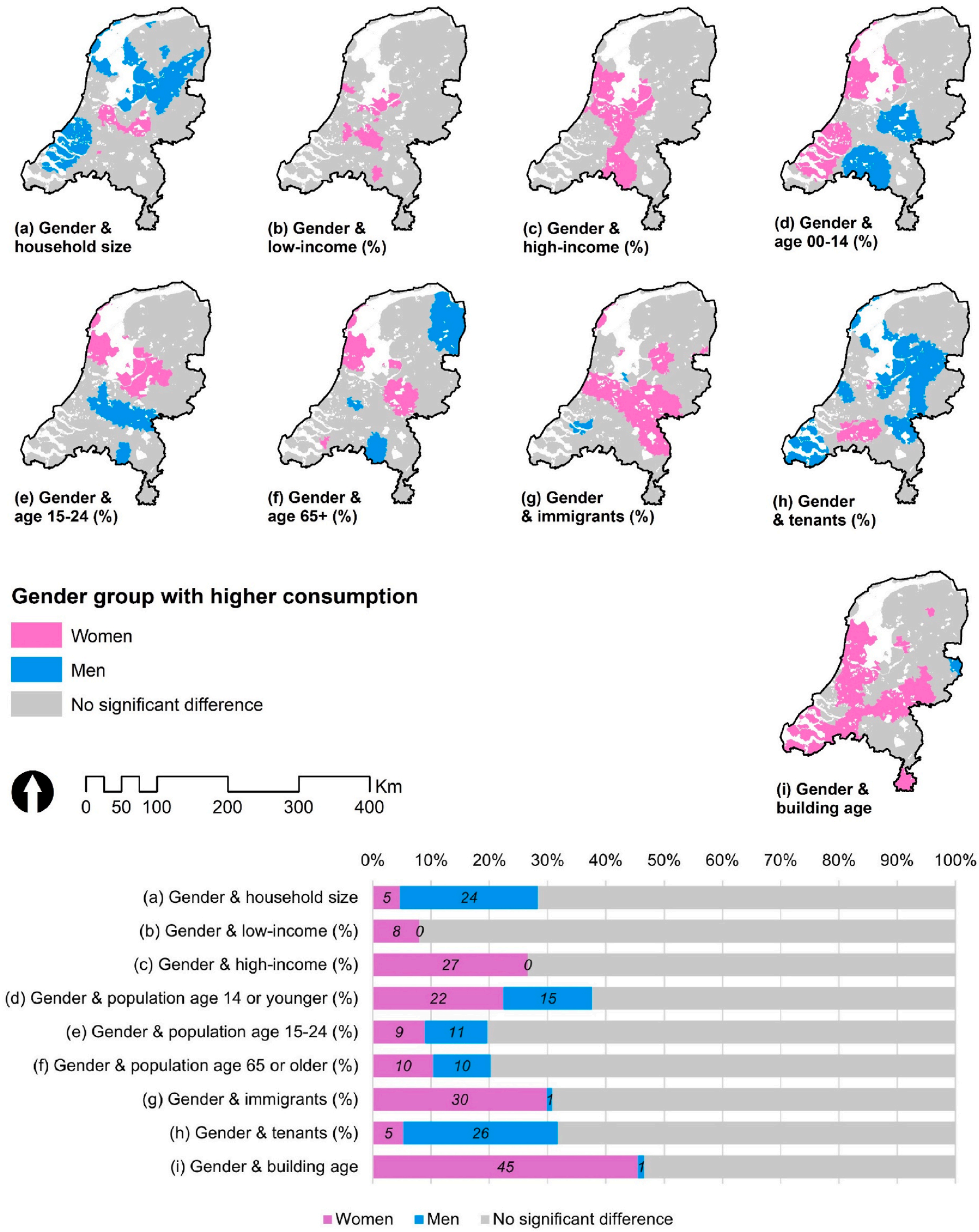

Fig. 3. Spatial variations of gender groups' energy consumption across the residential zones.

the zones where women have a higher HEC than men. The zones with blue colour indicate significant negative coefficients (*p-value* < 0.05), i.e. the zones where men have a higher HEC than women. Zones with no significant gender coefficient are coloured grey. Three types of gender coefficients can be distinguished. The first type are the socioeconomic characteristics are associated with higher female HEC in most of the zones: *low income* (Fig. 3b), *high income* (Fig. 3c), *immigrants* (Fig. 3g), and *building age* (Fig. 3i). The second type of socioeconomic characteristic is associated with higher male HEC in most of the zones: *household size* (Fig. 3a) and *tenants* (Fig. 3h). The third type of variables affects males' and females' HEC in roughly a similar fraction of the residential zones: *population age 14 or younger* (Fig. 3d), *population aged 15–24* (Fig. 3e) and *population age 65 or older* (Fig. 3f).

4.3. *The geography of the gender group with the highest level of energy consumption*

Fig. 4 maps the gender group with the highest level of HEC in each residential zones. The map is based on the interaction terms of the *Females (%)* and the socioeconomic variables. To identify the gender group

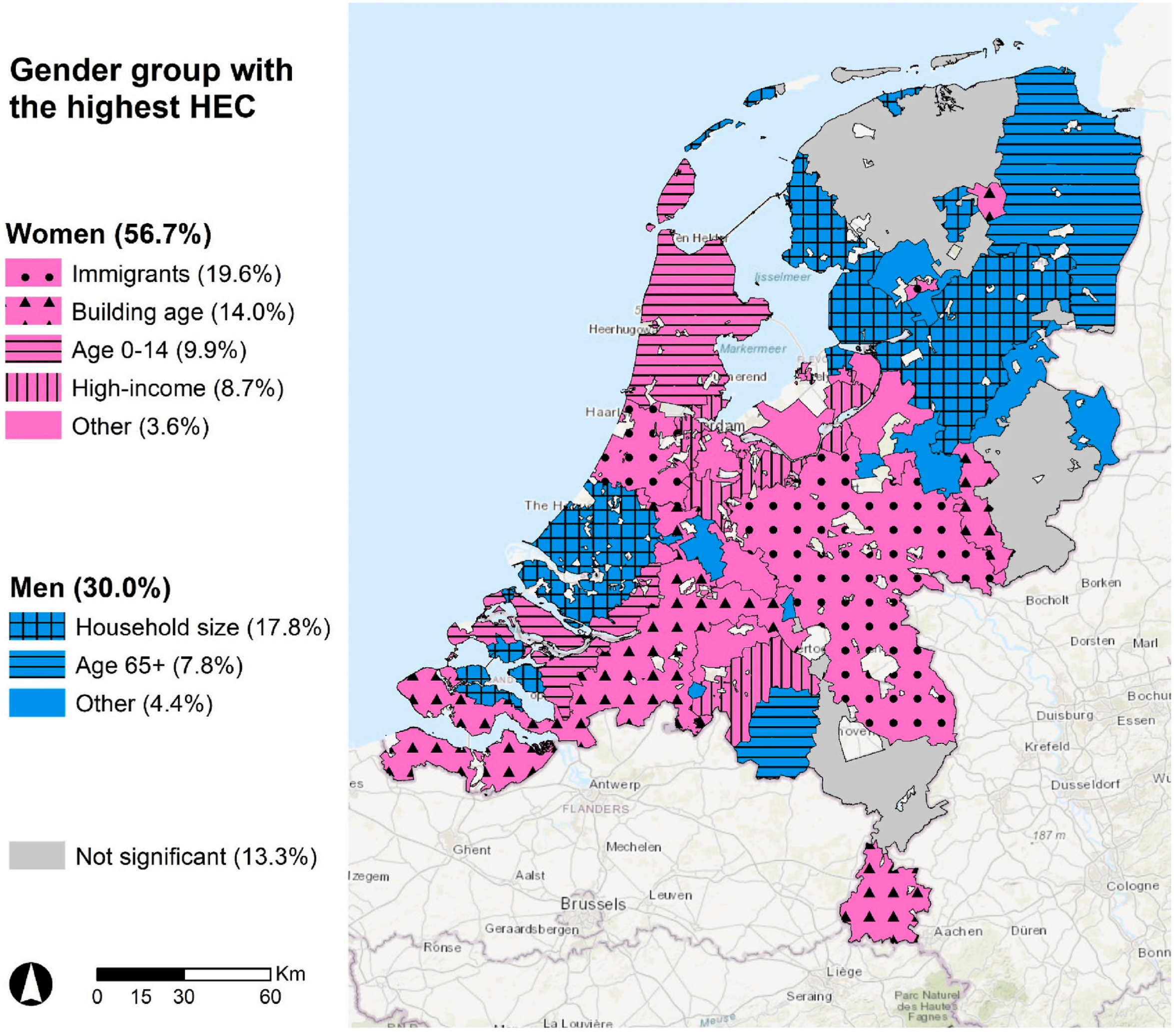

Fig. 4. Spatial distribution of gender groups with the highest level of energy consumption.

with the highest level of HEC, the maximum absolute value of the significant (*p-value* < 0.05) coefficients in the zones is used. The results show that women (57%) are the most energy-intensive gender group in more zones than men (30%). In 13% of the zones, no significant association between gender and HEC is found. Six gender groups with particular socioeconomic characteristics are the most consuming in at least 5% of the zones. Among women, immigrants (19.6%), residents of relatively older dwellings (14%), families with children younger than 14 years old (9.9%), and high-income households (8.7%) are the most energy-consuming energy group. Among men those who live in relatively larger households (17.8%) or aged 65 years or older (7.8%) are the most energy-consuming gender group in substantial numbers of zones (Fig. 4).

5. Discussion

The results of this study show significant variations in gender groups' HEC across the residential zones of the Netherlands. In particular, four female and two male groups are identified as the most energy-intensive gender groups in substantial portions of the zones. In the following paragraphs, the potential reasons for the high HEC of these groups are discussed, and links to the findings of previous studies are established.

5.1. *Female high consumption*

The results identify four energy-intensive female groups in substantial portions of the residential zones: (1) immigrant women, (2) women in old dwellings, (3) women with children younger than 14 years old, and (4) high-income women. Immigrant women are the most energy-intensive gender group in almost 20% of the residential zones, presumably due to lower participation in the labour market and higher hours spent at home compared to other gender groups. Two sets of statistics support the presumption about low labour participation of immigrant women. First, men work longer than women in the Netherlands, 3.6 billion hours compared to 2.1 billion (CBS, 2022a), have more full-time contracts, 3.4 million compared to 1.3 million (CBS, 2022b), and fewer part-time contracts, 1.4 million compared to 3 million (ibid). Second, immigrants (ethnic minorities) participate between 3% and 13% less in the labour market than native Dutch (CBS, 2018b). Another possible reason could be the higher engagement of female immigrants in domestic work compared to other gender groups. Female immigrants in Spain are more likely to compromise their professions for domestic household duties (Sánchez-Domínguez & Abenza, 2021), and even in the most gender-equal country of the world, Sweden, female immigrants' participation in the labour market is significantly lower than native females (Spehar, 2022). Japanese women consume more electricity than men because of staying up longer at night for house-related work (Matsumoto, 2019).

In 14% of the residential zones, women living in old dwellings (as a proxy for low quality) are the most energy-intensive gender group. The zones are located in the Southern parts of the country, particularly the provinces of Zeeland and Limburg, with the highest annual number of warm days. As noted earlier, women could have a stronger demand for thermal comfort than men in warm (Indraganti & Humphreys, 2021) and cold climates (Karjalainen, 2007) and consume more energy for space cooling and heating. The higher sensitivity of females to temperature (Jowkar et al., 2020; Yang et al., 2017) presumably is exacerbated in low-quality buildings in areas with a warm climate.

In almost 10% of the residential zones, women with children younger than 14 are the most energy-intensive gender group. This presumably identifies the households headed by single mothers. In 2019, 3.4 million children, 16% of the total minors population, in the Netherlands lived in single-parent households. Most of these children, 89%, lived with their mothers (CBS, 2020). The observed energy intensity is presumably due to high HEC for domestic water heating in single-mother households. The number of children is a robust factor for high domestic water heating, DHW (see the review by Fuentes et al., 2018), particularly for gas consumption (Braun, 2010). Such demand can impose higher HEC on single mothers (Castaño-Rosa & Okushima, 2021) and trigger the "Feminization of energy poverty" (Sánchez et al., 2020).

High-income women are the most energy-consuming gender group in almost 9% of the residential zones. This is presumably due to the difference in "preferences and choices" among gender groups (Shrestha, Tiwari, Bajracharya, Keitsch, & Rijal, 2021). Various previous studies observed that women tended to be more concerned about the household economy and energy saving than men (Arachchi & Managi, 2021; Shrestha, Tiwari, & Bajracharya, 2021; Urban & Ščasný, 2012). The high level of energy consumption among high-income women is presumably due to the paling of such tendencies when household income increases. This is in line with the results of various previous studies, which identified higher income levels as a trigger of higher energy consumption due to a possible increase in dwelling size (Estiri, 2014) and affordability of higher energy bills (Cayla et al., 2011).

5.2. Male high consumption

The results identify two energy-intensive male groups in substantial portions of the residential zones: (1) men in larger households and (2) men older than 65. Men in larger households are the most energy-consuming gender group in almost 18% of the residential zones, presumably due to a stronger feeling of financial security in two-parent households (Taulbut et al., 2016; Zagel et al., 2022). This assumption is supported by previous studies which observed that man-headed households might consume more energy (Aslam & Ahmad, 2018; Räty & Carlsson-Kanyama, 2010; Soltani et al., 2019), and woman-headed households are more energy efficient (Permana et al., 2015). Additionally, two-parent households are likely to consume more energy (Guerra-Santin et al., 2018), possibly due to living in dwellings with larger floor areas and more bedrooms (McLoughlin et al., 2012, Houttekier et al., 2010).

Men aged 65 years or older are the most energy-intensive gender group in almost 8% of the residential zones. One possible reason for such an observation is the different locations of senior men and women in the Netherlands. Earlier studies show that Dutch senior men are more likely to live in rural areas than senior women (Houttekier et al., 2010) and that men outnumber women in rural and non-urbanized areas of the Netherlands (authors' computation based on CBS, 2018a). Living in rural areas can boost the energy consumption of senior men due to a variety of impacts, among them a higher surface-to-volume ratio of the dwellings (Bernabé et al., 2015; Steemers & Yun, 2009), a higher thermal loss of dwellings due to stronger wind (Sanaieian et al., 2014; van Moeseke et al., 2005). Such impacts could be excessive, given that in cold seasons senior citizens find their comfort at higher temperatures than young adults (Schellen et al., 2010), can consume an extensive amount of gas (Brounen et al., 2012), and that energy-saving attitudes are weaker among men compared to women (Grünewald & Diakonova, 2020).

6. Conclusions

Given its impact on effective communication, transportation and use of technologies, energy plays a significant role in the life of women and men. It can affect one's opportunities for personal development and widen gender inequality (European Institute for Equality, 2022). The results of this study show that in 87% of Dutch residential zones, a gender perspective on energy consumption can provide insights into the life circumstances of the most energy-intensive households. Most identified gender groups include households that expectedly cannot easily reduce their consumption levels due to various socioeconomic circumstances, e.g. women with an immigration background, single mothers, women in low-quality buildings and warm climates, fathers in large households, and elderly, rural men. The results of this study show that gender has a spatially-variant association with HEC, and gender groups with various ages, incomes, ethnicity and housing tenure can be the most energy-intensive in different neighbourhoods. This study's results urge adding a gender angle to the district-oriented approach to energy transition in the Netherlands (Ministry of Economic Affairs and Climate Policy, 2019). The approach needs to be amended by district-oriented social plans to protect and support gender groups who may face difficulties affording energy bills, adequately meeting their basic needs, or adapting the measures necessary for transition to a sustainable energy system. Current policies focus on the "effects" of energy vulnerability, e.g. high energy expenses or losing access to the energy grid, and offer financial assistance to mitigate such effects. In the Netherlands, two types of policies are in place to protect consumers from the "effects" of energy vulnerability. The first type protects the consumers who could not pay their energy bills and lost their access to energy. Such policies address the life-endangering effect of energy vulnerability on households (Csiba et al., 2016). The second type, introduced after the breakout of the Ukraine conflict and the rise of energy prices in the EU, sets a temporary price cap on gas and electricity tariffs for households and small businesses, provided that their overall energy consumption is less than certain thresholds (Government of the Netherlands, 2022). The latter policies protect consumers from the "effect" of hefty energy expenditure on their life or businesses.

An additional set of policies must address the "causes" of such vulnerabilities, i.e. the life circumstances of vulnerable gender groups, and offer district-specific measures in the neighbourhoods where such vulnerable groups are identified. Such measures, for instance, have been introduced by the government of New Zealand as a part of the economic response package to COVID-19 through the program "Winter Energy Payment". The payment is designed to support consumers with certain life circumstances, including single parents, young parents, job seekers, and veteran pensioners (Government of New Zealand, 2023). The government of Spain offered the "Social Bonus", a discount scheme on electricity bills, to consumers with particular socio-economic conditions, such as those living in large families, shared dwellings, and suffering from permanent disabilities (Endea, 2022). The latter types of policies could include measures to protect certain gender groups and to address their life circumstances: e.g. vocational centres for further training of female immigrants, free-of-charge childcare and after-school-care in the districts with a high concentration of single-mother households, and community centres for senior, rural men. To help vulnerable gender groups to alter their daily routines and efficiently consume energy, neighbourhood-specific solutions need to be tailored. "Living labs" aim at understanding citizens' daily routines, emotions, and norms are a practical approach for such purposes (Sahakian & Bertho, 2018). Feasible neighbourhood-specific solutions must be proposed in collaboration between citizens and municipal aids (for example, see Sahakian et al., 2021).

Gender inequality in Europe has different dimensions, such as food insecurity (Grimaccia & Naccarato, 2022), pay gap (Redmond & McGuinness, 2019), inequality in academic positions (Rong et al., 2020), disparities in job satisfaction and work-life balance (Beham et al., 2019). The results of this study show that energy consumption constitutes yet another dimension of gender inequality. These findings urge the introduction of energy policies that ensure equal life chances for all citizens within the "right to energy" framework. Such efforts date back to the UN's women's rights convention in 1979, which introduced the "right to electricity" for women living in rural areas, and recent elaborations on the rights to overall energy needs and sustainable energy sources. However, the efforts need to be materialised in the frameworks of binding local regulations (Hesselman et al., 2021). The observed gendered geography of energy consumption in this study contributes to this academic discussion by proposing that the "right to energy" approach needs to be location specific and extend the safety net for the vulnerable gender groups in all geographic contexts. Will energy be a new face of gender inequality in the world facing climate change and geopolitical turmoils? The answer is not yet clear and requires further interdisciplinary studies. However, one thing is clear: the question should not go unnoticed.

7. Limitations and further studies

Further studies and readers need to mind two limitations of this study. The first limitation is that this study uses data from 2018, before the outbreak of the COVID-19 pandemic and vast lockdowns in the Netherlands. The lockdowns boosted remote working, which partially outlived the pandemic (Adekoya et al., 2022; Sahut & Lissillour, 2023) and shifted the time use and energy consumption within dwellings (Chen, de Rubens, Xu, & Li, 2020). Such a shift can alter the gap between gender groups' energy consumption, given that Dutch women work for fewer hours and more on part-time contracts than men (CBS, 2022). The second limitation considers the interpretation of the results of the study. Although the study uses rich and fine-grain data at the neighbourhood scale, the outcome cannot be extended to every individual living in a neighbourhood. Policymakers, in particular, need to approach and interpret the maps of gendered HEC carefully. For instance, identifying immigrant women as the most energy-intensive group in the eastern parts of the country does not mean that every single individual with such characterise is energy-intensive, nor that other men and women could not be energy vulnerable.

Author statement

Bardia Mashhoodi: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft; Writing - review & editing.

Thijs Bouman: Conceptualization; Investigation; Writing - original draft; Writing - review & editing.

Declaration of competing interest

The author has no conflict of interest to declare.

Acknowledgments

This research is part of the Flexible Energy Communities: Coupling e-mobility and energy communities (FlexECs) project funded by the Dutch Research Council's (NWO) Knowledge and Innovation Covenant programme (KIC) on Energy transition as a socio-technical challenge.

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