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Original research article

Does the sun shine for all? Revealing socio-spatial inequalities in the transition to solar energy in The Hague, The Netherlands

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ABSTRACT

With technological advances and decreasing prices, solar energy is a key technology in the urban energy transition. However, the focus on increasing the overall installed capacity has overshadowed energy justice considerations, leading to inequalities in solar energy adoption. This paper adopts an equity perspective to analyse the transition to solar (photovoltaic) energy in the city of The Hague, The Netherlands. Access to solar energy is at the core of the research, encapsulating factors that influence the ability of a household to adopt solar energy. Through a socio-spatial analysis at the postcode level, we identify four distinct groups with varying levels of access to solar energy. Our results show that these groups are not only strongly segregated across the city but also overlap with existing socio-spatial inequalities. The four levels of access to solar energy are then compared to current solar adoption rates and technical rooftop energy potential in the city. Results show that decreasing levels of access to solar energy align with decreasing adoption rates, revealing that current policies fail to provide equitable access to solar energy leading to inequalities in adoption rates. Furthermore, we show that most of the technical potential available in The Hague is in areas where access to solar energy is limited, representing opportunities to exploit a significant amount of untapped technical potential while addressing existing socio-spatial inequalities. Here, we also identify two groups of interest and related leverage points for future policy interventions to address equity in the transition to solar energy in The Hague.

1. Introduction

The energy system strongly contributes to greenhouse gas emissions and thereby drives the process of climate change [1]. Reports by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) estimate that cities are responsible for around two-thirds of the total primary energy use and more than 70% of global carbon emissions [2,3]. To reduce the impact on the climate, the renewable energy transition aims at redesigning our energy systems to minimise fossil fuel emissions [4]. In urban areas, one technology that is expected to play an essential role in the energy transition is solar photovoltaics (PV) [5,6]. Solar PV technologies have become cost-competitive and, with improved battery technology, demonstrate high system reliability, provide the possibility of generation in physical proximity of consumption, and, above all, is more environmentally friendly since greenhouse gas emissions are not emitted during operation [6,7]. It is the combination of these favourable characteristics that motivated the impressive growth from 0.81 GW of global installed solar capacity in 2000 to 843 GW in 2021 [8].

Yet, the benefits and costs of the recent growth in solar PV capacity have been unequally distributed [9–14]. Current energy policies have focused on increasing the overall solar PV capacity from a technical feasibility and utility perspective, overseeing issues of equitable transition [15,16]. This is evident not only in current policy plans such as the REPowerEU initiative, which is a plan by the European Commission dedicated at rapidly increasing the EU solar capacity through a “massive, rapid deployment of renewable energy” [16], but also in recent solar PV literature, with a strong focus on the technical aspects of the technology. For example, many studies focus on improving estimations of the technical energy potential of building roofs and facades [17–21], without considering whether the estimated technical potential can actually be realised given the socio-economic situation of people living under these roofs and behind these facades.

In Europe, the promotion of residential PV adoption by the EU and national governments has in many ways reinforced the unequal distribution of benefits and burdens of renewable energy technology [15,16]. Solar subsidies, feed-in tariffs (FiT), and tax breaks, which have been common instruments to stimulate the adoption of solar PV technologies during recent decades [22], have mainly benefited wealthier households as these mechanisms still require a high amount of upfront capital [11,23,24]. These policy instruments have thus remained

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largely out of reach for less advantaged households, even though the costs of these schemes are often distributed across all of society through fixed charges in energy taxes [11]. In addition, the costs of maintaining grid balance due to increased fluctuations in electricity production are also borne by all electricity consumers connected to the grid [25]. As a result, socioeconomically disadvantaged households end up cross-subsidising solar PV systems for wealthier households [11,25].

Attempts to address equity concerns in the energy transition are centred around the concept of energy justice [26]. Energy justice is now a rapidly emerging research field that addresses equity and fairness in energy systems by evaluating the distribution of its benefits and burdens beyond a merely technical or economic perspective [26–30]. Principles of equity and fairness are – besides addressing unjust conditions leading to and arising from a renewable energy transition – also of crucial importance to attain the societal support for the renewable energy transition to move forward and succeed [30–32]. Despite widespread information and availability of subsidies and policies [33], energy justice literature shows that the energy transition has been a highly exclusive process. In other words, a large part of society still does not have *access* to renewable energy technologies. In energy justice literature, access to energy has a strong equity component that considers the socioeconomic conditions of people [34,35]. Again, this contrasts with the technical perspective that dominates energy transition literature, in which access to solar energy considers only geometric and morphological factors related to technical feasibility studies (such as roof area, presence of shade casting elements, building orientation, etc.) [36,37].

Going beyond technical feasibility studies requires a comprehensive understanding of the complex factors that influence the adoption of renewable energy technologies. An important body of research exists highlighting factors and barriers that influence the adoption of solar energy [38–41]. However, there is a need for a conceptual understanding on how these factors drive solar PV adoption, and how these factors are spatially distributed and associated with different social groups in urban spaces [34]. Much of the energy justice literature has focused on existing inequalities between socio-demographic groups [34], often overlooking underlying spatial inequalities, even though inequalities within the urban environment have a strong spatial context [42]. Despite important efforts made in the field, it is uncommon to take a spatial perspective on the distribution of burdens and benefits of the energy transition [34,43]. Yet, such a spatial perspective is critical because the renewable energy transition is likely to further spatial differentiation and uneven development [44] across regions and within cities.

In this paper, we take a social-spatial perspective to evaluate equity in the transition to solar energy. To bridge the gap between energy justice and technical literature on solar energy, we place *access* to solar energy at the core of our research. While policies aim to promote the adoption of solar energy via multiple mechanisms, like feed-in tariffs and subsidies, in general, they cannot enforce the adoption of new technologies. We thus understand that policies can act to change how *accessible* a certain technology may be, but the eventual adoption of solar energy is a decision taken at the household level and involves other complex behavioural factors. To frame our research within the complex process of technology adoption, we use the Theory of Planned Behaviour (TPB) [45].

To demonstrate our approach, we selected the European city of The Hague in the Netherlands. The Hague is a suitable case study because of both policy context and data availability. Our analysis is based on high spatial resolution data at the postcode level with an average of 330 households per spatial unit. Through a socio-spatial analysis, we identify four groups with distinct characteristics that represent different levels of access to solar energy in The Hague. These results are used for two analyses. First, to evaluate current policies with respect to equity in the adoption of solar energy. Here, we compare access to solar energy to adoption rates to reveal socio-spatial inequalities in the adoption of solar energy. Second, to identify potential policy strategies that could lead to a more equitable utilisation of the solar PV potential available in the city. Here, we compare the technical solar energy potential with access to solar energy to identify targeted policies suitable to the underlying socio-spatial characteristics across the city.

2. Access to solar energy: Conceptualisation

What is Access? In literature, the relation between the terms solar energy and access (or accessibility) is often understood as how suitable is the built environment for exploiting solar energy [36,37,46,47]. The suitability is evaluated based on geometrical and morphological characteristics such as building orientation, roof area and inclination, as well as the presence of surrounding elements and other elements that cast shade on the building. This, however, does not address the socioeconomic factors that influence the adoption of solar PV technologies. In contrast, this research takes a different perspective on access, in line with the accessibility definition proposed by Burns [48]: "the freedom of individuals to decide whether or not to participate in different activities". Applied to our case, we interpret access to solar energy as the freedom of individuals to decide whether or not to adopt solar energy. This freedom is either limited or enforced by the existence or lack of specific barriers. These barriers are explored later in this chapter.

Understanding Adoption of Solar Energy. The social process of adopting solar energy technologies has been approached from various perspectives, indicated by the application of different behavioural theories. Three main theories are common in the literature. First, the Diffusion of Innovation Theory (DOI) has been applied during the emergence of the technology in earlier years to identify the different characteristics of adopters and non-adopters [49]. Second, the Value-Belief-Norm Theory (VBN) approaches the adoption of solar PV as a decision rooted mainly in environmental awareness and concern [50]. Third, the Theory of Planned Behaviour (TPB) has been used when approaching the decision to adopt solar PV systems as a form of consumer behaviour [41]. In this paper, we use the Theory of Planned Behaviour as overarching framing because it is a commonly applied framework for the analysis of consumer adoption patterns, including the adoption of energy efficient technology, and more comprehensively includes socioeconomic factors of an individual, relevant to understanding the complex notions of inequalities, equity and justice [51–53].

The Theory of Planned Behaviour states that intentions to perform behaviours of different kinds can be predicted with considerable accuracy by a combination of three elements [45]. These are the *attitudes toward the behaviour*, *social norms*, and *perceived behavioural control* [45]. Wolske et al. [52] describe these three elements as: first, one's attitude toward the behaviour, which is formed by beliefs about consequences of performing the behaviour and the likelihood of those consequences occurring; second, social norms as the expected perceived approval or disapproval of others when performing the behaviour; and lastly, behavioural control as an assessment of one's ability to perform the behaviour. Within this assessment, a distinction is to be made between the perceived ability and the actual ability to perform a behaviour. These two factors differ when someone thinks it is more difficult to perform a behaviour, than what might be the case in reality. This has an influence on the intention to perform the behaviour. The difference between perceived ability and actual ability is dependent on how well people are capable of judging their ability to perform a behaviour. When perceived ability to perform the behaviour is lower than the actual ability to perform, the intention to perform the behaviour will be limited.

In this paper, we focus on the element of behavioural control out of the three elements listed above. As described above, both access to solar energy and behavioural control refers to the ability or freedom perceived by households to adopt solar PV systems. Thus, given the similarity of their definitions, this research interprets behavioural

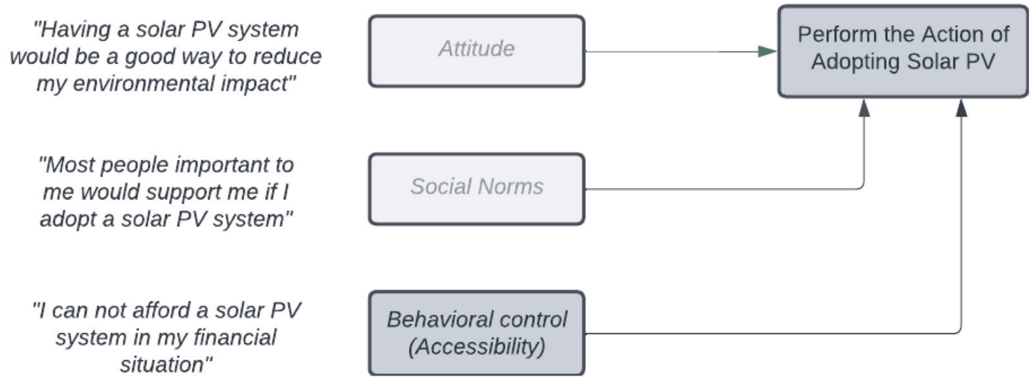

Fig. 1. Theory of Planned Behaviour applied to performing the behaviour of adopting solar energy. Attitude refers to one's attitude towards performing the behaviour, social norms entails the expected perceived approval or disapproval of others when performing the behaviour, and behavioural control is one's assessment of their ability to perform the behaviour.

control as equivalent to access to solar energy. This decision has key implications for our research, as it helps to distinguish access to solar energy (which can be influenced in a targeted way by policy mechanisms) from the adoption of solar energy (which happens as a result of a complex process of technology adoption). Fig. 1 illustrates how, given the right conditions of attitude and social norms, the Theory of Planned Behaviour can be used to understand how *access* influences household decisions to adopt solar energy. There are many factors that influence one's level of behavioural control over the action to adopt solar energy and, thus, their level of access to solar energy. In the following section, we elaborate on the factors identified in the literature.

2.1. Identification of factors influencing the access to solar energy systems

Literature highlights an extensive variety of factors influencing the adoption behaviour regarding solar PV systems. According to a recent review by Alipour et al. [54], a total of 333 factors could be distilled across literature. However, as pointed out by Schulte et al. [41], many of these factors are just different operationalisations of the same constructs. This lack of consistent operationalisation has prevented a comprehensive set of factors from emerging throughout the years [41]. In addition, much of the work in this field has been done in widely varying temporal, geographical, and policy contexts. The combination of a lack of consistent operationalisation and varying contexts has made it particularly difficult to compare different results in a systematic way. To identify the factors that limit one's access to solar energy, our research focuses specifically on literature mentioning barriers to the residential adoption of solar PV technologies in advanced economies (see supplementary information for more details on the selection of literature). From the relevant literature, four key factors have been identified as having the strongest influence on the adoption of solar PV systems. These factors are *affordability*, *home ownership*, *housing type*, and *availability of suitable information*.

Affordability of solar PV, or more accurately the lack thereof, is often cited as the main barrier to adopt solar PV [38,40,41,54–57]. All of the studies within the selected literature name high investment cost as one of the main barriers to solar PV adoption. Even though the costs of solar PV have gone down significantly throughout recent years [6], it still requires a significant initial investment to purchase a solar PV system. Households that do not have access to this amount of capital or do not have other means to secure financing, thus have lower access to solar energy.

Home ownership is frequently mentioned as an important factor influencing solar PV adoption [38,41,55,57]. The two main reasons for this are detailed below. First, there is the legal inhibition to install solar PV systems on a property that people do not own. This is a barrier for any household that is willing and able to install solar PV systems but does not own the roof under which it is living. Second, it has been proven to be difficult to align the interests of both the renters and the homeowners to enable both to benefit from the installation of solar PV systems, also referred to as split incentives [38]. On the one hand, a renter does not benefit from the increase in property value that results from the installation of solar PV, making the initial investment much less attractive. On the other hand, a homeowner has little financial incentive to reduce the cost of the utilities as these are usually covered by the renter. This situation makes it very difficult for renters to install solar PV systems, even though they may be willing to do so [55].

Housing type is significant because not all types of housing have directly sun-exposed roofs, or have rooftops that are suitable for solar PV systems due to their specific building design. Therefore technical feasibility, or any other factor equivalent to this, is often listed as an important barrier to PV adoption [40,41,55,57–59]. Additionally, apartment housing that is part of larger buildings generally share ownership of their respective roofs. For these households, even though the apartments themselves are owner-occupied, adoption of solar PV systems is more difficult as the ownership of the roof is shared among the entirety of the building. The process of solar PV adoption is therefore more complex, making solar PV less accessible to this group. Zander [57] explicitly mentions that coordinating the solar PV adoption process with other unit parties within the apartment building is often considered a significant barrier.

Suitable information is key. As the process of installing solar PV systems is usually perceived as a highly complex process, with many complicated decisions to be made, it is crucial that *transparent, credible and suitable information* is available [38]. As this process involves what many would consider large sums of money, it is important people feel confident with their decision. This also includes the information regarding mechanisms of support that exist to install and maintain solar PV. Lack of inadequate information is frequently mentioned as a key barrier to solar PV adoption [38–40,58,59]. This information barrier is even higher for socioeconomic groups that are not native speakers of a language used for business and governance in a region [40].

This list of barriers is not exhaustive but the four factors described above are considered to be of high importance within literature. The integration of these factors into the Theory of Planned Behaviour results in the conceptual framework as demonstrated in Fig. 2. The figure illustrates how the level of behavioural control is influenced by the four factors displayed within the checkered box. It is the convergence of these factors that heavily impacts how accessible solar energy is for different households.

3. Access to solar energy: The case of The Hague

Fig. 3 presents a flow diagram of the methodology used in this work. The figure shows how *access* to solar energy, as explained in Section 2.1, is used to evaluate equity in the adoption of residential

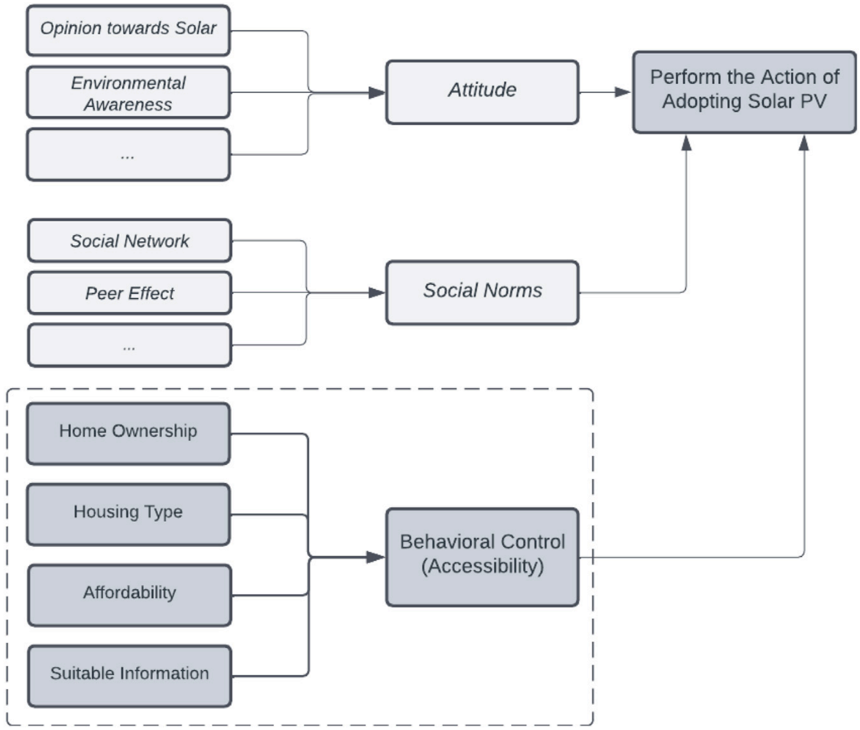

Fig. 2. Expanded conceptualisation of Theory of Planned Behaviour applied to residential adoption of solar PV systems. Four factors are listed to influence behavioural control. Home ownership refers to whether one is owner of the house it occupies. Housing type distinguishes between low-rise and high-rise housing, solar PV systems are considered less accessible to households in high-rise buildings. Affordability refers to whether one is able to finance solar PV systems. And lastly, suitable information involves the availability of credible and suitable information guiding the adoption of solar PV. Factors influencing both attitude and social norms are given for exemplary purposes, but are not the focus of this research.

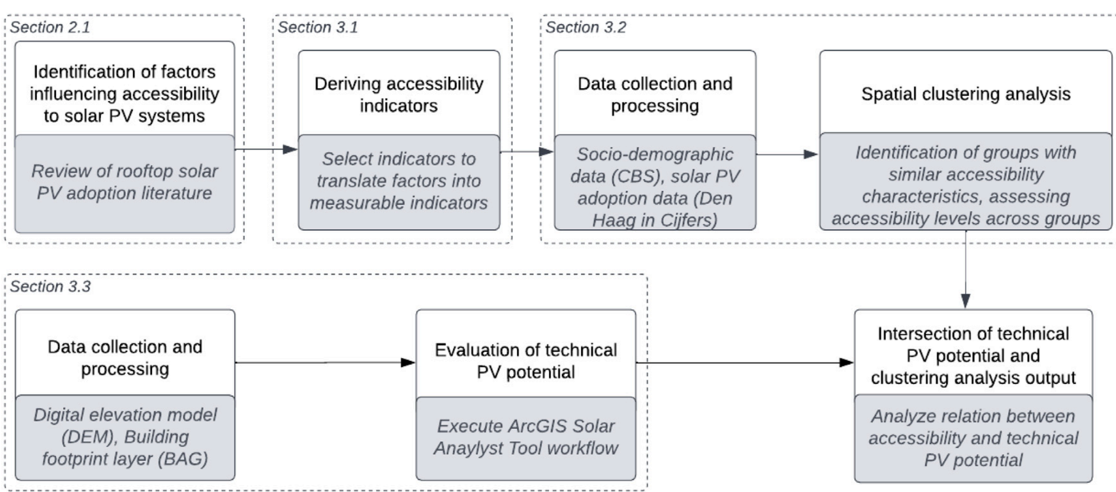

Fig. 3. Overall project workflow including conceptualisation, data collection, data processing and analysis. The blocks in grey describe either the process mentioned above the respective block, or the data source used. In Section 2.1, access to solar energy is described. In Section 3.1, access to solar energy is operationalised. Using this operationalisation, we perform a spatial clustering analysis described in Section 3.2. Section 3.3 describes the evaluation of technical PV potential. Resulting outcomes of these analyses are synthesised in the remainder of the research.

solar PV systems and identify potential policy strategies that could lead to a more equitable utilisation of the solar PV potential available in the city. The methodology thereafter consists of three main steps: (1) select indicators to represent factors that influence access (Section 3.1), (2) perform a socio-spatial analysis to identify patterns of access to and adoption of solar energy across the city (Section 3.2), and (3) evaluate the technical rooftop potential available to identify areas with high solar availability (Section 3.3). The outputs of these steps are synthesised by analysing the spatial intersection of access to solar energy with both the current adoption of solar energy and the technical potential for solar energy.

In this paper, we use the city of The Hague, The Netherlands, as a case study. The Hague is a suitable case study for two reasons. First, past and current policies adopted in The Hague to promote solar energy consist of tax credits and subsidies and have not been implemented from an equity perspective. Second, data sources necessary to evaluate equity in the adoption of residential solar PV systems, including barriers faced by existing households, are systematically collected at postal code level by the Central Bureau of Statistics (CBS) and the municipality of The Hague available for research and public inquiry [60,61].

3.1. Deriving access indicators

The first step is translating the factors influencing access to solar energy (Fig. 2) into measurable indicators. The process of translation is partially contingent upon on the availability of data describing the chosen case study. CBS provides open-access census data, enabling examination at a high spatial resolution [60]. In addition, the city of The Hague maintains an open-access database providing a wide range of indicators for analysis [61,62]. Administrative data help to ensure validity and reliability in our approach.

All factors are operationalised at the spatial level of PC5 postal code units. The PC5 is a postal code level in Dutch spatial administrative data, containing 5 out of 6 possible digits. The city of The Hague comprises 855 PC5 zones, with an average of 330 households per zone. This leads to variation in spatial unit size with varying density. Affordability is operationalised as the *average home value* per PC5 zone, which serves as a proxy for wealth, as income or other wealth indicators are unavailable at this level of spatial resolution due to privacy constraints. The second indicator, used to express levels of home ownership, is measured as the *percentage of owner-occupied homes* per PC5 zone. The third indicator, to evaluate *housing type*, is the *percentage of residential high-rise buildings* per PC5 zone. Lastly, the availability of transparent and suitable information is measured by the indicator *percentage of Dutch native inhabitants* present in a PC5 zone. This indicator serves as a proxy for access to suitable information as the information barrier is higher for social groups that are not native and for whom a language barrier exists [40]. From the available data and deliberate discussions with the municipality policymakers, this is considered the best available proxy. An overview of these factors and their corresponding indicators is given in the supplementary information.

3.2. Spatial clustering analysis

The second step is to perform a spatial clustering analysis to investigate the patterns of access to solar energy across the city on the basis of the factors identified as barriers in access. Although clustering analysis is inherently not of spatial nature, it is often applied in geographic data science to discern spatial patterns from complex multivariate spatial data [63]. In this paper, a k-means clustering algorithm is used to identify the spatial intersection of all four factors. The objective of this method is to form groups where the members are more similar to members within a clustered group based on the access factors than to members of any other group. The output of this analysis is a pre-specified number of clusters with similar statistical properties. By studying the nature of these clusters, we gain a spatial understanding of which areas have better access to solar energy across the city. It is important to note that the number of clusters obtained in the output is pre-specified by the researcher, which can introduce a degree of subjectivity. To limit this subjectivity, we performed a set of two statistical tests (Elbow method and Silhouette coefficient) to evaluate the level of coherence among the obtained clusters. The results of these tests can be found in the supplementary information accompanying this research. Based on the results of these tests, the number of clusters used in this research was set to four ($k = 4$).

3.3. Evaluation of technical rooftop solar potential

The last step is to evaluate the technical rooftop solar potential of residential buildings. This information is necessary to identify areas with high and low potential for solar PV energy, which is relevant for evaluating the impact of current energy policies and proposing policy recommendations capable of tapping into the existing potential in the city. To calculate the rooftop solar PV potential, we use the Area Solar Radiation Tool of the ArcGIS Spatial Analyst. The tool is based on the solar potential model developed by Fu and Rich [64] and has been calibrated and validated by Kausika & Van Sark [65]. The model provides the total amount of incoming solar radiation for a particular area by summing the total amount of direct, diffuse and reflected irradiation. The largest component of these three types of radiation is normally direct radiation, followed by diffuse radiation. The proportion of reflected radiation is usually negligible, except for highly reflective areas such as snow-covered regions. Therefore, the Area Solar Radiation Tool only considers direct and diffuse radiation [66]. Information on the specific input parameters of this model can be found in the supplementary information of this research.

4. Exploring the socio-spatial dimensions of solar energy

4.1. Current solar energy adoption

We start the analysis by looking at the current situation in the case study region, The Hague, with respect to the distribution of existing solar PV systems across the city. Fig. 4 depicts the spatial distribution of solar adoption rates for residential buildings across the city. Each colour class in the figure represents a quartile, thus each colour represents 25% of all PC5 zones within the city, equalling approximately 210 PC5 zones. The ranges of adoption levels within each quartile are shown in the legend in the top left of the figure. A high concentration of areas with relatively low solar adoption rates is observed in the geographical city centre, marked by the dark red-shaded areas in the centre of Fig. 4, while areas with relatively high solar PV adoption are situated in the peripheral areas of the city. On average, 8% of residential buildings in The Hague are equipped with solar PV systems. Compared to the Dutch national average of 25% [67], the adoption of solar energy in The Hague is still quite low. The average adoption rate of 8% implies that all blue coloured areas are close to or above the average adoption rates as their adoption levels are at least above 7.8%. The results also reveal that in 25% (the entire first quartile) of all PC5 zones within The Hague the percentage of residential buildings with solar PV systems is not higher than 0.4%. Upon closer inspection of the data, we find that in 20% of PC5 not a single residential building has been equipped with solar PV.

4.2. Unequal access to solar energy

Fig. 5a presents the spatial distribution of four groups across the city of The Hague, resulting from setting our parameter $k = 4$ in our clustering analysis. The figure reveals a significant degree of spatial clustering. A large cluster, displayed in dark brown, is located in the city centre, bordering the light brown cluster. The two remaining clusters, light and dark green, are distributed mainly along the city shore line and the south-eastern part of the city. Based on analysis of the cluster mean values, an *access score* has been assigned to each group, between 1 to 4, where 1 represents low access and 4 represents high access to solar energy. The scores corresponding to each group can be found in the legend of Fig. 5a. The upper table in Fig. 5b displays the mean values of the four access indicators for each group including the average value for The Hague. The lower table presents the adoption rate of solar PV systems among residential buildings in each cluster.

As indicated in Fig. 5b, group 1 has the lowest levels of home ownership, the lowest average home value, the highest share of non-native inhabitants, and a high level of high-rise apartment buildings, and thus has been assigned the lowest access score. Compared to group 1, group 2 has relatively higher levels of home ownership, a higher average home value, lower share of non-native inhabitants, and a slightly higher share of high-rise apartment buildings, and has therefore been assigned a higher access score. Group 3 is characterised by a higher average home value, high percentage of inhabitants with native background, and high percentage of owner-occupied homes. The

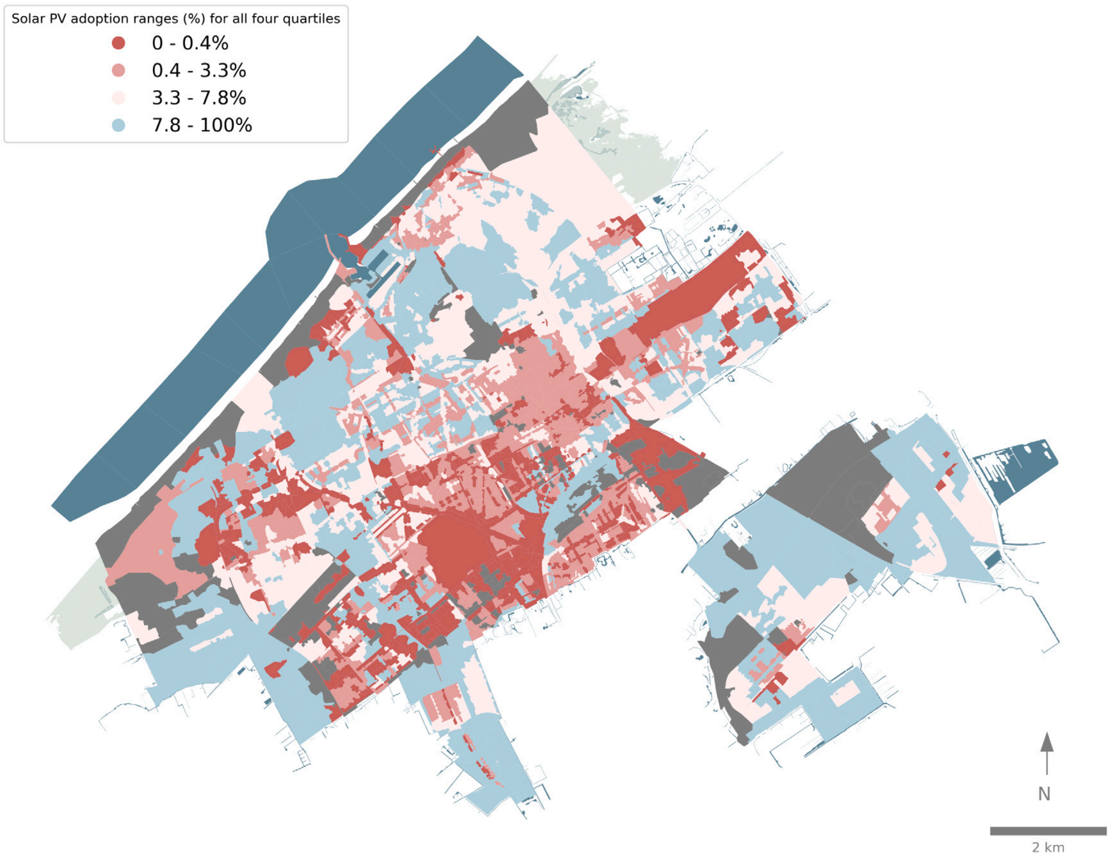

Fig. 4. Spatial distribution of the % of residential buildings with solar panels across The Hague per PC5 zone. Each colour class in the figure represents a quartile, thus each colour represents 25% of all PC5 zones within the city. The legend points out the minimum and maximum levels of adoption of solar energy for each of the quartiles.

main distinction between group 2 and 3 is the level of apartment buildings, which is much lower in areas part of group 3. Group 3 has been assigned a higher access score compared to group 2, because the average home value is higher in group 3 and low-rise housing without shared ownership of the roof enhances access to solar energy. Finally, group 4 displays the most favourable characteristics for the adoption of solar energy, with the highest share of owner-occupied homes, highest home value, highest share of population with a native background, and a low percentage of apartment buildings. As such, based on the results of the clustering analysis and the indicator mean values of this groups, we infer households within this group to have best access to solar energy.

4.3. How access to solar energy intersects with solar energy adoption

In this section, we analyse current levels of solar PV adoption for the four access groups defined above. Table 1 presents the *average percentage of residential buildings with solar panels* in each cluster, as well as the *average number of solar panels per capita* in each cluster. The average percentage of residential buildings with solar panels is calculated by, first, taking the number of residential buildings with solar panels per PC5 zone and dividing this by the total number of residential buildings within the respective PC5 zone. After which, a weighted average is computed weighted by the total number of residential buildings for each PC5 zone. The average number of solar panels per capita is calculated by adding the number of solar panels per PC5 zone, and dividing this number by the total number of residents of the respective PC5 zone. Then, again, to calculate the average number of solar panels per capita for a particular cluster, a weighted average is computed, weighted by the total number of residents per PC5 zone.

The results in Table 1 indicate that the percentage of buildings with solar panels (row 5) is the lowest within clusters 1 and 2, and that the highest rate of residential buildings with solar panels is found in cluster 3, as opposed to cluster 4. However, if we look at the average number of solar panels per capita (row 6), also a commonly used metric to indicate levels of solar adoption, it can be seen that cluster 4 has the highest level of solar panels per capita, as opposed to cluster 3. The different ranking noted between clusters 3 and 4 for the two metrics can be explained as follows. When, for example, an apartment building with a large number of inhabitants is equipped with only few solar panels, this will have an equal weight to the percentage of buildings with solar panels as a single person dwelling with a higher amount of solar panels. However, when looking at the number of solar panels per capita, the value will be much lower in the case of the large apartment building than for the single person dwelling. Nevertheless, both metrics demonstrate that clusters with low access to solar energy tend to have low rates of solar adoption, and vice versa.

Table 2 provides additional insights into the skewed equity levels of solar PV distributions. It is interesting to point out that almost 25% of all solar panels installed in The Hague are located in cluster 4, while only 9.2% of inhabitants live here. In contrast, the largest percentage of the city population resides in cluster 1 (37.7%), while in this cluster we find the lowest share of solar panels (16.2%).

Fig. 6 presents a bivariate choropleth map, which allows for a geospatial visualisation of the intersection of solar adoption rate (%) represented by the percentage of residential buildings with solar panels (horizontal axes of bivariate legend in the plot) and the access scores 1 to 4 (vertical axes) depicted in Fig. 5. Each PC5 zone in the figure is coloured based on its values with respect to two variables. For example, a PC5 zone with the colour red, as portrayed in the bottom left of the legend, represents an access score of 1 and an adoption rate within the

Fig. 5. (a) Spatial distribution of the four access groups across the The Hague per PC5 zone. A short description of the characteristics of each group/cluster is provided in the legend presented in the top left of the figure. (b) The upper table in Figure *b* provides the mean values of the clusters for each of the indicators. This is compared with the average values for the respective indicator observed in the city. The lower table in Figure b presents the adoption rate across each cluster. The adoption rate (%) is defined as the percentage of residential buildings with solar PV systems.

Table 1
Comparing the indicator mean values to adoption metrics of solar PV systems per cluster. The solar PV adoption metrics represent average values for the particular cluster.

Metric	Cluster 1	Cluster 2	Cluster 3	Cluster 4	*The Hague avg.*
Home value (€)	169 000	237 000	339 000	640 000	*269 000*
% with native background	21.8	58.5	60.9	62.7	*44.3*
% of owner-occupied homes	28.9	46.1	63.9	73.5	*44.1*
% of apartment buildings	63.8	77.5	24.7	25.9	*58.0*
% of residential buildings with solar panels	3.78	3.94	10.71	9.99	*7.99*
Number of solar panels per capita	0.06	0.08	0.22	0.37	*0.13*

Table 2
Distribution of total number of solar panels installed per cluster compared to the total share of the city population that is provided housing in each cluster.

Metric	Cluster 1	Cluster 2	Cluster 3	Cluster 4
% of solar panels	16.2%	16.5%	43.4%	23.9%
% of population	37.7%	27.8%	25.3%	9.2%

first quartile range. The value ranges corresponding to the quartiles are listed below the legend, so for areas within the first quartile the adoption rates fall between 0 and 0.4%, and for areas within the second quartile within 0.4 to 3.3%, and so on.

Fig. 6 clearly delineates how PC5 areas where access scores are low also tend to have relatively low adoption rates, as represented by the prevalence of bright red shaded areas. In addition, areas with higher access scores generally tend to have relatively high adoption rates, as represented by the prevalence of bright blue coloured areas. The dark coloured areas, represent areas where the access score is low, while the adoption of solar energy is relatively high. These areas generally represent occasions where social housing corporations have taken initiative to adopt solar energy. The near absence of the grey colour indicates that areas where access is high seldom have low adoption rates. In other words, having good *access* to solar energy often translates into relatively high rates of adoption. The second blue-coloured legend informs how the total amount of solar panels is distributed across all colours portrayed in the map, showing that the highest amount of solar panels is located in the top-right quadrant of the legend representing PC5 areas that have high access.

4.4. Untapped potential

Following the same visualisation approach as before, we now explore the intersection of technical rooftop solar potential and access to solar energy in order to identify key areas for policy action to achieve a just transition. Fig. 7 presents the technical rooftop solar potential per unit area for each PC5 zone and its corresponding access score across the city of The Hague. A per unit area measure is chosen as the PC5 zones are not of the same size, but rather are designed to capture the same number of households. As wealthier neighbourhoods tend to be more spacious, PC5 zones in these areas tend to be larger in order to accommodate the required number of households. The dark grey areas illustrate areas within the city that have high levels of technical potential but low access to solar energy and are thus unable to exploit this potential. Red areas have both low technical potential and low access scores, whereas blue areas have high technical potential and adequate access. The additional legend in blue and white displays the total amount of solar potential in each tile by aggregating the product of the technical potential per unit area and the total area for all PC5 zones in this particular colour.

Fig. 7 indicates that a significant share of technical rooftop solar potential in The Hague is situated in areas where households have low access to solar energy (cluster 1 and 2). Table 3 complements these results with solar potential metrics in comparison with population share across the four access clusters. Clusters 1 and 2 hold 58.5% of technical potential, but are unlike to take advantage of this potential without targeted and tailored policy mechanisms that improve their access. The remaining 31.5% is located in clusters 3 and 4, where both access is better and adoption rates are higher. While the lowest share of potential

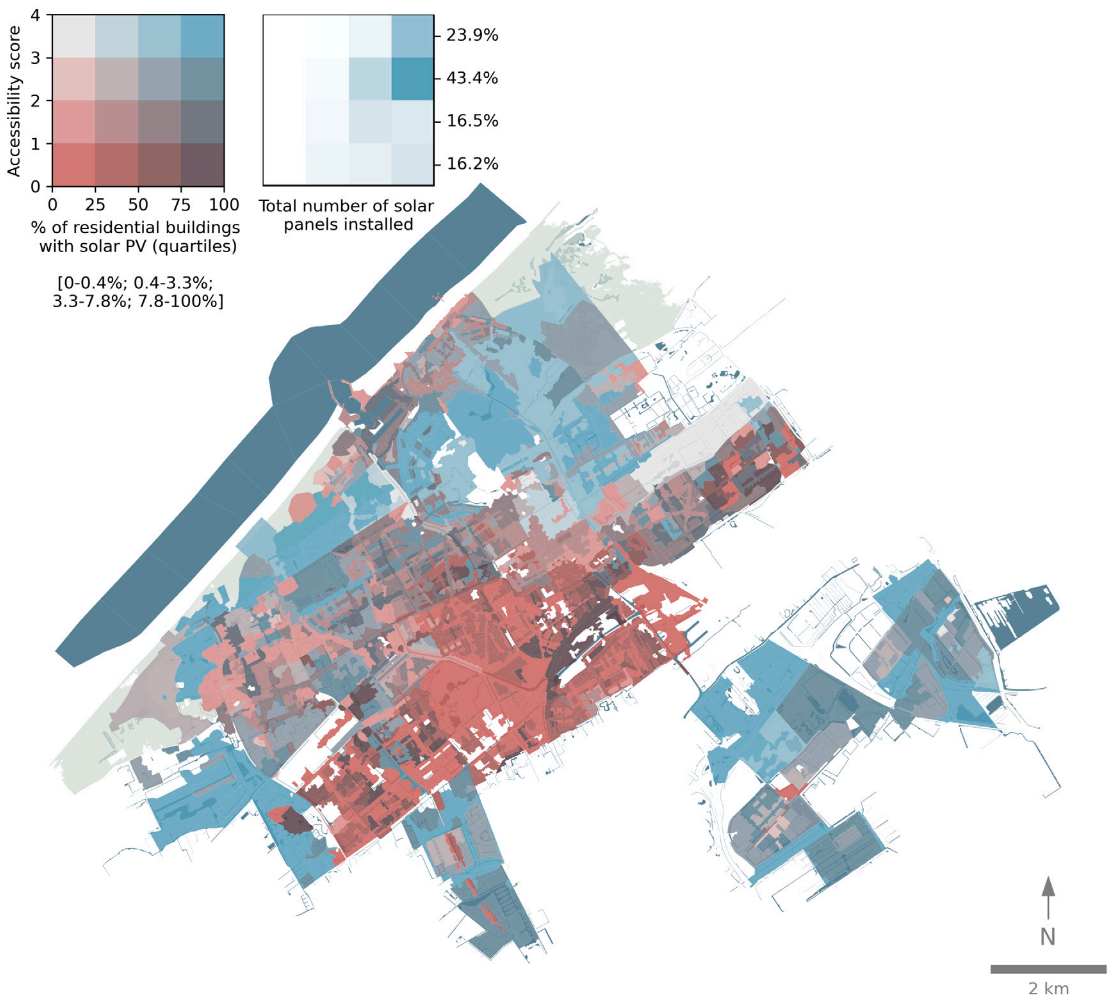

Fig. 6. Bivariate choropleth of quartile ranges of residential buildings with solar PV versus access score. Each PC5 zone in the figure is colour coded based on its values with respect to two variables. For example, a PC5 zone with the colour red as portrayed in the bottom left of the legend represents an access score of 1 and an adoption rate within the first quartile range. The value ranges corresponding to the quartiles are listed below the legend, so for areas within the first quartile these are between 0 and 0.4%, and for areas within the second quartile between 0.4 to 3.3%, and so on.

Table 3
Solar potential metrics among clusters versus population share.

Metric	Cluster 1	Cluster 2	Cluster 3	Cluster 4
% of solar potential	30.4%	28.1%	25.3%	16.2%
Total potential (MWh)	204 227	188 632	170 186	108 750
% of population	37.7%	27.9%	25.4%	9.2%

(16.2%) is situated in areas with the highest access and low population share (9.2%), the highest share of the technical potential (30.4%) is located in the cluster 1, which has the lowest level of access and houses large percentage of the population (37.7%). Cluster 1 thus provides opportunities for increasing the installed capacity while including a large part of the population in the energy transition.

4.5. Target groups for policy

This section focuses on finding opportunities to exploit the existing solar potential in The Hague in an equitable manner. For that, we examine different housing structures. Housing in the Netherlands is divided into two sectors: social housing and private housing. The Netherlands is one of the countries with the largest share of social housing in the European Union, accounting for about 32% of the total housing stock and 75% of the rental stock in the country. Social housing associations are responsible for providing housing below a certain price range to sustain affordable housing for lower-income households. They are also responsible for large-scale repairs, renovations, and maintenance. The private sector, in contrast, exists of a private rental sector and the owner-occupier market. The owner-occupier market can be subdivided into single-family residential buildings and multi-family residential buildings. A single-family home refers to standalone residential buildings that are meant to accommodate a single family unit, while multi-family residential is used to classify housing where multiple separate housing units are contained within one building. By law, multi-family residential buildings are obliged to have a homeowner association (VVE), which is responsible for decisions concerning the common areas of the building, including the rooftop.

Fig. 8 presents the state of the transition to solar energy in The Hague, according to the structure of the Dutch housing system. In The Hague, 31.0% of households reside in social housing, 48.9% are part of homeowner associations (VVE), and 20.1% belong to other housing structures, like single-family buildings. Despite holding 17.7% of the technical rooftop solar potential, the adoption of solar energy has been slow in buildings owned by social housing corporations, at a rate of only 4.2%. Similarly, homeowner associations represent 38.5% of the technical potential with a even lower adoption rate of 2.9%. The remaining 43.8% of the technical potential is represented by the private rental sector and the owner-occupied single-family buildings. This group shows a significantly higher solar adoption rate of 11.8%.

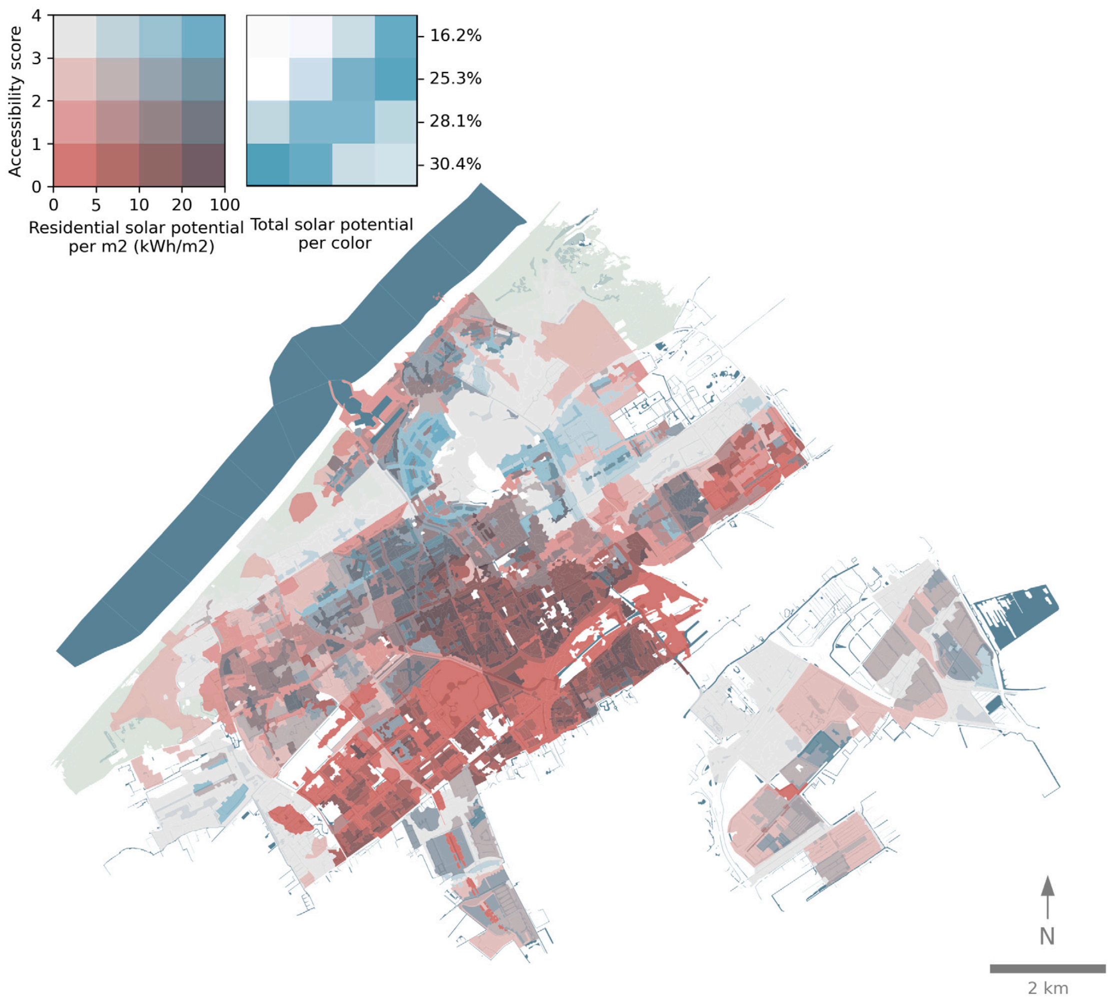

Fig. 7. Distribution of solar potential per unit area in a PC5 zone versus its access score. Each colour code is representative of an amount technical PV potential of that particular PC5 zone (kWh/m^2) and a corresponding access score. The legend on the right side in blue and white illustrates the total amount of technical PV potential per colour code. The percentages listed on the right side of the second legend represent the share of the total technical PV potential for that particular row.

Together, social housing and homeowner associations house almost 80% of the population and hold 56.3% of the technical rooftop solar potential in The Hague. This means that the large majority of households in The Hague are restricted in their decision to adopt solar energy, depending on the initiative of either social housing associations or homeowner associations. There restrictions could, however, be targeted by policy and regulatory mechanisms.

Concerning social housing, there are three clear policy leverage points: (1) exploit a substantial share of the available technical potential, (2) provide solar energy to a large share of the population within the city that otherwise has poor access to the technology, and (3) target a small number of housing associations instead of thousands of individual households. Here, it is important to note that all social housing in The Hague is consolidated under eight corporations.

Regarding homeowner associations, one reason for a low adoption rate within this group is the shared condition of the rooftop. This entails a variety of complex processes to deal with when adopting solar energy as a homeowner association, such as engaging a majority to agree to participate, arranging adequate financing, dividing the roof among participants and non-participants, deciding on insurance, and registering the homeowner association as a separate energy cooperation. Moreover, there are currently no support for homeowner associations to jointly go through the process of installing solar panels on their buildings. This provides two leverage points for policy: (1) reduce the complexity of solar installations in multi-family buildings, and (2) create collective models to facilitate access to solar energy for homeowner associations.

5. Discussion

This paper aims to evaluate the transition to solar energy in the city of The Hague from an equity perspective. Our research has access to solar energy at its core. We used the Theory of Planned Behaviour to frame the research within the broader field of decision-making behaviour and to make a distinction between access to and adoption of solar energy. Clearly distinguishing between access to and adoption of solar energy is critical in our approach to evaluate equity. The resulting conceptual framework in combination with a data-driven socio-spatial analysis enables the identification of geospatial structures underlying access to solar energy. Applying our approach to the city of The Hague, The Netherlands, our results show that areas with low access to solar energy also present low adoption rates of solar energy, and vice-versa. These outcomes support current consensus in literature [11,24,35] that primarily socioeconomically more advantaged groups have been able to adopt low-carbon energy technologies, such as residential solar PV systems, and thereby benefit from associated energy policies, reinforcing existing inequalities.

We also calculated the technical rooftop solar potential in The Hague. Our results show that the existing potential has been exploited only in the more advantaged socioeconomic areas of the city (those who

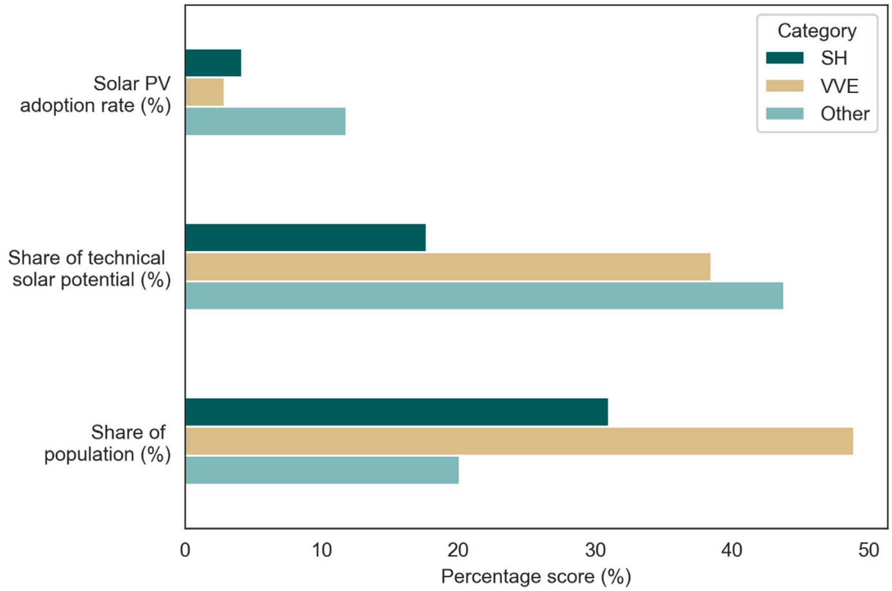

Fig. 8. Transition to solar energy in The Hague following the Dutch housing system: metrics for social housing (SH), homeowner associations (VVE), and 'Other' (representing all other housing structures besides social housing or homeowner associations). Solar adoption rate refers to the number of buildings within a certain category with solar panels. Share of technical solar potential refers to the share of technical potential of the total technical potential represented by the particular category.

have high access), while adoption of solar energy in less advantaged areas remains incipient (those who have less access). With these results, we argue that policies that do not promote equitable access to solar energy are likely to lead to inequalities in the adoption of solar energy. In addition, most of the technical rooftop solar potential is located in areas where households are socioeconomically disadvantaged regarding the adoption of residential solar energy or, in other words, where access to solar energy is low. This indicates the presence of substantial amounts of untapped potential in these areas that are likely to remain underutilised if access does not improve, asking for tailored and targeted policy efforts. To this end, our work identifies several policy leverage points concerning two groups of interest: social housing and homeowner associations. Translating these leverage points into concrete policy and action is no trivial task [68] and, thus, beyond the scope of this paper.

Our findings are also in line with recent research on the broader topic of energy poverty in The Netherlands [69], which shows that approximately half of the population lives in low energy quality homes but do not have the independence to make their homes more energy efficient and, therefore, are unable to participate in the energy transition. Although this group might still be able to afford their energy bills right now, they could still be considered energy poor. When energy prices rise or remain high for a sustained period, households residing in low energy quality homes could face issues with energy affordability because they have fewer options to upgrade or renovate their homes, thus underlining the importance of having access to transition technologies [69].

Although not the focus of our study, we highlight that the burdens of the transition to solar energy have also not been equally distributed. In the case of The Hague, our results show that a large part of the population has low levels of access to solar energy, being unable to take advantage of the benefits of solar energy policies, even though they also contribute to the overall financing of these technologies through taxation. Yet, the costs associated with transmitting surplus solar-generated electricity to the grid are passed on to all energy consumers, including those who do not utilise solar energy [70]. The Dutch Authority of Consumer and Market (ACM) estimates that the additional expenses incurred by the average household can reach tens of euros monthly [70]. Thus, despite bearing a portion of the financing costs through energy taxes and increased energy bills, households with low access to solar energy remain unable to reap the benefits of energy transition policies.

The fact that benefits and burdens of the transition to solar energy have been unequally distributed across the city is highly problematic, potentially leading to the lock-in or perpetuation of current socio-spatial inequalities [24]. As inequalities manifest spatially [42], this research connects the literature on energy poverty and spatial analysis, developing a geospatial process to identify spatially varying levels of access to solar energy. While our paper focuses on solar energy because of its maturity and popularity, other energy transition technologies, such as electric vehicles and heat pumps, can also be evaluated using the same approach. Here, it is important to adapt the operationalisation of access to include factors that are specific to a certain technology, such as the availability of parking or charging stations for electric vehicles and building characteristics relevant to heat pump installations. Moreover, the context may also influence which factors play a more important role in household decision-making. For example, financial system instability or lack of trust in institutional actors may be decisive factors in some contexts.

The Theory of Planned Behaviour is used in this paper to frame the research within the complex process of technology adoption. While most Theory of Planned Behaviour studies are correlational and require randomised experiments (e.g., [71–73]), our study makes use of open administrative data and takes an explicit spatial dimension, but it does not aim at providing correlational insights. Instead, our approach recognises and reinforces the importance of considering the socio-spatial dimension of energy transition in cities, in line with recent research that highlights a higher prevalence of energy poverty in urban areas [74] and the need to examine geographic issues of access to energy carriers [34]. Further, we do so at a high spatial resolution, not commonly found in the literature. Although we acknowledge the importance of correlational studies within the Theory of Planned Behaviour literature and statistical studies in general (e.g., [9,12,13,71–73]), our methodology and findings highlight the need for policies tailored to groups that currently have been unable to benefit from the advances of solar technologies and its associated financial benefits.

Finally, we highlight that this study interprets access to solar energy as equivalent to behavioural control. This is an interpretation that enabled us to distinguish between access to and adoption of solar energy, which was important to identify leverage points for targeted policies.

Going back to the Theory of Behaviour Control, an interesting avenue for future work could be testing the operationalisation of (perceived) behavioural control as access in quantitative statistical analysis, as there is no consensus on this matter [41]. Alternatively, access could be yet another element in an expanded version of the Theory of Behaviour Control, in addition to behavioural control, attitude, and social norms. Nevertheless, we recognise the need for a deeper reflection on what access to solar energy means, or more broadly access to the energy transition. Because access (and accessibility) are also core elements of urban planning and policy, with strong implications for the housing and transportation sectors, establishing a shared definition of access to urban transitions, encompassing the full complexity of justice debates in the urban environment, could be a worthy collective effort to transcend disciplinary boundaries in urban planning and policy.

6. Conclusion

Residential solar energy is expected to play a major role in the ongoing and future energy transition due to its capability of providing renewable energy in a cost-effective manner. Although all buildings have a roof and, thus, the opportunity to generate electricity through solar panels, not all households are equally capable of exploiting this opportunity and, therefore, remain unable to seize the benefits of the transition to solar energy. This raises concerns regarding principles of energy justice. To get better insights into justice questions in the energy transition, this paper evaluates the adoption of solar energy in the city of The Hague, The Netherlands, from an equity perspective.

Using the Theory of Planned Behaviour as overarching framing, we consider four factors influencing access to solar energy: affordability, home ownership, housing type, and availability of suitable information. Based on these factors, we identify four groups that represent different levels of access to solar energy. Through a socio-spatial analysis at the postcode level, we demonstrate that these groups are strongly segregated across the city, overlapping with existing socio-spatial inequalities. Furthermore, our results demonstrate that areas with low levels of access to solar energy (lower home value, lower % of natives, lower % of owner-occupied homes, higher % of apartment buildings) present low adoption rates, which means that policies have not been able to attend to these groups. As a consequence, the adoption of solar energy in The Hague has been highly unequal, with higher adoption in already advantages areas of the city: Almost 25% of all solar panels currently installed in The Hague are located in advantaged areas, while only 9.2% of inhabitants live here. In contrast, the largest percentage of the city population (37.7%) resides in areas with the lowest share of solar panels (16.2%).

To reach a more equitable adoption of solar energy in the urban environment, we argue that policy needs to target groups that have lower access to solar energy and address their unique socio-spatial characteristics. Groups with low access to solar energy currently hold 58.5% of the total rooftop solar potential in The Hague. They also house about 65% of the city's population, encompassing mostly non-homeowners, homeowners with inadequate access to financing, homeowners that have collective and shared ownership of their roofs, and households living in housing provided by social housing associations. Yet, the average adoption rate of solar energy in these groups is below 4%. Improving their access to solar energy has thus a twofold contribution to the energy transition, helping to exploit a large part of the technical rooftop solar potential in The Hague and promoting to a more equitable adoption of solar energy across the city. Ultimately, ensuring an equitable access to solar energy creates support for the energy transition and contributes to efforts to mitigate energy poverty.

CRediT authorship contribution statement

Chiem W. Kraaijvanger: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Trivik Verma:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration. **Neelke Doorn:** Writing – review & editing, Supervision. **Juliana E. Goncalves:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this research is open source data provided by the municipality of the Hague. Research code can be provided on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.erss.2023.103245. Supplementary information includes details about the literature review, the data preparation, the spatial clustering analysis (application of the Elbow method and the Sillhouette coefficient), and the calculation of the technical rooftop solar potential.

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