Spatial-Temporal Social Analysis of Households Energy Consumption in Southern Denmark

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***Abstract*—The pattern of energy consumption and the share of energy produced in any society depend on various factors such as social conditions, population size, user behavior, cultural norms, employment, and level of education. For residential consumers, these patterns vary spatiotemporally, showing notable instantaneous and seasonal fluctuations. Analyzing the social impacts on energy production and consumption requires access to precise, geographically segmented data to define meaningful indicators that provide insight into the social conditions of a community through its electricity consumption and production. This paper presents a comprehensive spatiotemporal study examining the social factors influencing residential electricity consumption in southern Jutland (Sydjylland) in Denmark. It investigates household shares of energy consumption and renewable energy production, the effects of gender, youth population, employment rate, household dependents, education, and renewable energy self-sufficiency across seven urban areas in southern Denmark. Correlation analysis shows that although the short-term and seasonal behaviors across the seven regions align, neighboring regions do not exhibit significant relationships in terms of the introduced indicators. Furthermore, the consumption per capita in each region has a direct correlation with the employment ratio and an inverse relationship with youth rate and education levels, where an increase in individuals aged 15-25 decreases consumption, while a higher number of employed populations tends to grow energy consumption.**

***Keywords*—energy consumption, social analysis, Denmark, education, employment, gender ratio.**

I. INTRODUCTION

By the end of 2023, households represented 26.8% of total energy consumption in the EU [2]. This level of consumption depends on factors such as household dependents, age, gender, cultural conditions, and employment status. Each of these factors has varying effects depending on the region's geography. Therefore, a spatiotemporal analysis is essential to examine the social factors impacting energy consumption [3]. Southern Denmark, Sydjylland, due to its proximity to Germany, is an important region with a population of over 475,000. Denmark is a leader in the installation and utilization of renewable energy sources, and the southern part of the country is no exception. Fig. 1 shows the map of the Sydjylland, including Sønderborg, Aabenraa, Tønder, Esbjerg, Haderslev, Vejen, and Kolding with corresponding population and total electricity consumption in the household sector.

Although the population size of each region is a key factor in the growth of daily and seasonal consumption, however, social conditions in each area have influenced residential energy consumption patterns. In [4], the authors examine the relationship between household energy footprints and well-being in the UK. The study finds that high-income and high-energy users contribute the most to energy footprints, primarily through car and air transportation. It highlights significant inequalities in energy consumption, with wealthier individuals driving excess energy use while benefiting from higher well-being. Additionally, the research

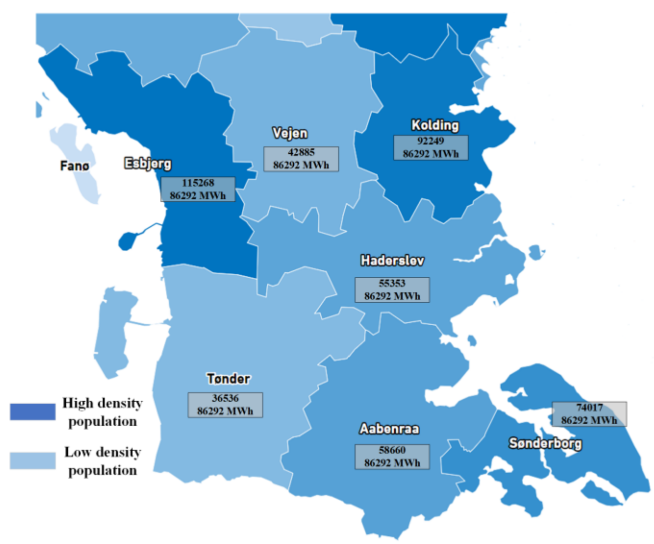

Fig. 1. Geographical graph of Southern Denmark, and corresponding population

reveals that individuals with protected characteristics are particularly vulnerable to energy poverty, despite their negligible contribution to overall energy demand. A comprehensive review of open datasets on city-level building energy use and their applications is presented in [5]. This paper critically examines 33 building energy datasets, categorizing and summarizing them while analyzing 11 subdomains where these datasets have been applied. The study also explores potential policy implications, introduces non-energy datasets frequently used in urban energy research, and discusses solutions to privacy concerns raised by data publishers. The mediating role of energy subsidies in improving social well-being and alleviating energy poverty in Bangladesh is analyzed in [6]. Using data from three waves of the National Household Income and Expenditure Survey for 2005, 2010, and 2016, the study employs mediation analysis and mixed-effect regression to reveal that energy subsidies significantly reduce energy poverty, which in turn enhances social well-being. The results are robust to endogeneity concerns, confirmed by Lewbel's two-stage least squares method. The spatial dynamics of household consumption-induced carbon emissions in China are examined in [7]. The study calculates the information entropy of the direct household consumption-induced carbon emission structure from 2005 to 2019 and constructs a spatial association network using a modified gravity model. Indeed, this research employs social network analysis to examine spatial association characteristics and identifies influential factors using a quadratic assignment procedure model. Furthermore, it provides valuable insights into China's path toward achieving a low-carbon society in alignment with its carbon peaking and neutrality goals. The impact of green finance on energy inequality in China is explored in [8]. Using a comprehensive green finance development index and a Chinese provincial panel dataset, the study identifies a U-shaped relationship between green finance and urban-rural energy disparity. The results suggest that moderate expansion of green finance can effectively reduce energy consumption, particularly in China's western region.

In [9], the authors explore how different types of social interactions influence energy-saving behaviors in buildings. Using over 1,000 survey samples, the study examines how social relationships, interaction styles (interpersonal/passive vs. public/active), and individual characteristics affect behaviors ranging from habit adjustments to housing retrofits. The findings reveal that low-difficulty behaviors are more influenced by interpersonal and passive interactions, while high-difficulty behaviors are shaped by public and active interactions. Additionally, perceived value and information processing mediate these behaviors. The relationship between energy forms and energy poverty across varying degrees of urbanization in Europe is explored in [10]. Using data from twelve European countries between 2005 and 2018, the study analyzes how residential energy consumption (oil, wood/biomass, natural gas, and electricity) impacts energy poverty in cities, towns, suburbs, and rural areas. Based on feasible generalized least squares analysis, the findings show that energy sources like wood/biomass and natural gas are effective in reducing energy poverty in less densely populated areas. In [11], the authors assess the social capital and energy consumption patterns of farmers in the Qinba mountainous area of southern Shaanxi, China, using survey data from 746 participants. The study finds that farmers' energy consumption is diverse and stable, primarily relying on electricity, coal, and firewood. Social capital was found to be positively associated with the use of commercial and new energy sources, while negatively correlated with non-commercial energy consumption, highlighting its role in shaping energy consumption transitions. In [12], researchers examined the link between social capital and energy poverty in China, using a microscale multidimensional energy poverty index. The study reveals that social capital significantly reduces energy poverty and complements economic development efforts. However, households with severe energy poverty experience limitations in social capital benefits, highlighting a disparity in impact favoring those with greater resources.

In the case of Denmark, some limited studies focused on the social assessment of energy consumption and production spatially. In [13], the authors analyzed two Danish municipal energy governance networks with different structures: the municipality-led Energi2020 in Ringkøbing-Skjern and the public-private partnership ProjectZero in Sønderborg. The study finds that institutional design affects private funding mobilization, municipal resource access, and political control, shaping energy plan outcomes. Specifically, Ringkøbing-Skjern has excelled in renewable installations, whereas Sønderborg has advanced in industrial energy efficiency and sector coupling. A comparative analysis of Danish and English perspectives on housing-related mold and cold is provided by [14]. Using the heuristic framework, the authors reveal that Denmark views mold as a building issue, while England links it to underheating caused by fuel poverty. These differing problematizations lead to distinct management approaches, affecting public health outcomes in rental housing in each country. A critical framework for assessing Europe’s energy transition, emphasizing environmental, economic, and social justice, is presented by [15]. This study identified key indicators, both quantitative and qualitative, to evaluate progress on sustainability and circularity in the energy sector. The findings offered valuable insights for stakeholders, citizens, and policymakers on enhancing efficiency, renewable integration, and technology development to support a sustainable and circular energy transition. Authors in [14] have analyzed Denmark’s consumption-based CO_2 emissions, focusing on the interactions between financial stability, energy productivity, and economic growth from 1995 to 2018. Based on a nonlinear autoregressive distributed lag model, they have found that increased financial stability reduces CO_2, while economic and energy consumption growth exacerbates emissions. Additionally, positive shifts in energy productivity improve environmental quality, whereas declines in energy productivity and financial stability worsen it. The study suggests policy strategies relevant to Denmark and other affluent, smaller nations. In [16], researchers examine a Danish heat metering experiment in social housing, addressing resident perspectives on justice, cost distribution, and metering systems. The study highlights diverse understandings of metering among residents, particularly vulnerable groups, and situates these within broader climate and intergenerational justice discussions, showing the relevance of these issues across Europe.

This paper examines the impact of the social parameters including education level, employment level, number of household members, age, and youth ratio of the society on electricity consumption in the domestic sector across 7 urban areas in Southern Denmark. For this purpose, the required information is collected from the relevant database from January to October 2024, and after defining the meaningful indicators, the necessary analyses are performed. Moreover, this paper conducts a temporal analysis alongside a spatial social assessment to evaluate consumption patterns in different regions within the neighborhood.

The rest of this paper is organized as follows: Section II presents the methodology of the research. In the following, the studied indicators to analyze the social assessment are provided in Section III. Finally, Section IV concludes the paper and discusses about main achievements.

II. Methodology

This study follows a structured approach to analyze the social factors affecting energy consumption. Initially, general data including population, household numbers and types, age distribution, education levels, and employment status were extracted from a comprehensive database, and categorized by municipality codes for each region [1] and [17]. In the next step, specific indicators were defined based on the available data, including per capita consumption, youth population index, education level index, employment index, and renewable energy self-sufficiency index. Each of these indicators was then analyzed across the seven regions.

To illustrate regional relationships and examine consumption patterns, spatial correlation, and hotspot mapping were employed which helped to reveal any significant connections or the lack among neighboring regions. To further understand the influence of social parameters on the defined indicators, a correlation analysis was conducted. It facilitates the assessment of the extent to the performance of each region, influenced by social factors, providing insight into the varying impacts of these parameters on regional energy consumption.

III. Social Impact Assessment

A. Energy consumption analysis: hourly and seasonal analysis

This section examines household electricity consumption patterns for the first ten months of 2024. Fig. 2 illustrates the monthly consumption profile for each region. Although the absolute consumption levels, minimums, and maximums are unique to each area, the general monthly consumption profile is strikingly similar across all seven regions. The city of Esbjerg, due to its larger population, exhibits a higher consumption level compared to other areas.

In Fig. 3, a heatmap of the seven regions is presented. A higher correlation between two regions is represented by values closer to 1, with a greener color indicating a stronger correlation. The analysis results reveal that no two neighboring cities correlate precisely. However, Aabenraa, Tønder, and Vejen, Haderslev have a higher correlation value among all adjacent regions.

Statistical analysis indicates that the peak consumption occurred on January 31, 2024. Hourly consumption on this day, shown in Fig. 4, is consistent across the regions. As observed, in all seven areas, the daily peak occurs at 7 a.m., a time when energy use spikes due to lighting, heating, and cooking demands as children leave for school and employed individuals head to work.

B. Population, household, youth index, and family type analysis

Fig. 5 presents the total energy consumption along with the per capita consumption index. This analysis clearly shows that per capita energy consumption varies across regions. For example, although Esbjerg has a higher population and therefore a greater annual energy consumption, its per capita

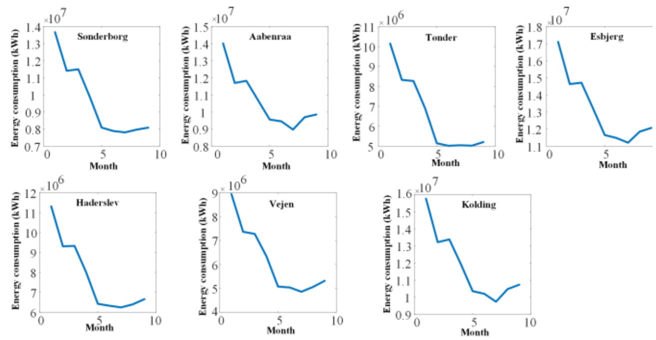

Fig. 2. Seasonal energy consumption for 7 regions [1].

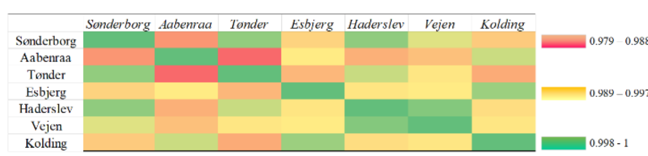

Fig. 3. Heat map for indicating the correlation of neighborhood regions.

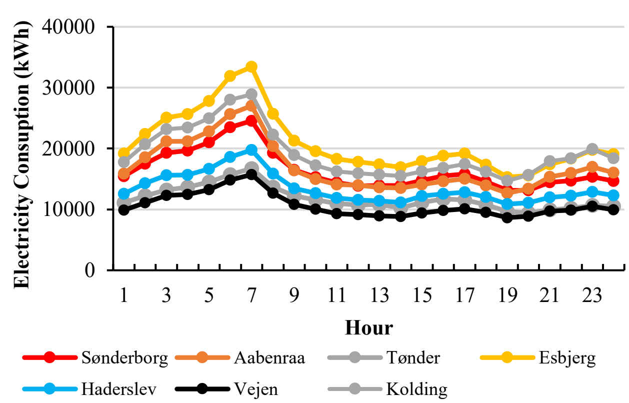

Fig. 4. Hourly energy consumption for 7 studied regions

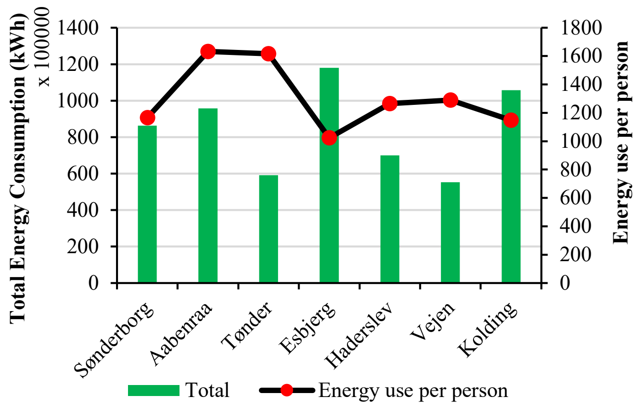

Fig. 5. Total energy consumption and per capita energy used.

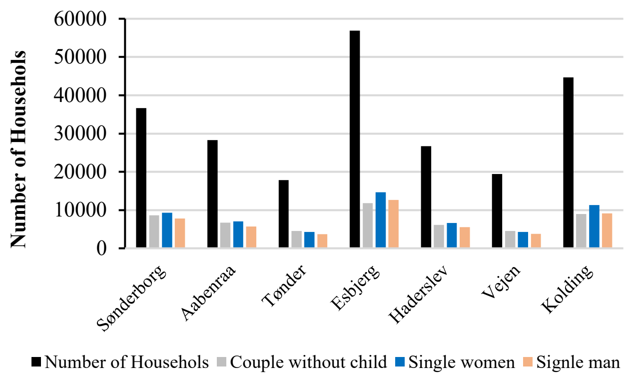

Fig. 6. Distribution of different household types based on the number of dependents.

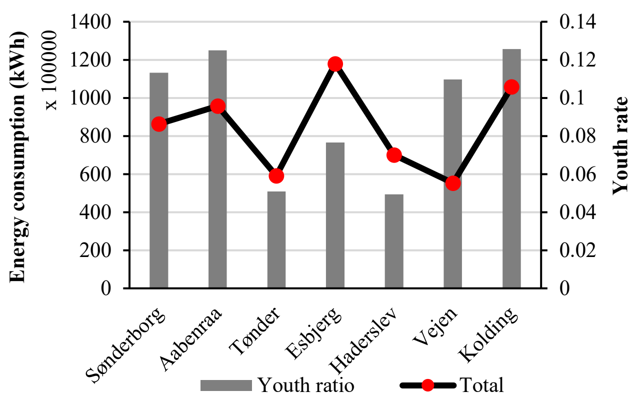

Fig. 7. Youth rate analysis per energy consumption.

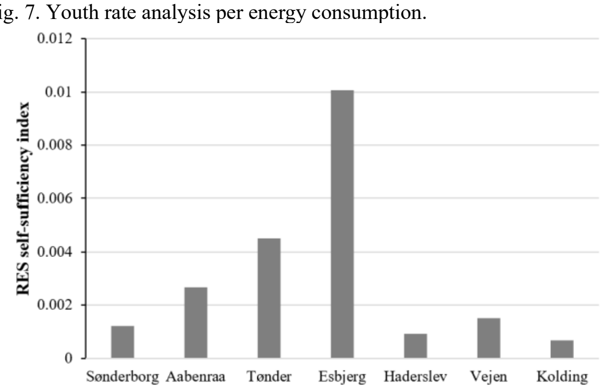

Fig. 8. Renewable energy self-sufficiency index for the studied region.

consumption is lower than all other studied regions. This discrepancy is likely due to a variety of social, economic, and cultural factors.

Population distribution across the seven regions indicates that over 80% of households are comprised of single individuals or couples without children. This distribution is illustrated in Fig. 6. To examine the impact of household dependents on energy consumption, a correlation analysis was conducted between energy consumption and households with one child. The correlation coefficient in this analysis is 0.34, indicating a moderately positive relationship, suggesting that an increase in single-child households is generally associated with higher energy consumption.

In this study, the youth index is defined as the ratio of the population aged 15-25 to the total population. This index, along with total energy consumption, is depicted in Fig. 7. Correlation analysis between the youth population and total energy consumption yields a coefficient of -0.93, indicating that there is no consistent direct or inverse relationship between the youth of the population and energy consumption across the regions studied. However, an exception is observed in the city of Tønder, where a direct relationship exists between the youth population index and energy consumption. In Tønder, as the youth population index decreases, energy consumption also decreases proportionately. This suggests that in Tønder, lower youth representation correlates with reduced energy consumption.

C. Share of RES and self-sufficient index

Renewable energy source (RES) self-sufficiency, defined as the ratio of energy generated from wind and solar sources to total consumption, is an important indicator of community sustainability [18]. This index, shown in Fig. 8, demonstrates that the installed renewable energy capacity in Esbjerg is notably high relative to its total energy consumption, outperforming other regions.

Fig. 9 illustrates the per capita share of wind and solar energy production for each of the seven areas. Notably, despite Esbjerg's significantly larger population, its per capita share of wind energy is remarkably high. In contrast, this pattern is reversed in Kolding, the second-most populous city, where the per capita wind energy share is comparatively lower. Another interesting observation from these results is the substantial per capita solar energy share in Sønderborg, where, unlike other regions, the solar energy contribution surpasses that of wind energy. This distinct pattern highlights Sønderborg's greater reliance on solar energy.

D. The ratio of men to women

The gender ratio index, defined as the ratio of men to women in the population, is another important factor studied in relation to electricity consumption. Fig. 10 presents this index for the seven regions. A lower index value indicates a higher proportion of women. This index is especially notable in larger cities like Kolding, where the gender imbalance is more pronounced.

Correlation analysis between energy consumption and the gender ratio index reveals a direct relationship between electricity consumption and the presence of women in the population. Specifically, areas with a higher proportion of women tend to have higher electricity consumption. The correlation coefficient in this case is -0.56, indicating a moderately negative correlation, where lower gender ratios (i.e., more women) are associated with increased energy use.

E. The ratio of employed individuals to the total population

The employment rate index, calculated as the ratio of employed individuals to the total population, is another significant indicator affecting electricity consumption. While a more detailed analysis would require information on job types, working hours, and income levels, this study assumes that higher employment correlates with greater social welfare, which in turn leads to increased access to advanced facilities and technology.

Fig.11 illustrates the employment rate index across the seven regions. This index is particularly notable in smaller cities like Vejen, and Aabenraa and shows a downward trend in Esbjerg. Correlation analysis indicates a strong positive relationship between employment level and electricity consumption, with a high correlation coefficient of 0.73. This suggests that areas with higher employment levels tend to exhibit greater electricity usage, supporting the hypothesis that improved social welfare leads to increased energy consumption.

F. Education analysis

Education level within a community can significantly impact energy consumption and energy management. While a higher number of educated individuals may correlate with the presence of educational institutions (and thus higher associated energy consumption), this study focuses solely on the relationship between the number of educated individuals (those with upper secondary education) and electricity usage.

Fig. 12 presents the percentage of educated individuals and per capita energy consumption. This figure shows a clear trend: regions with a higher proportion of individuals educated beyond high school tend to have lower per capita energy consumption. This trend is particularly evident in cities like Sønderborg, Kolding, Esbjerg, and Haderslev. Correlation analysis yields a coefficient of -0.75, indicating a strong inverse relationship between education level and energy consumption. This suggests that education and increased awareness can act as drivers for energy management within a community, highlighting the role of education in promoting sustainable energy use.

IV. Conclusion

This study conducted a spatiotemporal analysis of the social impacts on electricity production and consumption across seven urban areas in southern Denmark. It examined individual and household consumption shares, renewable energy self-sufficiency, the correlation between consumption and peak load, and factors such as age, gender, household

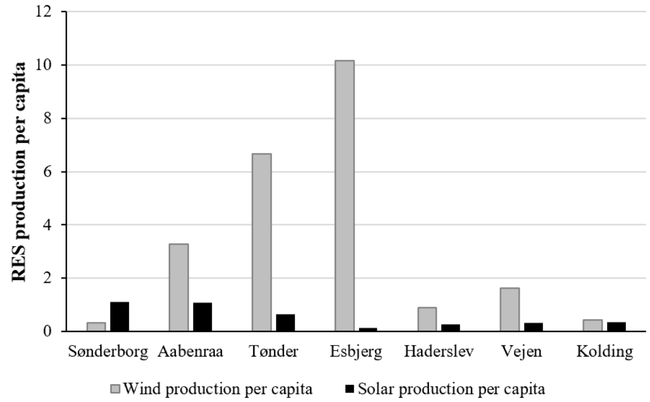

Fig. 9. Share of wind and solar energy production per capita.

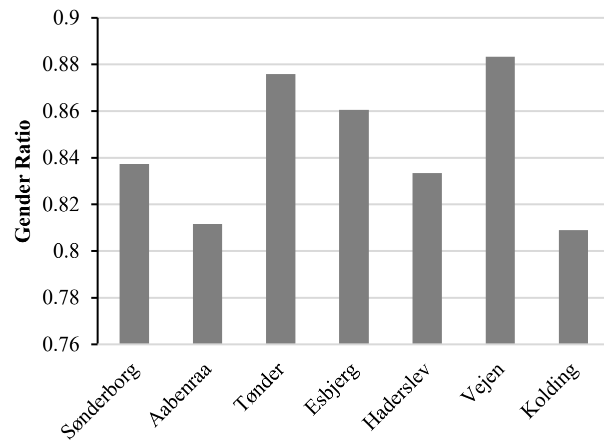

Fig. 10. The ratio of men to women in 7 studied regions.

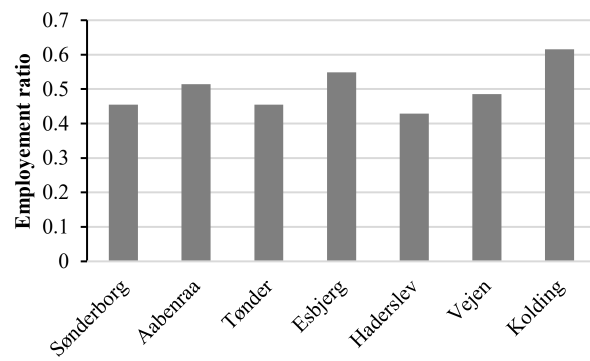

Fig. 11. The ratio of employed individuals to the total population in 7 studied regions.

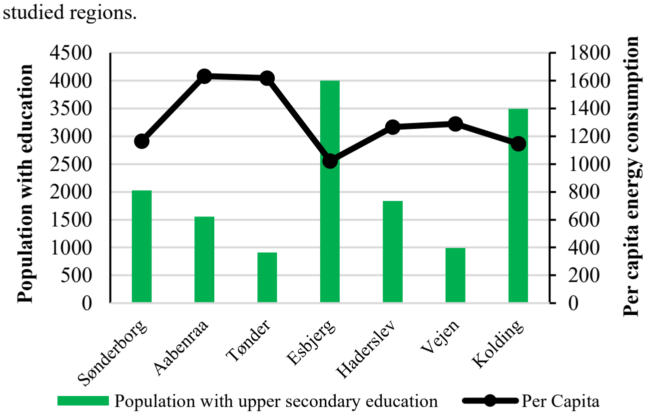

Fig. 12. Analyze the range of education on energy consumption.

dependents, employment, and education about residential electricity usage. The main findings can be summarized as follows:

- Despite the daily peak and monthly consumption patterns being consistent across all regions, no significant correlation was observed in consumption patterns between neighboring regions.
- Areas with a higher concentration of young residents do not tend to have higher electricity consumption, with a colocation analysis coefficient of -0.93. This trend only works for the Tønder region.
- Regions with higher employment levels show higher electricity consumption, with a correlation coefficient of 0.73.
- An increase in household size (e.g., households with one child) showed no significant relationship with consumption across the seven regions.
- Lower gender ratios (higher female populations) correlate directly with higher electricity consumption, with a correlation coefficient of 0.5.
- Education level has a significant inverse relationship with electricity consumption. The correlation coefficient is -0.75.
- Households in more populous cities like Esbjerg contribute a larger share of RES production, indicating greater wind resource capacity in densely populated areas. However, Sønderborg has a greater share of solar resources per capita in comparison with other regions.

This study focused on the impact of social conditions on residential electricity production and consumption over the first ten months of 2024. Future research could expand the analysis to cover longer periods (e.g., the past 20 years) to uncover behavioral patterns among consumers, accounting for socio-cultural factors. Such insights could play a vital role in establishing a roadmap to enhance energy efficiency in the residential sector.

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References

[1] E. d. service, "https://www.energidataservice.dk/," *Energinet.dk,* 2024.

[2] IEA, " World Energy Outlook 2023, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2023, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)," 2023.

[3] M. Hemmati, N. Bayati, and T. Ebel, "Life cycle sustainability assessment of waste-to-electricity plants for 2030 power generation development scenarios in western Lombok, Indonesia under multi-criteria decision-making approach," *Journal of Building Engineering,* vol. 95, p. 110335, 2024.

[4] M. Baltruszewicz, J. K. Steinberger, J. Paavola, D. Ivanova, L. I. Brand-Correa, and A. Owen, "Social outcomes of energy use in the United Kingdom: Household energy footprints and their links to well-being," *Ecol. Econ.,* vol. 205, p. 107686, 2023.

[5] X. Jin, C. Zhang, F. Xiao, A. Li, and C. Miller, "A review and reflection on open datasets of city-level building energy use and their applications," *Energy and Buildings,* vol. 285, p. 112911, 2023.

[6] S. Hosan, K. K. Sen, M. M. Rahman, S. C. Karmaker, A. J. Chapman, and B. B. Saha, "Evaluating the mediating role of energy subsidies on social well-being and energy poverty alleviation in Bangladesh," *Energy Research & Social Science,* vol. 100, p. 103088, 2023.

[7] J.-B. Liu, X.-B. Peng, and J. Zhao, "Analyzing the spatial association of household consumption carbon emission structure based on social network," *Journal of Combinatorial Optimization,* vol. 45, no. 2, p. 79, 2023.

[8] C.-C. Lee, H. Song, and C.-C. Lee, "Assessing the effect of green finance on energy inequality in China via household-level analysis," *Energy Economics,* vol. 128, p. 107179, 2023.

[9] H. Li, Z.-H. Wang, and B. Zhang, "How social interaction induce energy-saving behaviors in buildings: Interpersonal & passive interactions vs public & active interactions," *Energy Economics,* vol. 118, p. 106515, 2023.

[10] D. S. Pereira and A. C. Marques, "How do energy forms impact energy poverty? An analysis of European degrees of urbanisation," *ENERG POLICY,* vol. 173, p. 113346, 2023.

[11] F. Su, J. Chang, X. Li, S. Fahad, and I. Ozturk, "Assessment of diverse energy consumption structure and social capital: a case of southern Shaanxi province China," *Energy,* vol. 262, p. 125506, 2023.

[12] Z. Ren, Y. Zhu, C. Jin, and A. Xu, "Social capital and energy poverty: empirical evidence from China," *Energy,* vol. 267, p. 126588, 2023.

[13] S. Sillak, "All talk, and (no) action? Collaborative implementation of the renewable energy transition in two frontrunner municipalities in Denmark," *Energy Strategy Reviews,* vol. 45, p. 101051, 2023.

[14] S. Bonderup and L. Middlemiss, "Mould or cold? Contrasting representations of unhealthy housing in Denmark and England and the relation to energy poverty," *Energy Research & Social Science,* vol. 102, p. 103176, 2023.

[15] A. Arias, G. Feijoo, and M. T. Moreira, "Advancing the European energy transition based on environmental, economic and social justice," *Sustainable Prod. Consumption,* 2023.

[16] K. Gram-Hanssen, S. Bonderup, L. K. Aagaard, and A. S. M. Askholm, "Energy justice in heat metering: Findings from a Danish experiment of metering and distribution in residential apartment buildings," *Energy Research & Social Science,* vol. 104, p. 103250, 2023.

[17] S. Denmark, "https://www.dst.dk/en," *statbank.dk,* 2024.

[18] I. Zafar, V. Stojceska, and S. Tassou, "Social sustainability assessments of industrial level solar energy: A systematic review," *Renewable Sustainable Energy Rev.,* vol. 189, p. 113962, 2024.