Exploring the Spatial and Built Environmental Characteristics of Residential Solar Photovoltaic Implementations in Luxembourg

Alexander Skinner*, Prof. Catherine Jones†

[1]Department of Geography and Spatial Planning, University of Luxembourg

GISRUK 2024

Summary

Residential Solar Photovoltaics (RSPV) offer a promising path towards partial energy self-sufficiency and enhanced national energy security by allowing households to inject surplus energy back into the grid. However, the challenges of RSPV implementation in urban environments, influenced by urban form, need to be better understood and addressed. Using a machine learning approach combined with spatial regression analysis this search aims to investigate the interplay between urban spatial configurations and the existing patterns of rooftop PV installations in Luxembourg. By examining building layouts, environmental conditions, and architectural diversity, we identify *gaps* in RSPV implementation and understand their relationship with urban form.

KEYWORDS: Solar Photovoltaics, Renewable Energy Transition, Convolutional Neural Network, Solar PV adoption, Urban Form

Introduction

We investigate the interplay between urban spatial configurations and existing rooftop Photovoltaic (PV) installations in Luxembourg. Climate change and energy security issues, exacerbated by fossil fuel dependency and increasing urbanisation combined with anthropogenic viewpoints, necessitate the development of improved low-carbon energy solutions at both national, regional, local and neighbourhood scales. Despite Luxembourg's 283.3% rise in the share of renewable energy sources in gross energy consumption (Bórawski et al., 2019), only 6.85% of Luxembourg's energy is from renewable sources, there is also a lack of solar photovoltaics (1.75%) in relation to wind power (2.23%) (Ritchie et al., 2022). Residential solar photovoltaics (RSPV) offer a promising path towards partial energy self-sufficiency and enhanced energy security by supporting households to produce energy to meet their own needs.

However, the challenges of RSPV implementation in urban environments need to be better understood and addressed in the context of different societal norms. The urban form itself presents challenges and obstacles that are currently disregarded or poorly understood and under researched. Rooftop PV potential is limited by the size, variance, and aspect, which depend not only on the building itself but also on the physical and social environment it inhibits (Moraitis et al., 2018). By examining building layouts, environmental conditions, and architectural diversity, by applying machine learning and spatial regression techniques this study aims to identify *gaps* in RSPV implementation to understand the relationship with urban form. The research proposes policy directions for better energy equity at the neighbourhood level.

* Alexander.Skinner@uni.lu

† Catherine.Jones@uni.lu

Literature overview

Renewable energy systems, particularly PV, mitigate greenhouse gas emissions, combat climate change, and facilitate the transition towards carbon zero societies (Breyer et al., 2015). Analysing the patterns of existing solar PV adoption within a specific region holds significance for policymakers as the results indicate where additional support, such as alternative policies and incentives, may be necessary to expedite the energy transition (Alipour et al., 2021; Tidwell et al., 2018). Emerging literature also illustrates the role urban form plays in determining the efficiency and effectiveness of solar PV installations (Zhang et al., 2023). Thus, examination of the interrelation between the built environment and solar PV systems using geospatial models and analysis allows for informed decision-making in urban planning and design (Kucher et al., 2021).

The prevalence of solar PV on buildings has been attributed to three main factors: occupant behaviour and world views, building design, and systems performance (Cheng et al., 2011). However, the variables within these factors are not mutually exclusive; they are part of a network of connections and interdependencies (Dolter & Boucher, 2018). Solar PV acceptance in relation to its landscape has been less studied than other renewable energy sources (Vuichard et al., 2021), yet, the relationship between solar PV and urban form is even less understood (Florio et al., 2018). Moreover, within previous literature, visibility is the primary focus for social acceptance in urban areas (Parkins et al., 2018). Whereas other factors such as affluence, sociocultural factors, knowledge and awareness, attitudes and values are also relevant (Ali et al., 2020; Cousse, 2021; Hanger et al., 2016).

Insufficient geospatial consideration worsens the current understanding amid these barriers. There is currently no openly available database of solar implementations for Luxembourg. This hampers coherent research, planning and policy development, inefficiently allocates resources, hinders market development, and impedes monitoring and evaluation efforts (Hofierka & Kaňuk, 2009; Kim & Kim, 2015; Wen et al., 2021; Ansari et al., 2021). Establishing a comprehensive neighbourhood mapping system would shed further light on these implications and provide valuable information for informed decision-making, fostering the growth and effectiveness of solar energy adoption in the country.

Methods

A convolutional neural network (CNN) model of 87% accuracy was created to detect solar PV using 10cm ground resolution RGB orthoimagery from 2022 over Luxembourg's entirety, available from data.public.lu. The model was created using ArcGIS's image classification and deep learning tools whereby a meticulous examination of 7 contrasting communes was carried out to obtain labelled polygons containing imagery of solar PV for training and testing. These results were then deployed to detect PV across the rest of Luxembourg. To evaluate the effectiveness and accuracy of the trained model, a separate assessment was conducted using 7 other contrasting communes. For this evaluation, a random sampling technique was employed, employing a random number generator in conjunction with the building's polygon identity number. This approach ensured unbiased ground truthing, providing reference data for comparison against the model's predictions.

These results were then aggregated into a custom hexagonal neighbourhood grid, each hexagon with a length of 800m along the major diagonal, to emulate a 15-minute walkable neighbourhood that could tessellate with surrounding neighbourhoods. In the absence of small area neighbourhood data for Luxembourg, this presented a pragmatic and practical solution to the development of focal statistics. This spatial efficiency diminishes problems associated with a-priori-defined neighbourhoods (Cabrera-Barona et al., 2016), especially considering size irregularities between Luxembourg's communes. Hexagonal neighbourhoods also help mitigate the modifiable areal unit problem, orientation and sampling biases.

A digital terrain model taken from LIDAR data was used to determine rooftop characteristics such as slope, aspect and variance. Ordinary least square (OLS) models were then used to explore the relationship between urban form and the prevalence of RSPV, whilst Moran's I and Local Indicators of Spatial Association (LISA) examined spatial patterns and clustering.

Results & Discussion

In Figure 1 we observe only 4,420 residential buildings in Luxembourg currently have solar PV, representing a mere 4.1% of the total 107,000 residential buildings, which pales in comparison to Germany’s 11% or the Netherlands at 16% (Dillon, 2022). The regions with the highest PV concentration are the larger towns of Luxembourg, Esch-sur-Alzette, and Diekirch. However, a nuanced understanding emerged when normalising for number residential buildings within each neighbourhood. Suburban areas show a higher proportion of solar PV installations, a pattern that we were expecting to see due to higher levels of affluence (Dharshing, 2017). Whilst inner city areas as well as the southwest region, exhibit a scarcity of installations relative to the number of dwellings. A coarser municipal-scale analysis was also conducted, confirming deficiencies in solar PV installations in southwestern towns and the northern town of Diekirch. Contrarily, suburban areas like Garnich, Kehlen, or Weiler-la-Tour, and periphery communes including Junglinster, Betzdorf, and Bech, show higher prevalence. Some rural communes deviate from the pattern. Non-standardised examination indicates peri-urban areas have more solar PV, with Luxembourg City and the southwest accounting for over 35% of the overall amount, possibly due to favourable conditions or incentives.

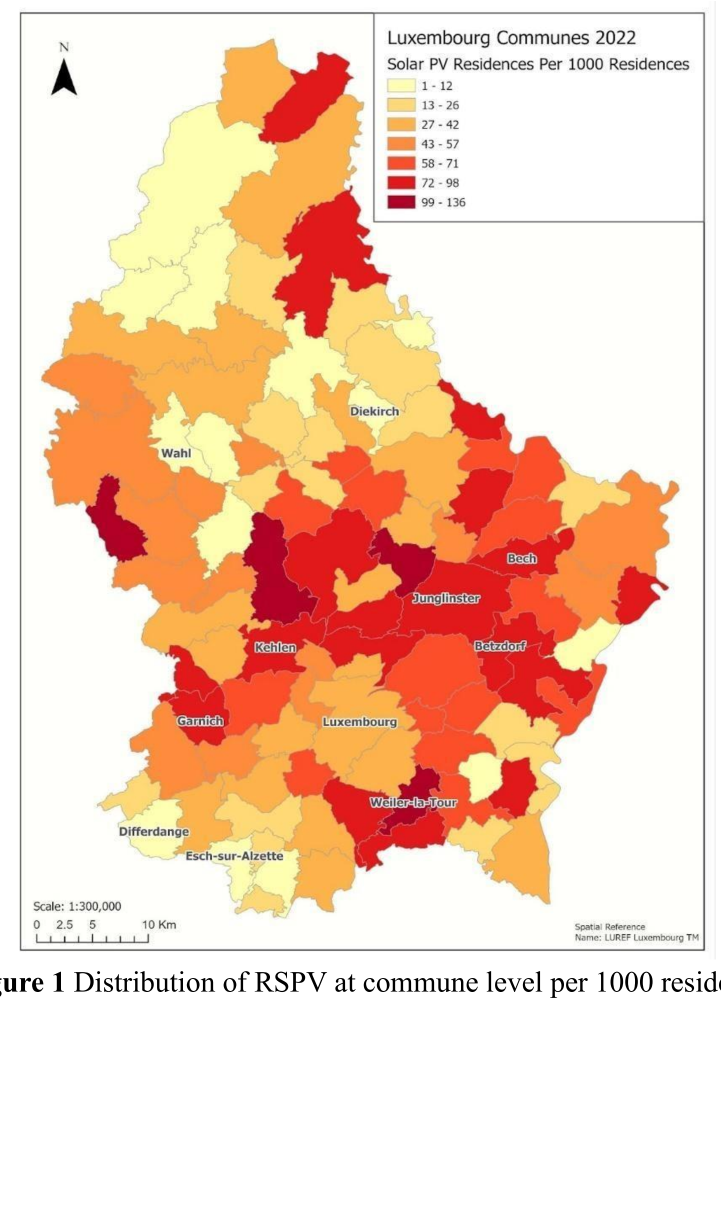

Figure 1 Distribution of RSPV at commune level per 1000 residences.

The CNN model results were used to analyse normalised residential PV values for spatial autocorrelation. A Global Moran's I Index (0.068898) indicated positive spatial autocorrelation, confirming clustering in residential PV distribution. The low variance (0.000057) suggests consistent spatial clustering. A high z-score (9.2) and a significantly low p-value support the deviation from spatial randomness, affirming significant clustering. However, the low R^2 value (0.04) suggests limited explanatory power of residential PV, indicating additional factors at play. Municipal-level clustering, though less pronounced, still deviates significantly from spatial randomness. The LISA analysis confirms distinct spatial clusters of high-high and low-low residential PV installations in Luxembourg (see figure 2.). High-high clusters in central Luxembourg suggest favourable conditions that have supported implementation, while low-low clusters in northern rural areas and inner-city regions indicate barriers to adoption. Further research is needed to explore additional factors influencing spatial clustering.

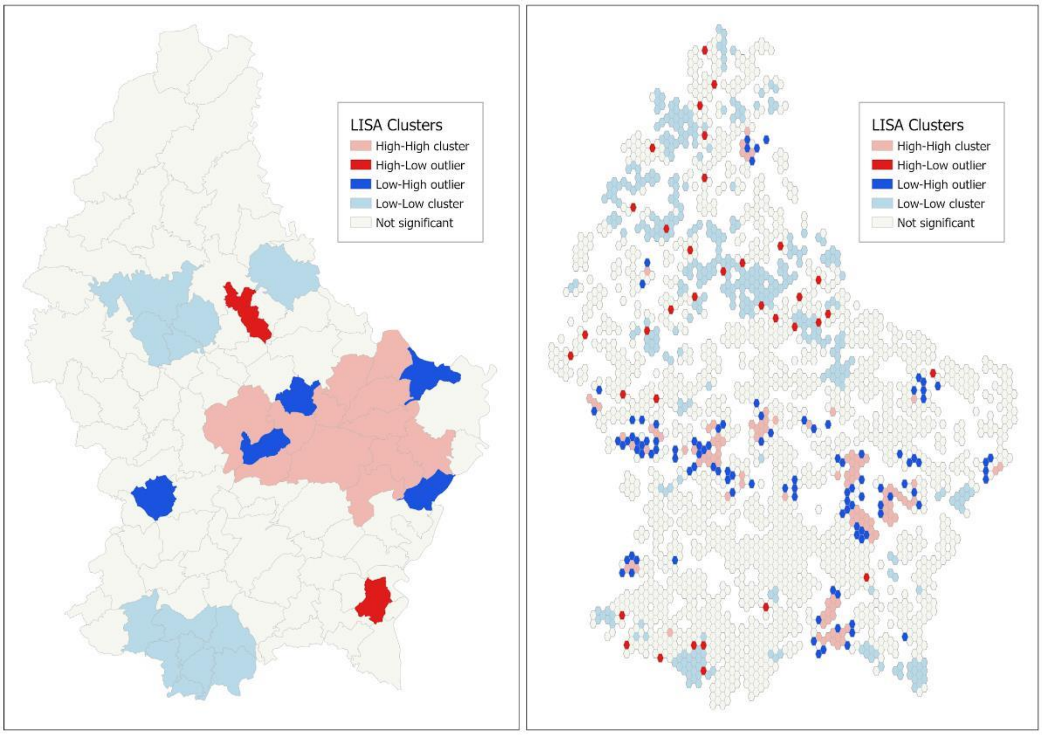

Figure 2: (a) LISA neighbourhood cluster and (b) LISA commune cluster map illustrating spatial autocorrelation of RSPV.

Three regression models were employed to analyse the impact of factors related to urban form on the adoption of solar PV systems. The first model focused on building characteristics and found that roof area, slope, and compactness significantly influence solar PV presence. The second model incorporated neighbourhood factors, which improved its explanatory ability. Building characteristics remained important, alongside factors like openness and population density, although population density's significance was unexpected. Though the explanatory power was limited at 6.8%, this is to be expected, as literature has determined that affluence is the predominantly important factor regarding residential solar PV adoption. Surprisingly, the third model suggested that the physical environment has minimal impact on solar PV implementation, contradicting existing literature.

Conclusion

The results indicate urban form plays a part in determining the patterns of residential solar photovoltaic implementation. However, further investigation is needed to extrude these effects from affluence itself, as variables such as roof area and distance from the road, although significant, we suspect are highly correlated with affluence (no local scale data are openly available so at this stage cannot be included in the model). This could be achieved by looking beyond Luxembourg to the Grande Region, as data on affluence, though at a courser scale than neighbourhood level, is more readily available.
The study suggests focusing on lower quartiles of values for variables like area and distance to the road as proxies for relative deprivation, offering valuable insights into disparities in RSPV adoption. This, understanding the relationship between urban form and RSPV adoption is helpful for tailoring effective strategies and challenging conventional assumptions about solar PV placement. Policymakers could allocate resources more effectively and implement targeted policies, such as subsidies, to promote adoption in underserved areas. Future studies and policies should shift focus to analysing existing RSPV distribution and identifying gaps, promoting a more equitable and sustainable transition to solar power.

References

Ali, S. *et al.* (2020) 'Determining the Influencing Factors in the Adoption of Solar Photovoltaic Technology in Pakistan: A Decomposed Technology Acceptance Model Approach', *Economies*, 8(4), p. 108.

Alipour, M. *et al.* (2021) 'Residential solar photovoltaic adoption behaviour: End-to-end review of theories, methods and approaches', *Renewable Energy*, 170, pp. 471–486.

Ansari, S. *et al.* (2021) 'A Review of Monitoring Technologies for Solar PV Systems Using Data Processing Modules and Transmission Protocols: Progress, Challenges and Prospects', *Sustainability*, 13(15), p. 8120.

Bórawski, P. *et al.* (2019) 'Development of renewable energy market in the EU with particular regard to solar energy', *Conference Proceedings, Determinants Of Regional Development*.

Breyer, C., Koskinen, O. and Blechinger, P. (2015) 'Profitable climate change mitigation: The case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems', *Renewable and Sustainable Energy Reviews*, 49, pp. 610–628.

Cabrera-Barona, P., Wei, C. and Hagenlocher, M. (2016) 'Multiscale evaluation of an urban deprivation index: Implications for quality of life and healthcare accessibility planning', *Applied Geography*, 70, pp. 1–10.

Cheng, V. *et al.* (2011) 'A Study of Urban Form and the Integration of Energy Supply Technologies', in. *World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden*, pp. 3356–3363.

Cousse, J. (2021) 'Still in love with solar energy? Installation size, affect, and the social acceptance of renewable energy technologies', *Renewable and Sustainable Energy Reviews*, 145, p. 111107.

Dharshing, S. (2017) 'Household dynamics of technology adoption: A spatial econometric analysis of residential solar photovoltaic (PV) systems in Germany', *Energy Research & Social Science*, 23, pp. 113–124.

Dillon, J.D. (2022) *A Global Look at Residential Solar Adoption Rates*, *POWER Magazine*.

Dolter, B.D. and Boucher, M. (2018) ‘Solar energy justice: A case-study analysis of Saskatchewan, Canada’, *Applied Energy*, 225, pp. 221–232.

Florio, P. *et al.* (2018) ‘Assessing visibility in multi-scale urban planning: A contribution to a method enhancing social acceptability of solar energy in cities’, *Solar Energy*, 173, pp. 97–109.

Hanger, S. *et al.* (2016) ‘Community acceptance of large-scale solar energy installations in developing countries: Evidence from Morocco’, *Energy Research & Social Science*, 14, pp. 80–89.

Hofierka, J. and Kaňuk, J. (2009) ‘Assessment of photovoltaic potential in urban areas using opensource solar radiation tools’, *Renewable Energy*, 34(10), pp. 2206–2214.

Kim, K. and Kim, Y. (2015) ‘Role of policy in innovation and international trade of renewable energy technology: Empirical study of solar PV and wind power technology’, *Renewable and Sustainable Energy Reviews*, 44, pp. 717–727.

Kucher, O., Lacombe, D. and Davidson, S.T. (2021) ‘The Residential Solar PV in the Mid-Atlantic: A Spatial Panel Approach’, *International Regional Science Review*, 44(2), pp. 262–288.

Moraitis, P. *et al.* (2018) ‘Urban Environment and Solar PV Performance: The Case of the Netherlands’, *Energies*, 11(6), p. 1333.

Orthophoto officielle du Grand-Duché de Luxembourg, édition 2022 (ortho_2022) - Portail Open Data (no date). Available at: https://data.public.lu/fr/datasets/orthophoto-officielle-du-grand-duche-de-luxembourg-edition-2022/

Parkins, J.R. *et al.* (2018) ‘Predicting intention to adopt solar technology in Canada: The role of knowledge, public engagement, and visibility’, *Energy Policy*, 114, pp. 114–122.

Ritchie, H., Roser, M. and Rosado, P. (2022) ‘Energy’, *Our World in Data* [Preprint]. Available at: https://ourworldindata.org/energy (Accessed: 12 June 2023).

Tidwell, J.H., Tidwell, A. and Nelson, S. (2018) ‘Surveying the Solar Power Gap: Assessing the Spatial Distribution of Emerging Photovoltaic Solar Adoption in the State of Georgia, U.S.A.’, *Sustainability*, 10(11), p. 4117.

Vuichard, P., Stauch, A. and Wüstenhagen, R. (2021) ‘Keep it local and low-key: Social acceptance of alpine solar power projects’, *Renewable and Sustainable Energy Reviews*, 138, p. 110516.

Wen, D. *et al.* (2021) ‘Development of solar photovoltaic industry and market in China, Germany, Japan and the United States of America using incentive policies’, *Energy Exploration & Exploitation*, 39(5), pp. 1429–1456.

Zhang, J., Ballas, D. and Liu, X. (2023) ‘Neighbourhood-level spatial determinants of residential solar photovoltaic adoption in the Netherlands’, *Renewable Energy*, 206, pp. 1239–1248.

Biographies

Alexander Skinner is a Doctoral Researcher at the University of Luxembourg and holds an MSc in Geography and Spatial Planning. He is interested in the relationship between renewable energy acceptance, worldviews, and renewable energy adoption. He employs particular focus on GIS technology to analyse spatial patterns and geographical factors that may influence individuals' attitudes and behaviours toward renewable energy.

Catherine Jones, Assistant Professor in Digital Geography at the University of Luxembourg, is also the Director of Studies for the Master program in the Geography and Spatial Planning Department. With a PhD in Geographies of Health and an MSc in Geographical Information Science from University College London, her research focuses on mixed methods GIS and games for participatory environments, supporting the transition to sustainable places. https://orcid.org/0000-0002-9285-0656