SHARING OUR SUNLIGHT

EVALUATING ACCESS TO SOLAR ENERGY IN LIGHT OF A JUST ENERGY TRANSITION

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by

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Preface

This thesis has been written to finalize my master's programme Industrial Ecology at the University of Leiden and the TU Delft. I feel privileged to be able to have taken part in this program, as I realize that not everybody in this world is granted such opportunity. First and foremost, I would like to thank Juliana Gonçalves for introducing me to this topic, being open to taking on this project with me and subsequently always being ready for answering my questions and keeping me on track to reach my goal. I would also like to sincerely thank Neelke Doorn and Trivik Verma for your detailed feedback, interesting insights and ever constructive criticism that helped me forward during this project. In its entirety I would like to thank my committee for providing a very pleasant atmosphere in which I felt comfortable working towards this final product. Furthermore, I would like to thank everyone at the CUSP for their feedback and interesting discussions that have been very valuable. And lastly, I would like to thank my family and friends for supporting me throughout my entire a career as a student, of which I am slightly sad, but above all proud that it is now finally coming to an end.

Abstract

As the effects of climate change are more and more materializing around the globe it is ever more important to reduce our reliance on a fossil fuel based energy system. When coupling this to an ongoing trend of urbanization in many places across the world, the energy systems of our cities become of particular interest. However, the transition away from a fossil fuel based system towards a renewable energy based system is a complex sociotechnical process that in part relies on the extent to which households are able to adopt energy efficient technologies. Not all households are equally capable of investing in these technologies, causing some households to have better access to participate in the renewable energy transition. This unequal access to the renewable energy transition causes an unequitable distribution of energy efficient technologies and could potentially lock-in or perpetuate current injustices. To prevent this from happening there is a need for energy policy that supports socioeconomic groups across society, that have inadequate access to the renewable energy transition. In order to design such policy it is essential to first of all identify who these groups are, and secondly where they are located. As the renewable energy transition is still in its early stages, these insights are currently lacking in literature.

Considering the fact that solar PV is a major driver of the renewable energy transition, this thesis in part addresses this knowledge gap by spatially analyzing which socioeconomic groups in the urban environment lack access to solar PV and where these groups are located. Access to solar PV in this context is defined as: the freedom of individuals or households to decide whether or not to adopt residential solar PV energy resources, dependent on the existence of one or more barriers. Secondly, does the research assess how access to solar PV resources spatially intersects with the ability to generate solar energy through these resources. The location that is selected as the area of study for this research is the city of The Hague, Netherlands. A framework is constructed to assess access to solar PV using the Theory of Planned Behavior originating from social sciences, which is frequently used to model adoption behavior of novel energy technologies. To evaluate the technical PV potential of the case-study the ArcGIS Solar Analyst Tool is applied. A K-means clustering analysis is performed to find any meaningful patterns in the distribution of access to solar PV across the area of study.

The key findings of this study are:

- Access to solar PV resources is substantially unequally distributed across the Hague. Large parts of The Hague have unfavorable characteristics for solar PV adoption.
- The highest levels of technical PV potential are found in areas that are considered to have poor access to solar PV. As a consequence, currently the majority of technical PV potential within the case area is likely to remain unexploited due to poor access to solar PV within these areas.
- There is a need for energy policy that focuses on the groups that have poor access to solar PV and are unserved by current energy policy focused on stimulating adoption of solar PV. These groups are non-home owners in the private rental sector, home-owners that share ownership of the roof of a shared building and households that are provided housing by social housing corporations.

Further research could focus on exploring and evaluating policy design that is aimed at supporting socioeconomic groups that currently lack access to the renewable energy transition. This is important in order to ensure that the renewable energy transition makes its way throughout all layers of society.

Contents

List of Figures

List of Tables

1. Introduction

1.1. Topic context

Human activity is affecting the climate at a rate that is unprecedented, which is causing many weather and climate extreme events in every region across the globe (IPCC, 2021). Average annual greenhouse gas emissions during the period 2010-2019 were higher than in any previous decade (IPCC, 2022). The energy system is a large global contributor to these greenhouse gas emissions (Bilgen, 2014). To bring down the emissions generated by the energy system, changes will need to be made in the ways in which energy is consumed and produced. The current fossil fuel based energy resources will need to be replaced by renewable energy sources. Because ultimately, only fully renewable energy system scenarios can fulfil the highly demanding environmental, socioeconomic, and ethical sustainability requirements of a resilient future energy system (Child et al., 2017).

Solar energy is expected to be one of the major drivers of the renewable energy transition by providing a renewable energy source of energy (Sampaio et al., 2017). Theoretically, solar energy has the potential to fulfil the global energy demand multiple thousands of times based on the amount of solar energy that reaches the earth annually (Ellabban et al., 2014). However, being a form of decentralized electricity production, the success of solar PV technologies is partially dependent on the level residential adoption. Therefore the shift to a renewable energy system involves that at the residential level, households will need to choose renewable energy technologies over traditional fossil-based energy resources. A successful energy transition at residential scale is thus dependent on the residential adoption of renewable energy technologies (Schulte et al., 2022).

A household's decision to adopt renewable energy technologies is a complex sociotechnical process that depends on many more factors than merely having the financial resources to adopt. Besides the capital that's required to adopt a solar PV system, other factors that influence these decisions are for example social network structures (Sundaram, 2021), knowledge deficit (Hesselink & Chappin, 2021; Karakaya & Sriwannit, 2015), or level of environmental awareness (Kwan, 2012). It is the combination of multiple factors together that in the end determines whether a household or individual is likely to invest in solar PV technology or not. Therefore, whether households have real access to solar energy depends on the many factors that influence their decisions to adopt.

Due to large variance across these factors among different socioeconomic groups, access to renewable energy technologies like solar PV is not distributed equally throughout society (Carley & Konisky, 2020). Burns (1980) defined accessibility as: "the freedom of individuals to decide whether or not to participate in different activities." This definition of accessibility can be used to interpret access to solar PV. When interpreting accessibility along the lines of Burns (1980), this results in a definition for *access to solar PV* as: 'the freedom of individuals or households to decide whether or not to adopt residential solar PV energy resources, dependent on the existence of one or more barriers.

The fact that access to renewable energy technologies like solar PV is unequally distributed is problematic, because as a consequence of this more advantaged socioeconomic groups will be able to benefit from the transition to renewable energy technologies to a higher degree than less advantaged socioeconomic groups will be able to (Lacey-Barnacle, 2020), thus leading to forms of energy injustice. This development could potentially lead to the lock-in and perpetuation of current injustices over the course of the renewable energy transition (Sovacool et al., 2022a).

To prevent this from happening it is essential for future energy and climate policies to be considerate of their distributional consequences among different socioeconomic groups (Sovacool et al., 2022). Current energy policy however, is often focused on the effectiveness of renewable energy penetration, disregarding how the costs and benefits of the respective policy are distributed (Brugger & Henry, 2021). This means that energy policy is mainly focused on reducing fossil-fuel based energy production as quickly as possible, without considering who are the groups that benefit from these policies. An example is the cross-subsidization of low-income classes to high-income classes for feed-in-tariffs. The costs for policy measures to stimulate solar PV adoption such as feed-in-tariffs are usually carried by all layers of society, whereas only the wealthier consumers were able to benefit from these subsidies as significant upfront capital was needed to make the initial investment (Sovacool et al., 2019a). It is therefore important that principles of energy justice receive a more prominent place in energy decision-making to ensure that the technical PV potential is exploited across all socioeconomic groups of society. The technical PV potential is defined as the amount of useful electricity that can be generated through solar PV technologies in a specific area.

To design energy policy that is more considerate of an equitable distribution of its costs and benefits it is essential to know who the groups are that are limited in their accessibility to the energy transition, and secondly, where these groups are located (Carley & Konisky, 2020). A lack of systemic understanding however remains in literature on how access to renewable energy technologies such as solar PV is defined and how it is distributed across socioeconomic groups. Furthermore, a lack of understanding exists on how accessibility to renewable energy technologies spatially intersects with the technical potential to provide energy (Bouzarovski & Simcock, 2017).

This research aims to address this gap by firstly constructing a framework in order to define the concept of accessibility to solar PV, and thereafter evaluating the spatial distribution of accessibility to solar PV resources and assessing how this intersects with the technical capacity to generate electricity in the urban environment, otherwise known as the technical PV potential. By doing this it aims to contribute to designing energy policy that is not only effective in realizing higher levels of technology penetration, but also is considerate of the equity and fairness dimensions of these policies. It aims to reveal patterns in the spatial distribution of accessibility to solar PV energy and provide useful insights for the design of more equitable energy policy.

1.2. Knowledge gap

A review of the literature consisting of studies at the intersection of 1) accessibility to solar PV resources, 2) the technical potential of solar PV in the urban environment and 3) a just energy transition uncovers a lack of understanding on the distribution of accessibility among different socioeconomic groups to participate in the energy transition through the means of solar PV. There is a lack of understanding who these groups are, where they are located and what can be done to reduce their distance to the energy transition.

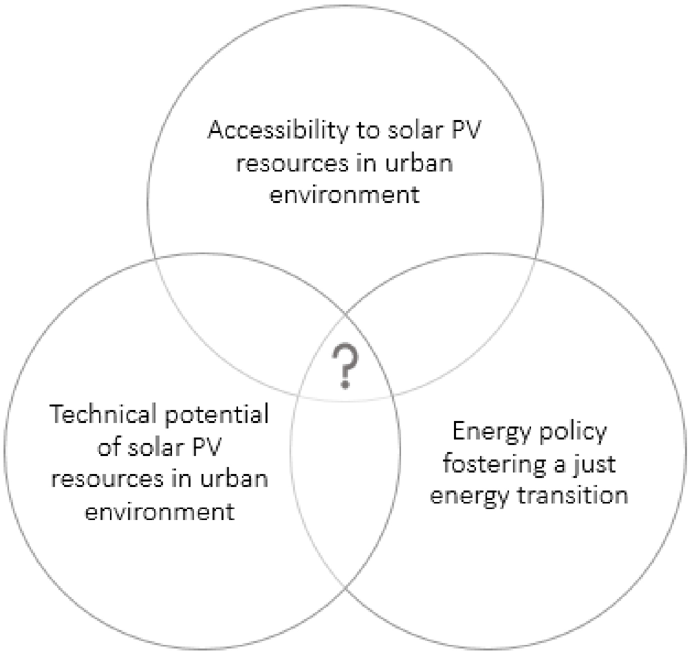

Fig. 1.1. Knowledge gap visualization

Figure 1.1 highlights the knowledge gap as it illustrates how the different concepts accessibility to solar PV resources, technical PV potential and a just energy transition intersect. Accessibility to solar PV is currently not yet clearly defined in literature, as there is no consensus on what exactly it means to have good access to solar PV. Technical PV potential however, can be evaluated at a high level of detail. Over the years, advancement in information systems has led to newer models that are capable of evaluating technical solar PV potential at high levels of detail (Gassar & Cha, 2021). The concept of a just energy transition is relatively new in literature, and currently numerous different interpretations exist (Jenkins et al., 2021), though in essence they all come down to a fair distribution of costs and benefits of the future energy system. This concept is advancing in literature as the energy transition progresses. While all three topics are being covered in literature, there remains little understanding on how these concepts interact.

Currently, the success of solar PV incentive and policy support programs is often driven by technical parameters such as PV penetration levels or overall adoption rates and little attention is paid to which socioeconomic groups are benefitting from these programs (Brugger & Henry, 2015; Grover & Daniels, 2017). This way, energy policy is inconsiderate of the social impacts that these policies have as it does not differentiate between who receives support and who needs it the most. In order to support the design of energy policy that is more considerate it is important to gain better insight into how the impacts of policy support is distributed across socioeconomic groups. It is therefore important for policy support to assess whom is helped and how its costs and benefits are distributed. In other words, to make solar PV resources more accessible to a larger part of society better insight is necessary into which socioeconomic groups lack access to this technology and is in need of better support (Carley & Konisky, 2020).

Combining the level of access to solar PV with the technical capacity that can be generated in a specific area offers a more complete perspective on true solar PV potential. It not only allows us to recognize areas that have high PV potential in purely technical terms, but also allows us to identify areas and groups that currently lack access to realize this potential and therefore have a higher necessity of policy support to realize this potential. The main research question of this research is therefore formulated as follows:

How can insight into the spatial intersection of access to solar PV and technical solar PV potential contribute to energy policy fostering a just energy transition?

To answer the main research question the following sub-research questions are formulated.

Sub-research question 1

How is accessibility to solar PV defined?

This sub-research question addresses the evaluation of the concept of accessibility or access to solar PV. Accessibility to solar PV is a core aspect to this thesis and it is therefore of high importance that this concept is clearly defined. No clear definition however exists in literature that describes this concept, and the factors that influence it. Therefore an important part of this research includes the construction of a framework that intents to define this concept, which is called the *access to solar* framework. This involves the assessment of which factors influence accessibility to solar PV, and in what way.

A literature review on the factors influencing adoption of solar PV and adoption of renewable energy technologies is used to answer this question. Since the decision whether or not to adopt solar PV systems is a complex sociotechnical decision, there is a high variety of factors that play a role in making this decision. This sub-research question aims at distilling the key factors that determine the level of accessibility to solar PV in order to construct the *access to solar* framework.

Sub-research question 2

How is accessibility to solar PV spatially distributed throughout the urban environment?

The framework constructed in order to answer sub-question 1 is used as the basis in order to answer this sub-question. Data should be collected on the factors of interest identified through the framework described in sub-question 1. By evaluating how the different factors derived from the framework are distributed across the urban environment and using these insights for a socio-spatial clustering analysis it can be assessed how accessibility to solar PV is spatially distributed across the urban environment. These outcomes will later be used for spatial analyses of the intersection of technical PV potential and access to solar PV.

Sub-research question 3

How is the technical rooftop solar PV potential distributed across the urban environment?

This sub-research question addresses the evaluation of the technical rooftop solar PV potential. To do this the city of The Hague, Netherlands is used as a case for this study. Answering this sub-research question involves calculating the amount of electricity that can be generated by using all suitable rooftop area across The Hague. Different models exist within literature to evaluate this potential, all for which the level of computational intensiveness increases with the desired level of detail of the final result. This study uses a model which is originally developed by Fu and Rich (1999). This method has been used and validated by multiple others studies and produces results which are sufficient for the level of detail required in this study (Kausika & van Sark., 2021).

The answers to these research questions should enable this study to answer its main research question and accomplish its research objective. By defining the concept of accessibility to solar PV, assessing its spatial distribution across the urban environment and evaluating the technical PV potential of this same area all elements are included to allow this research to answer the main research question. The outcomes should then provide insights that form the basis to contribute to designing energy policy that enhances a just and renewable energy transition.

1.3. Thesis outline

The full thesis outline is presented in figure 1.2. The diagram provides an overview of the steps taken in this research and the order in which they are taken. Chapter 2 includes a review of the relevant literature and presents the access to solar PV framework that is adopted. Chapter 3 involves the presentation of the research design. Chapter 4 presents the outcomes of the research. Chapter 5 includes a discussion and interpretation of the key findings of this research and comments on the implications for policy. And finally, chapter 6 summarizes the key findings and suggests avenues for further research.

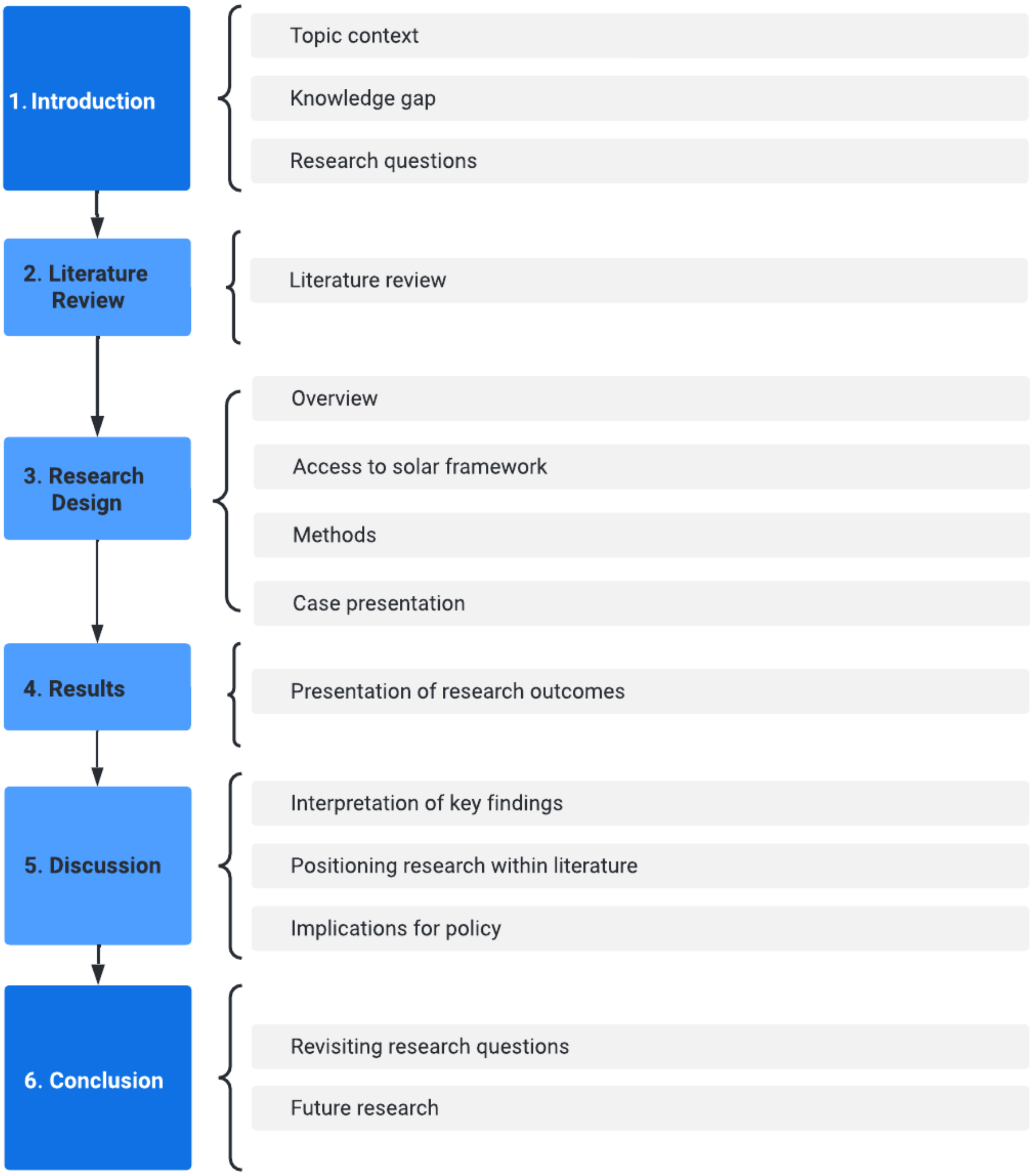

Fig. 1.2. Thesis outline

2. Literature review

In this literature review the concepts that are relevant to this research will be evaluated and it will be assessed how this research fits into the context that is shaped by these concepts. At the end of the review it should be clear how concepts of accessibility and energy justice apply to the energy transition, and to the transition towards solar PV systems in particular. The structure of this review is as follows: firstly, the concept of energy justice is explored and how it has developed throughout literature over time. Secondly, it is evaluated how principles of energy justice apply to a just transition towards renewable energy technologies, and in particular towards residential solar PV. Next, a review of renewable energy technology adoption and solar PV adoption literature is presented to distill factors that are relevant when assessing access to solar PV energy.

2.1. Energy justice

The application of justice theories and principles on the performance of energy systems has, since the start of the last decade, developed as a new social science research agenda, which is also commonly referred to as the concept of *energy justice* (Jenkins et al., 2016). Energy justice theories apply justice and equity principles to energy systems. Equity and justice in light of a renewable energy transition in this can be conceptualized as the quality of being fair or just, as is done by Sovacool et al. (2022a) in their review of equity implications of a low-carbon future. This encompasses different dimensions including equality of access, equality of resources and equality of representation in energy decision-making processes. Inequity, therefore, implies a situation of unequal access, unequal distribution of resources or unequal representation in relevant decision-making processes.

The most comprehensive definition of energy justice to date is given by Sovacool and Dworkin (2015): *"a global energy system that fairly disseminates both the benefits and costs of energy services, and one that has representative and impartial energy decision-making"*. This definition touches upon three aspects of energy justice that by McCauley et al. (2013) are recognized as the three tenets of energy justice, namely: distributional justice, recognition justice and procedural justice. These respective tenets try to encompass all the forms in which principles of justice apply to energy systems in order to reveal and alleviate these injustices. These three tenets of justice address the questions of *where do injustices occur*, *who do they apply to* and *what mechanisms lay to the root of the injustice*? Besides only evaluating where and to whom these injustices occur, it is at least equally important how to reduce these injustices. This is can considered to be the more normative part of energy justice. This is summarized by Jenkins et al. (2016) as demonstrated in table 2.1.

Tab. 2.1. Evaluative and normative contributions of energy justice (Jenkins et al., 2016)

Tenets	Evaluative	Normative
Distributional	Where are the injustices?	How should we solve them?
Recognition	Who is ignored?	How should we recognize?
Procedural	Is there fair process?	Which new processes?

Heffron and McCauley (2017) added to this the notion of restorative justice, aiming to repair the damage inflicted on society through the form of injustice, rather than solely punishing the offender. Later McCauley et al. (2019) added to this the form of cosmopolitan justice, stressing the fact that decisions on energy systems across the energy life-cycle that happen in one particular place, have effects that reach far across borders, affecting communities across the entire planet. Bouzarovski and Simcock

(2017) touched upon the concept of spatial energy justice, recognizing that many instances of energy injustice are also a matter of spatial (in)justice. And based on the three tenets of energy justice Sovacool and Dworkin (2015) defined eight principles that can be used to apply the concept of energy justice into decision-making. This leads to the current energy justice conceptual framework, presented in figure 2.1.

Fig. 2.1. Framework of Energy Justice Concepts (Heffron, 2022)

Although after McCauley et al. (2013) many other interpretations of the term energy justice have followed, almost all of these interpretations build upon the three tenets; distributional justice, procedural justice and recognition.

2.1.1. Distributional justice

The equal distribution of environmental benefits and burdens, as well as the even distribution of the corresponding responsibilities are recognized by distributional justice (Jenkins et al., 2016). An illustrative issue of distributional justice is the siting of energy infrastructure. Communities that are for instance closely situated to coal-fired power plants experience more of the negative effects due to air pollution than communities situated further away, while experiencing the same benefits in the form of electricity consumption.

Apart from the siting of energy infrastructure, distributional justice also refers to the access attained by people to energy services (Jenkins et al., 2016). This applies to access to existing forms of energy services, but is just as applicable to new forms of energy services. One of the main areas of interest of this research, equitable distribution of access to solar PV, can thus be considered a form of distributional justice.

2.1.2. Recognition justice

Recognition justice applies to energy systems mainly in two ways. Firstly, in the form of non-recognition of energy needs of certain social groups, and secondly, as misrecognition and disrespect of specific beliefs and values of social groups (Jenkins et al., 2016). An example of non-recognition is encountered in UK's policy on fuel poverty. By not recognizing the reliance of specific social groups - such as the elderly or chronically ill – this policy has always focused on tackling the presumed 'knowledge deficit' of these social groups to make efficient use of energy resources. This however failed to establish understanding of the actual reasons behind the specific consumption patterns of these social groups. Misrecognition and disrespect occurs in situations where although the values and needs of specific groups are recognized, the sincerity of these values and needs are underestimated. Leading to what for these specific social groups and communities feels as unjust treatment (Jenkins et al., 2016).

2.1.3. Procedural justice

Lastly, procedural justice concerns equal levels of access to decision-making processes on energy systems by all stakeholders while maintaining equitable procedures of decision-making. It requires the mobilization of local expertise on energy related issues, transparent procedures with full information disclosure by government and industry and fair representation of the diverse range of stakeholders that is often found in energy decision-making processes (Jenkins et al., 2016; Sovacool & Dworkin, 2015).

Applying the concept of energy justice to our energy systems enables us to get an essential understanding of the impact of our energy decision-making on the different layers throughout our society (Jenkins et al., 2016). It surpasses using effectiveness of emission reduction, affordability and reliability as the only measures of the functioning of energy systems but also includes the distribution of the benefits and costs the system. As a conceptual tool energy justice is a reminder that energy systems cannot only be seen through a lens of economic competitiveness, technological efficiency or national security but also very much as a matter of social inequality (Jenkins et al., 2018).

2.2. Implications for energy justice in a transition towards renewables

As the renewable energy transition has gotten more urgent in recent years due to worsening effects of climate change, the concept of energy justice is getting more often applied to the transition away from a carbon intensive energy system towards a low-carbon energy system (Carley & Konisky, 2020; Heffron, 2022; Sovacool et al., 2019). Besides being just a transition of technological change, the renewable energy transition is also an opportunity to reshape the institutions of the energy system to be more fair and equitable (Heffron, 2022).

The negative externalities of renewable energy facilities, infrastructure or other land-use are, as is the same case with fossil fuel equivalents, not equally distributed across society. Examples of local burdens experienced due to renewable energy transitions are noise and noise pollution from newly installed wind turbines in mainly rural areas (Carley & Konisky, 2020). Even though many of negative externalities inflicted by renewable energy production are less harmful than those inflicted through the production of energy through fossil-fuel based resources, these externalities do exist. These effects, on the other hand, in part replace the negative effects experienced through mining of fossil fuels and operations of the fossil fuel plants. Rather than only creating new burdens, there is a shift of burdens generated.

Opportunities to participate in the energy transition are everything but equally accessible for all socioeconomic groups of society. To take advantage of the potential benefits of participating in the energy transition, one must of course have access to opportunities that are part of this transition. The hurdles that exist to take part, can be so significant that certain socioeconomic groups are currently left out of the transition. This causes the access to energy transition opportunities to be unevenly spread across populations, as well as socioeconomic groups (Carley & Konisky, 2020).

There is ample evidence in research that opportunities that support the energy transition are to a large part only seized by higher income households. Research by Mullen & Marsden (2016) has shown that policy options pursued in the UK allocate financial resources for the adoption of low-emission vehicles to the relatively more wealthy households. Similarly, low-carbon heating technologies in the UK such as heat pumps or insulation often require significant upfront capital investments, making it much more difficult to adapt these types of technologies for low-income households or households that do not have ownership of their homes (Sovacool et al., 2019b). And in similar fashion does the adoption rate of residential solar photovoltaic systems in the US remain much lower in regions with lower average income and home ownership rates than other more wealthy areas (Kwan, 2012; Sunter, 2019). These examples all demonstrate that the opportunities to access the potential benefits of the energy transition are unequally distributed across socioeconomic groups. In other words, the lack of ability for certain socioeconomic groups to seize the benefits of the energy transition can be described as a lack of access to the energy transition.

2.3. Energy justice in a transition towards solar photovoltaics

Whereas the lack the of access to the energy transition applies to many new energy efficient technologies, the focus of this research is solar PV in particular. This section first zooms in on the justice implications for a transition towards solar energy, and then reviews literature relevant to how access to solar energy can be defined.

2.3.1. Justice implications of transition towards solar energy

Solar energy is one of the fastest growing sources of low-carbon electricity and has the potential to become the largest source of renewable energy of the future global energy system (Sovacool et al., 2022b). Solar photovoltaics has multiple advantageous characteristics that make it very suitable to be part of a future resilient and sustainable energy system. These are high system reliability, low cost of operation and maintenance, free source of energy, high availability, generation close to consumption, environmentally friendly, absence of noise pollution and continuous decline of solar PV and battery systems (Breyer et al., 2017; Sampaio et al., 2017).

But although solar photovoltaics offers great potential for contributing to the energy transition, when principles of energy justice are not comprehensively considered the benefits of residential adoption of solar photovoltaic resources are minimized. Sovacool et al. (2022b) listed justice concerns adherent to a transition towards solar energy along different dimensions such as demographic, spatial, interspecies and temporal inequity (see table 2.2). By applying a multidimensional, whole-systems energy justice framework the research tries to assess all instances of inequity in the varying dimensions.

Tab. 2.2. Justice concerns for transition to solar PV along different dimensions (Sovacool et al., 2022b)

Demographic inequity	Spatial inequity	Interspecies inequity	Temporal inequity
Adoption may be strongly mandated by gender roles	Perpetuation of a decarbonization divide between Global North and Global South	Building infrastructure	Failing to address the underlying causes of unsustainable practices
Diffusion patterns substantially shaped by class, income or wealth	Cross subsidization of energy costs that burden the poor	Electronic waste streams	The generation of toxic waste streams for future generations
Exclusion of non-homeowners or those without access to roofs	Exploitative labor practices	Solid waste streams or waste incineration	Rebounds in increased driving, energy consumption or resource use
Subsidies favoring wealthier households	Bias towards urban, wealthier areas	Environmental destruction through mineral extraction	Depletion of resources available for future generations
Dependence on education, training or digital skills and awareness			

Although the equity concerns listed in table 2.2, that can arise from a transition to solar PV are serious, they do of course not mean that a transition to solar PV is completely undesirable. Many of the concerns listed in table 2.2 are equally relevant, if not more, for a carbon intensive energy system. But it is crucial to be aware of the potential injustices that may arise, or that already happen in the transition towards solar PV, in order to be able to resolve them.

Although a whole-systems approach as applied by Sovacool et al. (2022b) is desirable to account for all justice concerns of the transition to solar PV, some of the dimensions such as interspecies inequity and temporal inequity are outside the scope of this research. Nevertheless, exploring the remaining dimensions of demographic inequity and spatial inequity of the transition to solar energy is still very much worth pursuing as there is a need for better understanding on how differences in socioeconomic groups influence accessibility to solar PV (Bouzarovski & Simcock, 2017).

2.3.2. Accessibility to solar energy

To be able to assess access to solar PV across different socioeconomic groups in the urban environment, a clear understanding must be established on the concept of accessibility. Multiple definitions of the concept accessibility exist in literature, also depending on the context in which the term is used. Definitions vary from “the capability of a physical location being reached” (Ingram, 1970), “the possibility to take part in something” (Iwarsson and Stahl, 2009) and probably the most frequently used definition of all: “the potential of opportunities for interaction” (Hansen, 1959). Although each of these definitions capture the meaning of the term accessibility in their own respect, they do not fully reflect the meaning of the term accessibility in the context of solar energy.

In literature, the relation between the terms solar energy and accessibility is usually understood in the way in which housing morphology is suitable for the incoming solar radiation (Lee et al., 2016; Lobaccaro et al., 2017). This addresses factors such as floor area ratio (FAR), number of story’s or other factors regarding the typology of buildings. This however, does not address in any way social factors that are of influence to whether households have access to solar PV. This research applies a very different interpretation to access to solar PV, which does not focus on technical parameters but focuses on socioeconomic and sociodemographic factors that determine to what extent households have access to solar PV energy.

As mentioned in the introduction, Burns (1980) defined accessibility as: "the freedom of individuals to decide whether or not to participate in different activities." This definition of accessibility can be used to interpret access to solar PV. High access to solar PV would mean individuals or households are very free in their decision to either adopt solar PV systems or not, while low access to solar PV would imply households are constrained to a large extent by one or multiple factors to adopt solar PV systems. When interpreting accessibility along the lines of Burns (1980), this results in a definition for *access to solar PV* as: 'the freedom of individuals or households to decide whether or not to adopt residential solar PV energy resources, dependent on the existence of one or more barriers.'

Because the decision to adopt solar PV systems is a complex sociotechnical process dependent on multiple factors, there are various barriers that have the potential to limit one's freedom to adopt solar PV systems. To improve the understanding of the accessibility to solar energy, better insight is needed in which factors are perceived or experienced as barriers impeding one's freedom to adopt solar PV. The next paragraph will provide a review of the literature relevant to the adoption of solar PV.

2.3.3. Theories on solar PV adoption

Throughout recent years the body of literature covering the adoption of solar PV has significantly expanded (Schulte et al., 2022). With the maturation of the technology, solar PV outgrew its status of being a niche technology into becoming a very promising, large-scale commercially produced product (Sovacool et al., 2022b). This development has led to adoption patterns of solar PV being researched extensively (Schulte et al., 2022). Since the success of solar PV energy largely depends on the ability and willingness of households to invest in and adopt these systems (Geels et al., 2018; Hesselink & Chappin, 2019), understanding what factors influence this is essential to being able to effectively stimulate the adoption of the technology.

The literature on the adoption of residential solar PV systems is approached from various perspectives and thus many different behavioral theories have been applied in research. 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 (Labay & Kinnear, 1981). The Value-Belief-Norm Theory (VBN) approaches the adoption of solar PV as a decision rooted mainly in environmental awareness and concern (Stern, 2000). And when approaching the decision to adopt solar PV as a form of consumer behavior, the Theory of Planned Behavior (TPB) is applicable (Schulte et al., 2022).

This research uses the Theory of Planned Behavior (TPB) as a basis to adopt and slightly adjust a framework used to assess the level of access to solar PV. The Theory of Planned Behavior is a commonly applied framework for the analysis of consumer adoption patterns, including the analysis of energy efficient technology adoption (Wolske et al., 2017). The DOI theory is considered less appropriate, as this theory is more applicable to technologies that are still in their infant stages of development, which solar PV is not as it has matured throughout the last decades. The VBN is not applied in this research, as it has a strong focus on attitudinal motives but leaves out practical barriers, which are an important part in this research to assess access to solar PV.

The Theory of Planned Behavior states that intentions to perform behaviors of different kinds can be predicted with considerable accuracy by the combination of three elements. These are the attitudes toward the behavior, subjective norms, and perceived behavioral control (Ajzen, 1991). Wolske et al. (2017) describes these three elements as:

1. *Attitude: one's attitude toward the behavior*; the attitude toward the behavior is formed by beliefs about the consequences of a behavior and the likelihood of those consequences occurring.
2. *Social norms: perceived social pressure to do the behavior*; in other words the expected perceived approval or disapproval of others when performing the behavior.
3. *Behavioral control: an assessment of one's ability to perform the behavior*; within this assessment a distinction is to be made within the perceived ability and the actual ability to perform a behavior. These two factors differ when someone thinks it is more difficult to perform a behavior, than what in reality is the case. This has influence on the intention to perform the behavior. The difference between perceived ability and actual ability is dependent on how well someone is capable of judging his or her ability to perform a behavior.

Sundaram (2021) illustrates the application of this theory to solar PV when evaluating the role of social networks in residential PV adoption. This is shown in figure 2.2.

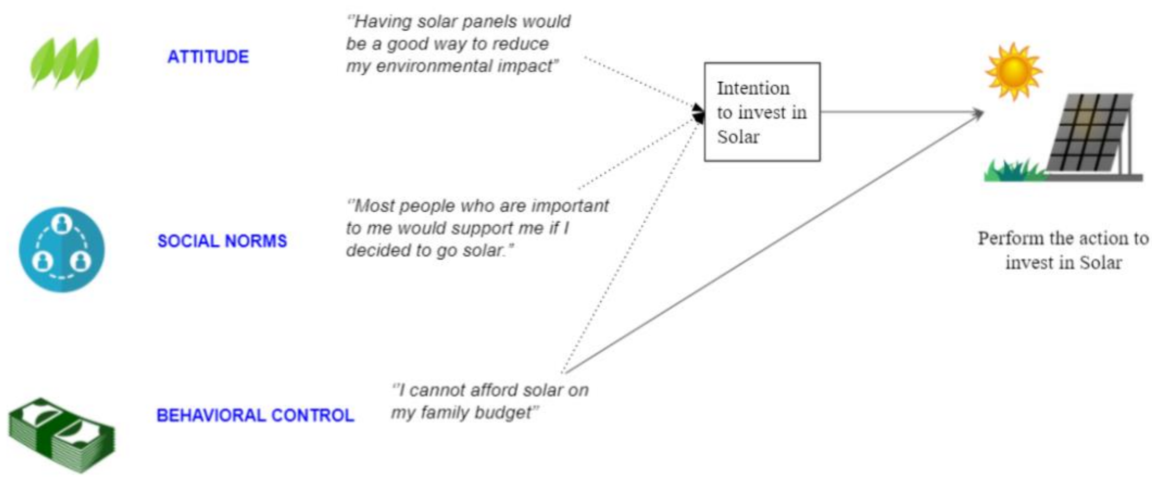

Fig. 2.2. TPB applied to solar PV adoption (Sundaram, 2021)

3. Research design

In this the chapter the design of this research will be presented. First, the concept of access to solar PV will be defined and explored leading to the construction of an access to solar framework. This framework forms the basis for the assessment of the spatial distribution of access to solar PV throughout the case used in this study. Then, a separate analysis will be performed to evaluate the technical rooftop PV potential. And lastly, the insights of the these analyses combined will allow this research to answer its main research question. Figure 3.1 illustrates how the research design relates to the research questions posed in chapter 1.

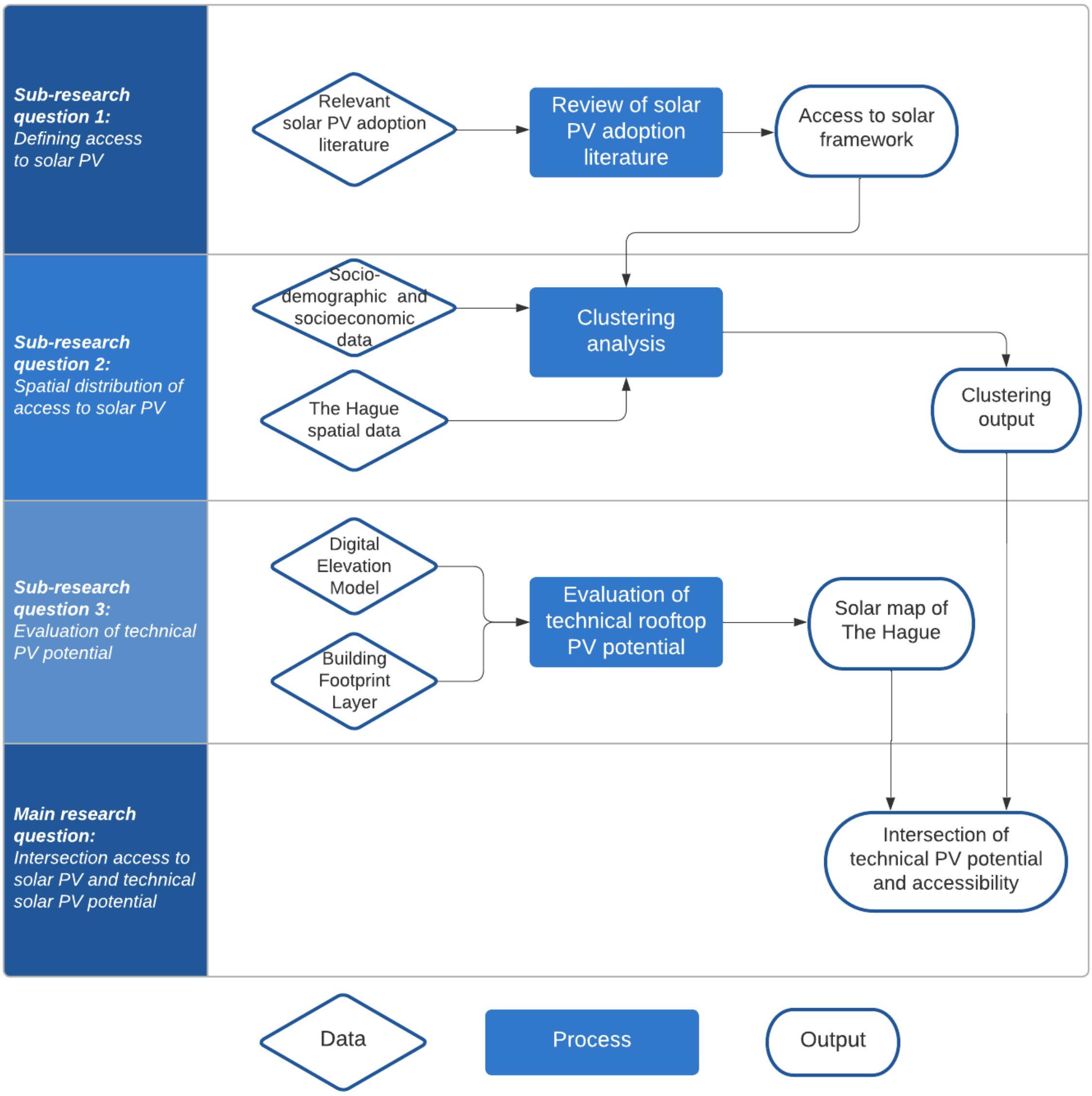

Fig. 3.1. High-level overview of research design.

The first section of this chapter, section 3.1, sheds lights onto how accessibility to solar PV relates to solar PV potential and how solar PV potential can be interpreted in different ways. Then, in section 3.2, the access to solar PV framework will be presented. Section 3.3 presents the methods used for the socio-spatial analysis that will be applied to get insight into the spatial distribution of access to solar PV. Section 3.4 elaborates on the method used to evaluate the distribution of technical PV potential within the case used. And lastly, section 3.5 provides more contextual information about the case that is used in this research, which is the city of The Hague.

3.1. Conceptual overview

Various different types of solar PV potential exist. This section will elaborate on these different types and will comment on how the concept of accessibility to solar PV relates to the broader concept solar PV potential.

3.1.1. Different types of solar PV potential

When analyzing solar PV potential, it is important to be aware of the type of potential that is being analyzed. Hoogwijk (2004) defined the potential of solar PV using a hierarchical approach consisting of five categories. These categories in hierarchical order from high to low are: (1) theoretical potential: the yearly solar energy irradiated to the surface of the earth (kWh/year), (2) geographical potential: the yearly irradiance integrated over the terrestrial surface suitable for the installation of PV systems based on geographical constraints (kWh/year), (3) technical potential: the geographical potential reduced by losses associated with the conversion from solar to electrical power (kWh/year), (4) economic potential: the technical potential restricted to electricity that can be generated in a commercially viable way, compared to the available alternatives (kWh/year) and lastly (5) implementation potential: the maximum amount of economic potential that can be implemented within a certain timeframe taking constraints and incentives into account (kWh/year). A conceptual figure of this hierarchical structure is shown in figure 3.2.

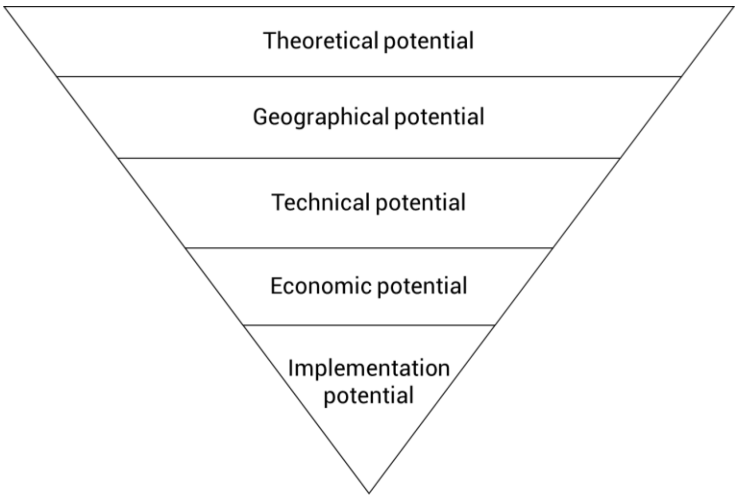

Fig. 3.2. Conceptual visualization of hierarchical structure of different levels of solar PV potential. While going down each level a bit of solar potential is lost, due to additional constraints.

Izquierdo et al. (2008) suggested to add the level of social potential to assure a more complete assessment of the deployment prospects of solar PV. The study suggests that to fully encapsulate PV potential social factors should too be taken into account besides the geographical and technical factors of solar PV potential. Schunder et al. (2020) and Kwan (2012) do this in their studies on solar PV potential. Although they do not provide a clear definition of social PV potential, these studies are just a few on many studies that provide evidence that levels of residential solar PV adoption are dependent on certain socioeconomic characteristics. Figure 3.3 provides an illustration of the different types of PV potential mentioned by Hoogwijk (2004) and highlights how social PV potential is related to other types of potential.

Fig. 3.3. Representation of different types of solar PV potential in reality. Theoretical potential refers to the level of solar irradiation towards earth. Geographical potential refers to places where this theoretical potential can be viably captured (rooftops eg.). Technical potential takes into account efficiency of solar panels. Ecocnomic potential includes only the potential that can also be ecnomically efficiently generated. Implementation potential refers to the fact that this should be done within realistic timesframes. And lastly, social potential refers to the people that live in these houses and their access to solar PV.

3.1.2. How does accessibility to solar PV relate to PV potential?

As many studies have shown, socioeconomic characteristics of households influence the decision to adopt solar PV systems by households (Kwan, 2012; De Groote et al., 2015; Schunder et al., 2020). It is important to acknowledge that households in areas with certain socioeconomic characteristics are more beneficially positioned for the adoption of solar PV systems than others, regardless of the level of geographical and technical PV potential. This concept is what Izquierdo et al. (2008) referred to as the social PV potential. This is the same concept as what this research refers to as accessibility to solar PV, which in this research is defined as '*the freedom of individuals or households to decide whether or not to adopt residential solar PV energy resources, dependent on the existence of one or more barriers*. By including the concept of accessibility to solar PV when assessing solar PV potential one does not only consider technical and environmental factors, but also socioeconomic factors that play a role in the ability of households to adopt solar PV.

3.2. Access to solar framework

This section presents the *access to solar PV* framework. Firstly, it explains the theory which forms the basis for the framework. And secondly, it elaborates on the factors that have been included in the framework. The design of the framework results in the answer to the first sub-research question of this research.

3.2.1. Theory

Using the Theory of Planned Behavior as portrayed in figure 2.2 as a basis, an adjusted framework is adopted to explain what factors are of importance when assessing access to solar and how this relates to the eventual decision to adopt solar PV. This is shown in figure 3.4.

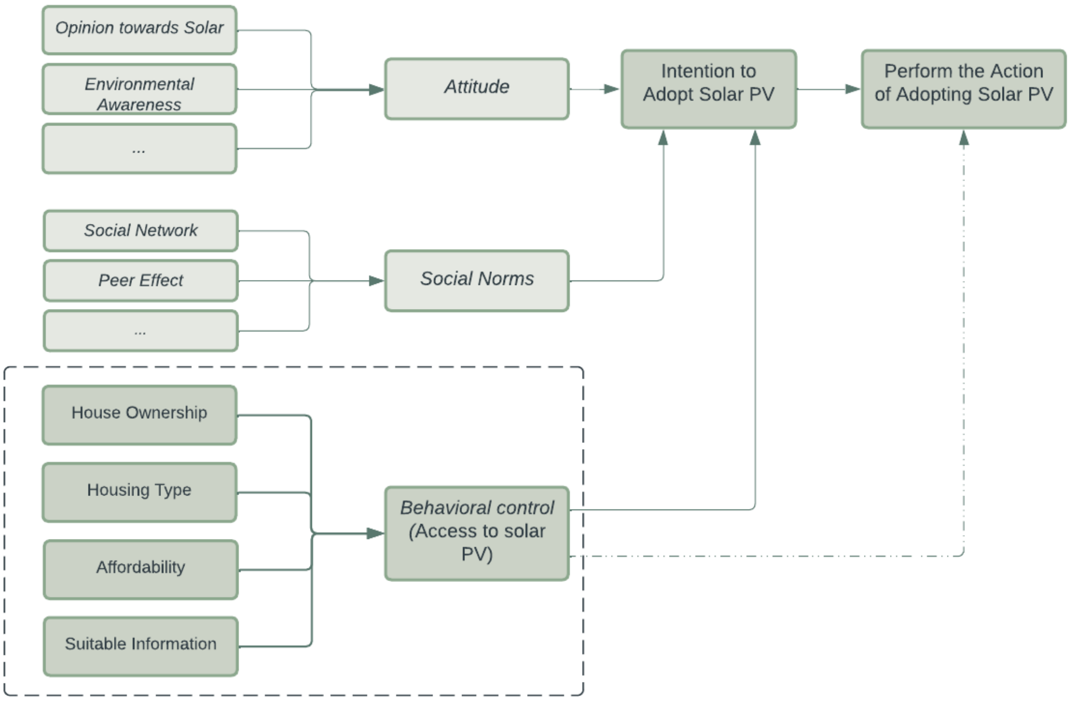

Fig. 3.4. Access to solar PV framework

Figure 3.4 presents the access to solar framework which is grounded in the Theory of Planned Behavior (TPB). In line with the TPB, the framework consists of the three elements *attitude, social norms* & *behavioral control.* The element *attitude* is shaped by one's attitude toward the behavior. One could for instance dislike the aesthetics of solar panels on their house and therefore have no intention to adopt solar PV. Or one does not value their environmental footprint, and thus has less intention to adopt solar PV. The fact however that one person is more likely to adopt solar PV because of increased environmental awareness, does not make solar PV more or less accessible to that person. The boxes containing an ellipsis mean these lists are not exhaustive.

The element *social norms* is formed by perceived social pressure to do the behavior. For example, one might be expected to install solar PV to be part of a certain social class or network. Or one might feel social pressure due to their direct surroundings all having installed solar panels.

Lastly, the element behavioral control is shaped by one's (perceived) ability to perform the behavior. The element behavioral control is what this research defines to be the equivalent of *access to solar PV.* This is done on the notion that the definition by Ajzen (1991) of behavioral control in the TPB– *one's ability to perform the behavior* – is arguably similar to the definition of accessibility by Burns (1980) – *the freedom of individuals to decide whether or not to participate in different activities*. Even though these two definitions are not identical, they do demonstrate similarities. One's freedom to decide, in this case is interpreted as one's ability to perform, and participating in different activities is interpreted as performing the behavior.

Access to solar PV is thus interpreted as the equivalent of the element *behavioral control* within the Theory of Planned Behavior. It is the factors, or barriers, that influence this level of behavioral control that define whether someone has access to solar PV. In the next section the factors influencing access to solar PV are discussed. These are the four elements within the checkered box in figure 3.4 that are related to access to solar PV.

3.2.2. Factors

In literature an enormous variety of factors is found influencing the decision to adopt solar PV. Since not all studies apply the TPB, these factors are not all classified as affecting either one of the three elements of the TPB. And the factors are operationalized into many different variables or predictors. According to Alipour et al. (2020) an aggregate of 333 predictors could be distilled when analyzing a large number of papers concerning the residential adoption of solar systems. As is pointed out by Schulte et al. (2022), even though many of these predictors are just a different operationalization of the same factor, still a large number of predictors remain that possibly have an effect on the decision to adopt solar PV systems. Little consensus exists on what factors most strongly influence the adoption of residential solar PV.

There are multiple causes that to some extent explain why little consensus is found in an large body of literature. Firstly, as mentioned, the operationalization of factors varies significantly throughout many of the different studies regarding the adoption of residential solar PV. Due to the lack of consistent operationalization of factors no comprehensive set of predictors has developed throughout the years in literature (Schulte et al., 2022). Secondly, much of the research done has been performed in very different contextual environments. These contextual environments are determined by factors such as the geographical area of interest of the research, the year in which the research was performed and the active policy scheme at that time. Due to a lack of reporting of the contextual environments of the different studies, it is impossible to correctly compare and aggregate the outcomes of these studies (Schulte et al., 2022). As a consequence of this, even though a large body of literature exists, there still is surprisingly little consensus on which factors are most important determining the decision to adopt residential solar PV.

As illustrated in figure 3.4, not all factors influencing the decision to adopt solar PV are part of the level of access to solar PV. For example, the level of environmental awareness is in some studies found to be a factor significantly influencing solar PV adoption (Kwan, 2012; De Groote et al., 2016), but it does not influence the level of access a household or person has to solar PV resources. At least, not according to the framework adopted in this research. The reasoning of which factors do influence the degree of *access to solar PV* (*behavioral control*) is one of qualitative nature rather than solely statistical, and will be explained in the following paragraph.

To identify factors that influence *access to solar PV* a subset of literature is reviewed that studies the barriers that are most commonly experienced when deciding whether or not to adopt solar PV. These barriers are assumed to limit one's ability to adopt solar PV, and thus are assumed to limit one's behavioral control. Table 3.1 lists the set of papers that have been selected, and the barriers they address.

Tab. 3.1. Studies that identify of barriers to solar PV adoption.

Authors	Scope	Barriers
Karakaya & Sriwannawit (2015)	Global	High cost, insufficient and ineffective policy support, lack of adequate knowledge, physical limitation
Rai & Robinson (2015)	Global	High system cost
Vasseur & Kemp (2015)	The Netherlands	Investment cost, not a home owner, energy yield too low, fear of gaining promised efficiency, living in apartment
Rai et al. (2016)	Northern Californa, USA	System cost, informational barriers, concern about operation
Walters et al. (2018)	Santiago, Chile	High system cost, incomplete information, technical unfeasibility, lack of institutional support
Hesselink & Chappin (2019)	Global	Split incentevies, uncertainty about investment, high investment cost, insufficient information to make investment decision, transaction costs, bounded rationality
Zander (2020)	Australia	High costs, energy not available when needed, lack of insitutional support, split incentives, fear of maintainance, too much hassle to coordinate with landlord or other parties
Schulte et al. (2022)	Global	High investment cost, high perceived risk of investment, technical unfeasbility, non homeownership
Alipour et al. (2022)	Global	No interest, too high system cost, knowledge deficit, house not physically suitable

From the above listed papers the following factors have been identified to influence the level of access to solar PV. These factors will later be operationalized into measurable variables.

1. Affordability

The affordability of solar PV is often cited as the main barrier to adopt solar PV (Rai & Robinson, 2015). All of the studies listed above name high investment cost as one of the main barriers to solar PV adoption. Even though the costs of solar PV have gone down throughout recent years (Sampaio et al., 2017), it still requires a significant initial investment to purchase solar PV. Households that do not have access to this amount of capital, automatically have less access to the technology. Therefore affordability is one of key barriers in this research assumed to influence access to solar PV.

2. Home Ownership

Home ownership is of significant importance for people to have access to solar energy. Home ownership, or non-homeownership is frequently mentioned throughout the studies as a barrier to solar PV adoption (Vasseur & Kemp, 2015; Hesselink & Chappin, 2019; Zander, 2020; Schulte et al. 2022). There are multiple reasons for why this is the case. Firstly, there is of course the legal inhibition to install solar PV systems on a property that you 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.

Secondly, and more relevant, it has been proven to be very hard to align the interests of both the renters and the house owners to enable both to benefit from the installation of solar PV systems, also referred to as split incentives (Hesselink & Chappin, 2019). As a renter, one does not benefit from the increase in property value that results from the installation of solar PV, making the initial investment much less attractive. As a homeowner on the other hand, there is 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 there is evidence that there is high willingness among renters to adopt solar PV (Vasseur & Kemp, 2015).

3. Housing Type

Housing type is of importance for the obvious reason that not all types of housing are equipped with a roof that is directly exposed to the sun. In The Netherlands 16% of all households are estimated to live in apartment buildings (CBS, 2016). Technical unfeasibility, or any other equivalent to this such physically unsuitable/live in apartment building/physical limitation, is often listed as an important barrier to PV adoption (Kirikaya & Sriwannawit; 2015, Vasseur & Kemp, 2015; Walters et al., 2018; Zander, 2020; Schulte et al., 2022; Alipour et al., 2022) For these households, even though they are homeowners, adoption of solar PV is much more difficult as they are not sole owner of the roof. The process of solar PV adoption for this group is therefore much harder, making solar PV less accessible to this group. Zander (2020) explicitly mentions that it is often experienced as too much hassle to coordinate with other unit parties within the apartment building.

4. Suitable Information

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 and credible information is available (Chappin & Hesselink, 2019). As the decision to adopt solar PV involves, what many would consider large sums of money, it is important people feel entirely confident with their decision. This also includes the information regarding mechanisms of support that exist to install solar PV. Lack of inadequate information is frequently mentioned as a key barrier to solar PV adoption (Karakaya & Sriwannawit 2015, Rai et al., 2016, Walters et al., 2018; Hesselink & Chappin, 2019; Alipour et al., 2022). This information barrier is even higher, for socioeconomic groups that are not native and for which a language barrier exists (Karakaya & Sriwannawit, 2015).

These factors are identified as the main factors influencing access to solar PV. They will be operationalized in the next chapter of the research. It is clear that this list could be extended to include many more factors, as certain very specific barriers might apply to particular contexts. The barriers identified in the framework above, however, are what this research assumes to be the key barriers to solar PV adoption.

As a final note to this section, it should be stressed that it is important to note that the concepts of *access to solar energy* and the *adoption of residential solar PV* are two different concepts. A household can have excellent access to solar energy but still decide not adopt solar PV systems, due to various other motives. This study thus assumes that the variables that influence the different levels of adoption in certain areas can be explained by the different degrees of access to solar energy, but it does understand that even households with high access to solar energy can still opt to not adopt solar PV systems. In other words, the decision to adopt solar PV systems is not all based on the level of access to solar energy, but the level of access is assumed contribute to the decision to adopt solar PV.

3.3. Socio-spatial analysis

Through the framework presented in the previous section critical factors influencing access to solar PV have been identified. In order to evaluate how access to solar PV is spatially distributed across the urban environment (sub-research question 2) the factors identified in the access to solar framework will have to be operationalized into measurable variables. This section involves the operationalization of the access to solar framework.

3.3.1. Operationalization of *access to solar framework*

The operationalization of the factors listed in the access to solar framework is important in order to translate the factors into measurable variables. The choice of operationalization is too a large extent dependent on data-availability. The factors identified in the access to solar framework are operationalized as follows:

Percentage of owner-occupied homes

This is the percentage of homes that is occupied by the owner him of herself in a neighborhood relative to the total amount of homes in that neighborhood. This construct is easy to convert into a measurable indicator, as data is available on the *% of owner-occupied homes per neighborhood*, making this construct easily measurable.

Percentage of apartment buildings

This is the percentage of total housing stock of a neighborhood that is characterized as apartment buildings relative to the total housing stock in that neighborhood. The concept of housing type is measured as the *% percentage of apartment buildings* in a given neighborhood. This indicator is chosen because when assessing housing type, the essential factor is whether a household has access to its own roof or whether multiple households share a roof, which is the case for apartment buildings in an apartment block. Therefore the *% of apartment buildings per neighborhood* is chosen as a measure for the construct housing type.

Percentage of Dutch natives

This is the percentage of residents in a neighborhood that have no migration background compared to the total amount of residents per neighborhood. This number is used as a proxy for access to information. Since much of the necessary information is unavailable in the native language of people with foreign backgrounds, it is assumed that their access to information is more limited compared to Dutch natives. Dutch natives thus are assumed to easier gain access to adequate information regarding the installation of solar PV. This is supported through research by Karakaya & Sriwannawit (2015) confirming the existence of higher information barriers for non-native socioeconomic groups.

Average yearly household income

The average yearly household income per neighborhood is used as a measure for affordability of solar PV. It’s assumed that solar PV is more affordable for households with a higher average household income. Average household income is not the only measure for affordability, this could also be dependent on the amount of capital that is already acquired by a household. Though this indicator is chosen for this research as data on savings or capital acquired is not available.

The data required for assessing access to solar PV according the access to solar framework is all provided by a database managed by the municipality of The Hague. The municipality of The Hague maintains an extensive public database called 'Den Haag In Cijfers' that contains data on many sociodemographic and socioeconomic indicators describing the municipality of The Hague. The data in this database is available at neighborhood level, which is the finest level of granularity for which this data is publicly available, due to privacy protection. Table 3.2 lists the factors for which data is collected.

Tab. 3.2. Data collected for K-means clustering analysis.

Data description	Unit	Data source	Date
Percentage owner-occupied homes per neighborhood	%	Den Haag in Cijfers	2022
Percentage of apartment buildings per neighborhood	%	Den Haag in Cijfers	2022
Percentage of Dutch Natives per neighborhood	%	Den Haag in Cijfers	2021
Average household income per neighborhood	€/yr	Den Haag in Cijfers	2021

These indicators are the results of the operationalization of the factors identified to influence access to solar PV in section 3.2. In order to perform the socio-spatial analysis, supplementary data is necessary. The indicators for which extra data is collected are listed in table 3.3.

Tab. 3.3. Supplementary data for K-means clustering analysis.

Data description	Unit	Data source	Date
Number of households per neighborhood	#/nb	Den Haag in Cijfers	2021
Number of residents per neighborhood	#/nb	Den Haag in Cijfers	2021
Number of solar panels per neighborhood	#/nb	Den Haag in Cijfers	2022
Surface area solar panels per neighborhood	m2/nb	Den Haag in Cijfers	2021

Number of households/residents per neighborhood

The number of households and number of residents per neighborhood can for instance be used to normalize the level of access to solar PV per household.

Number of solar panels per neighborhood

This indicator is used as a measure of the degree of solar adoption within a neighborhood. This variable can be used to verify whether the indicators that measure the level of access to solar are reflected in the level of solar PV adoption.

Surface area solar panels per neighborhood

This indicator is used as a measure of the degree of solar adoption within a neighborhood. It can be used to compare the saturation of solar energy within a neighborhood when compared with the total available solar area.

3.3.2. Clustering analysis

The factors that are operationalized into measurable indicators in the section above form the basis for the socio-spatial clustering analysis to spatially evaluate access to solar PV. This section involves the explanation of the type of clustering analysis that is performed as part of the socio-spatial analysis. A clustering analysis is performed to find clusters that are of similar nature based on the cluster input variables. In this case the analysis is performed to investigate which neighborhoods of The Hague, on the basis of the specific input variables discussed in the previous section, form clusters of similar nature. The results of this analysis provide insight into how access to solar PV is spatially distributed throughout The Hague.

3.3.2.1. K-means clustering

To gain insight into the distribution of accessibility to solar energy in the urban environment a K-means clustering analysis is performed. Clustering analyses often involve the sorting of observations into groups without any prior knowledge what these groups are (Rey et al., 2020). By forming groups based on statistical nature without any prior knowledge of what these groups might look like, statistical clustering is considered a form of unsupervised statistical learning. The goal of the clustering analysis is to from groups of which the members are more similar to members internally within their own group than to any member of another group. The groups, that are the output of the analysis, are called clusters. Although clustering analysis is inherently not of spatial nature, they are often applied in geographic data science to discern spatial patterns in complex multivariate spatial data (Rey et al., 2020). In this case the observations used for the clustering analysis represent geographical areas, therefore this analysis is considered to be a form of geodemographic clustering analysis.

K-means clustering is a popular clustering algorithm. The algorithm groups the observations into a pre-specified number of clusters, where each observation is closer to the mean of its own cluster than to the mean of any other cluster that is formed (Rey, Arribas-Bel & Wolf, 2020). As a first step of the algorithm, observations receive one of the pre-specified *k* number of labels (*k* is equivalent to the number of clusters formed). Then, the multivariate mean is calculated for each of the clusters after which all observations are assigned to the cluster nearest to their mean. When the new clusters are formed, the same calculation is repeated until no further changes occur to the formed clusters. Figure 3.5-3.7 show this process for a two-dimensional dataset. In the first figure two centroids (blue and yellow squares) within the dataset are randomly positioned representing two clusters. Every data point is assigned to the cluster corresponding with the nearest centroid.

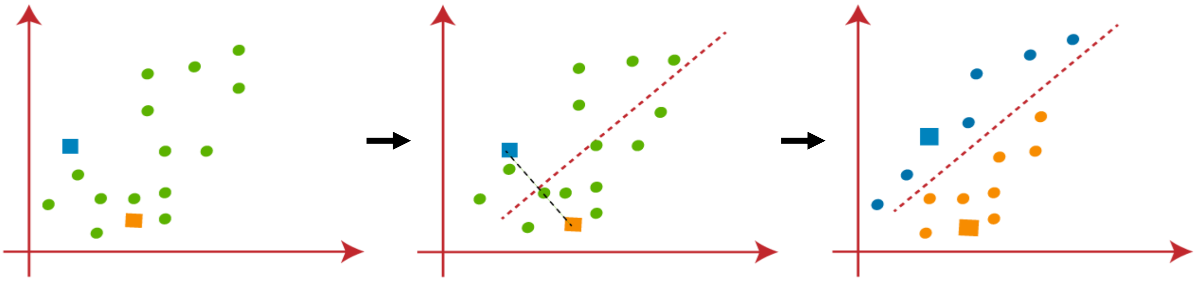

Fig. 3.5. Illustration K-means clustering algorithm (1)

Next, a new centroid is calculated for the two clusters and the data points are reassigned to the clusters corresponding to the centroids nearest to them. This results in two new rearranged clusters.

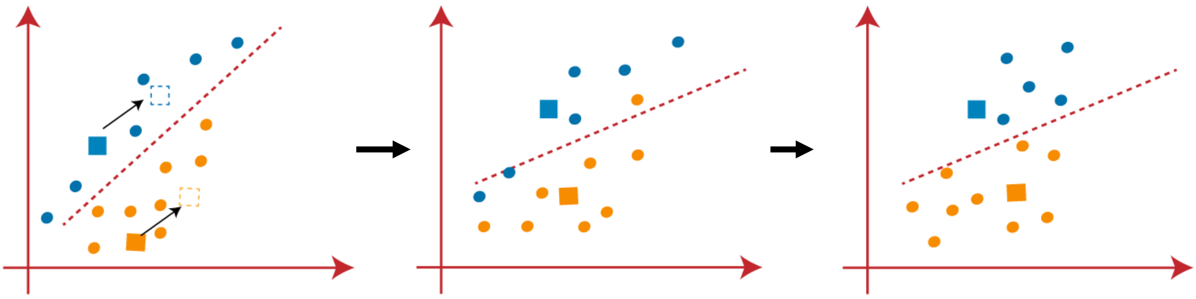

Fig. 3.6. Illustration K-means clustering algorithm (2)

This process is repeated until no further changes occur to the positioning of the centroids and thus the assignment of the observations to the clusters remains the same, see figure 3.7. At this point the algorithm is finished and the results can be interpreted. This process here is illustrated for 2-dimensional data, but can also be performed for multi-dimensional data. Though for the purpose of illustration the example given here is 2-dimensional, as this is of course a lot harder with 4-dimensional data.

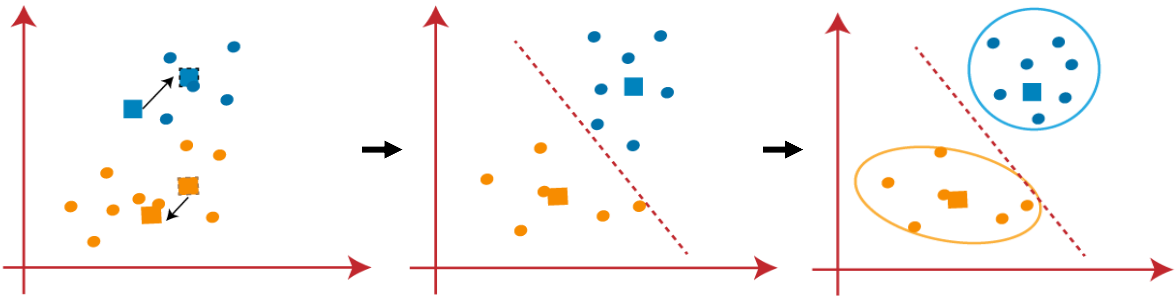

Fig. 3.7. Illustration K-means clustering algorithm (3)

3.3.3. Validation of clustering analysis

In this section the meaningfulness of the results produced by the clustering algorithm is validated. Since the K-means clustering algorithm applied in this research is an unsupervised algorithm, many of the metrics used to check for goodness of fit that are used for supervised algorithms do not apply in this case. An essential parameter for the application of K-means clustering is the value for the parameter *k*. As the output of the clustering analysis is dependent on this pre-specified number of clusters (k), a choice is to be made on the value for *k*. No right number of clusters exists, but different methods exist to find an optimal number of clusters to work with in the analysis.

3.3.3.1. Elbow method

A method that is commonly applied to find an appropriate number of clusters is the Elbow method. In this method the Within-Cluster Sum of Square (WCSS) is calculated for varying number of clusters. The WCSS is the sum of squared distance between each point and the centroid in a cluster (Rey et al., 2020). The WCSS will decrease every time a cluster is added, until it reaches 0 when the level of clusters is set equal to the number of observations. In this case each observation is its own cluster, and the sum of squared distance between each point and the centroid is naturally 0. The optimal number of clusters according to the Elbow method is the number of clusters for which the marginal reduction of WCSS is big enough to be worth adding an extra cluster. By plotting the levels of WCSS, this point can often be recognized as by a knack, also referred to as the elbow point. The elbow plot for the k-means clustering performed in this research is shown in figure 3.8.

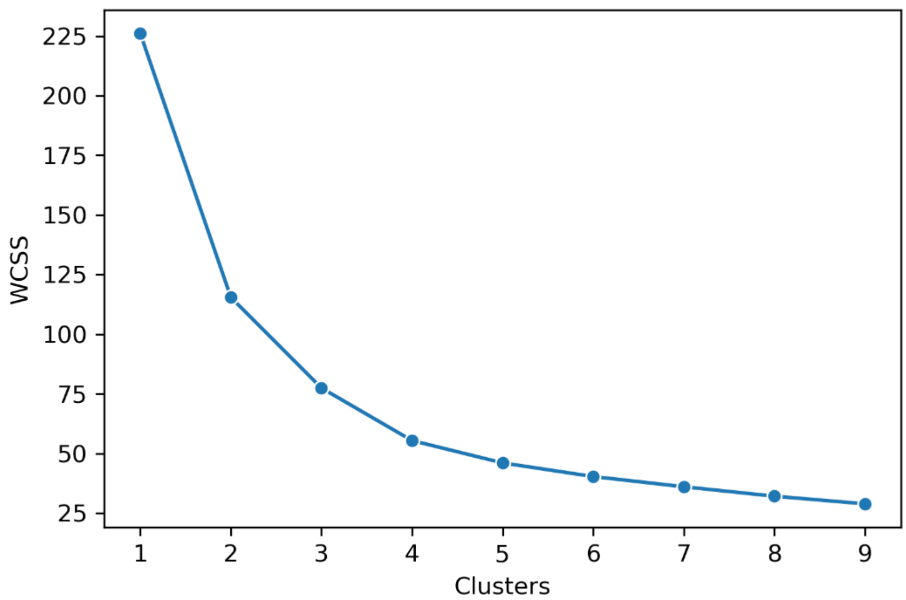

Fig. 3.8. Elbow plot.

It can be argued that through visual inspection, this point is found to be *k=4*. From *k*=3 to *k*=4 clusters, there is a still a rather steep gradient, but from 4 onwards the gradient has more or less flattened. Because there is not one right answer for the value for *k,* multiple interpretations can be drawn from the elbow plot. In this case it is chosen to initially set *k=4,* because it can be seen that from 4 clusters onwards the level of WCSS only marginally decreases and thus the value added of an extra cluster is small.

3.3.3.2. Silhouette coefficient

A second method that is used to validate the outcomes generated by the clustering analysis is the Silhouette coefficient. The Silhouette coefficient, also known as the Silhouette score, is a measure that assesses how well clusters within the model are defined relative to other clusters (Scikit-learn, 2022). The Silhouette coefficient is computed for each of the data points and is determined by two components:

- *a,* the mean distance between a data point and all other points in the same cluster

- *b,* the mean distance between a data point and all other points in the next nearest cluster

The Silhouette coefficient is calculated according to the following equation:

$$s = \frac{b - a}{\max{(a, b)}}$$

A well-defined cluster, is a cluster that has lower distance relative to data points within its clusters and greater distance relative to other clusters. This means that a higher value for *s* implies a better defined cluster. When calculating the value for *s* for all data points, an average Silhouette coefficient can be calculated. The average Silhouette coefficient takes values between -1 and 1; -1 meaning that clustering is likely to be incorrect, 0 meaning that clusters overlap and 1 meaning highly dense clustering. The average Silhouette coefficients for the different number of clusters are plotted in figure 3.9. This shows that the except for *k=2, k=4* has the highest coefficient with a value of 0.421. Thus the Silhouette coefficient too indicates that 4 is the optimal value as input for the clustering algorithm. Even though *k=2* has a higher Silhouette score, it does not provide much insightful information due to the existence of only 2 clusters.

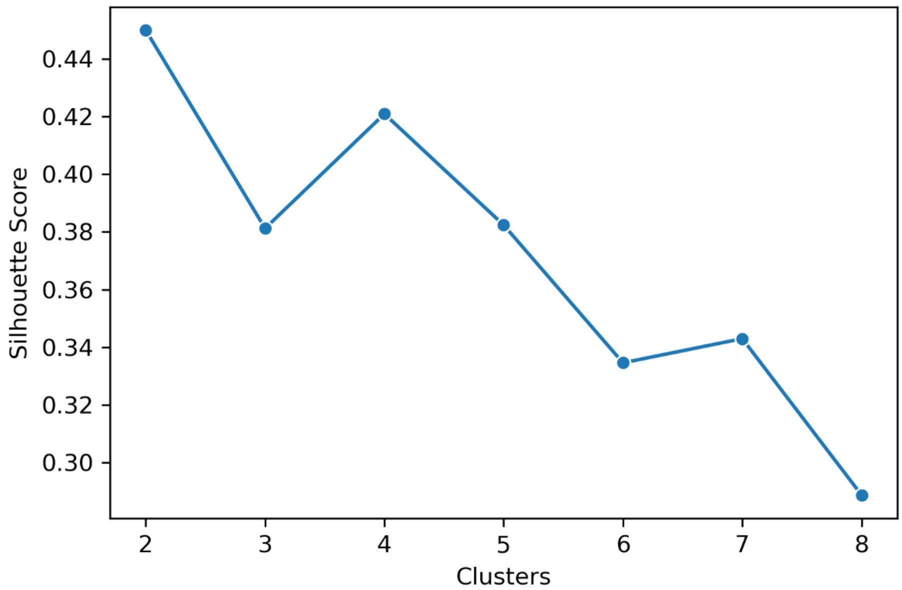

Fig. 3.9. Silhouette plot.

3.4. Model for analysis of PV technical potential

Besides analyzing the spatial distribution of access to solar PV, another crucial part of this research is evaluating the technical PV potential across our case. This section describes the model that is used to evaluate the technical PV potential. Furthermore does it comment on the data that is used and explains the set-up that is chosen when applying the model to the case.

3.4.1. Model description

A variety of models exists that can be used to evaluate technical rooftop PV potential within the urban environment. A way to analyze the solar PV potential of the existing built environment is through the use of solar maps, which are GIS systems providing the annual solar irradiation on building surfaces mostly accompanied by the output of solar thermal or photovoltaic systems (Kanters et al., 2014). Due to the great advancement of information technology, solar mapping models are currently very powerful, allowing user-friendly detailed analysis and representation of radiation phenomena. An emerging trend is the use of these GIS tools for energy analysis in the urban environment (Freitas et al., 2015).

For this research it has been chosen to work with the Area Solar Radiation Tool of the ArcGIS Spatial Analyst. The Area Solar Radiation Tool is a tool than can be used to calculate rooftop PV potential based on a model developed by Fu and Rich (1999), and has most recently been calibrated and validated by Kausika & Van Sark (2021). The model calculates the total amount of insolent solar radiation for a particular area by summing the total amount of direct, diffuse and reflected irradiation. This is illustrated in figure 3.10. 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 areas. Because of this, the Area Solar Radiation Tool only considers direct and reflected radiation (ArcGIS, n.d.).

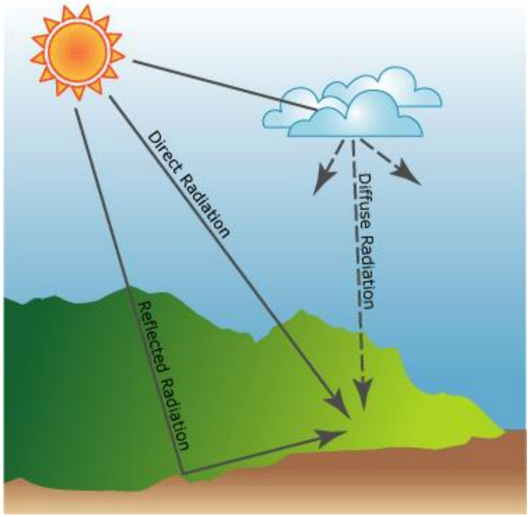

Fig. 3.10. Overview of radiation types (ArcGIS, n.d.)

A detailed analysis of the process involved to evaluate the rooftop technical PV potential across the city of The Hague is shown in Appendix A.

3.4.2. Data sources

The necessary data for this evaluation is gathered from multiple sources in order to answer the set research questions. Table 3.4 shows the different datasets that are used for the evaluation of the technical rooftop PV potential.

Tab. 3.4. Data used for evaluation technical PV potential.

Data description	Data source	Date
Digital Elevation Model (DEM)	Actueel Hoogtebestand Nederland	2019
Building footprint layer	Basisregistratie Adressen Gebouwen (BAG)	2022
Building footprint layer social housing corporations The Hague	Den Haag Data Platform	2022
Building footprint layer owners associations The Hague	Den Haag Data Platform	2022

The evaluation of the technical rooftop PV potential requires two main sources of data input. 1) A Digital Elevation Model (DEM), which is a model in the form of a map that stores information on the elevation of each point on the map of the city of The Hague. This data can be used to generate a hemispherical viewshed. And can later also be used to calculate the slope of an area, the orientation and the blocking of solar radiation through other objects. The DEM has a resolution of 10-24 datapoints per m^2, which is sufficient to perform valid evaluation of the incoming solar radiation (Kausika et al., 2017). Figure 3.11 shows the DEM outlined by the borders of the municipality of The Hague. To illustrate the difference in height, pixels that have a more dark grey color have lower elevation than pixels with a more light grey color. To illustrate this 3D effect a figure with hill shade effect is added to appendix B, in order to more adequately notice the 3D effect that's present.

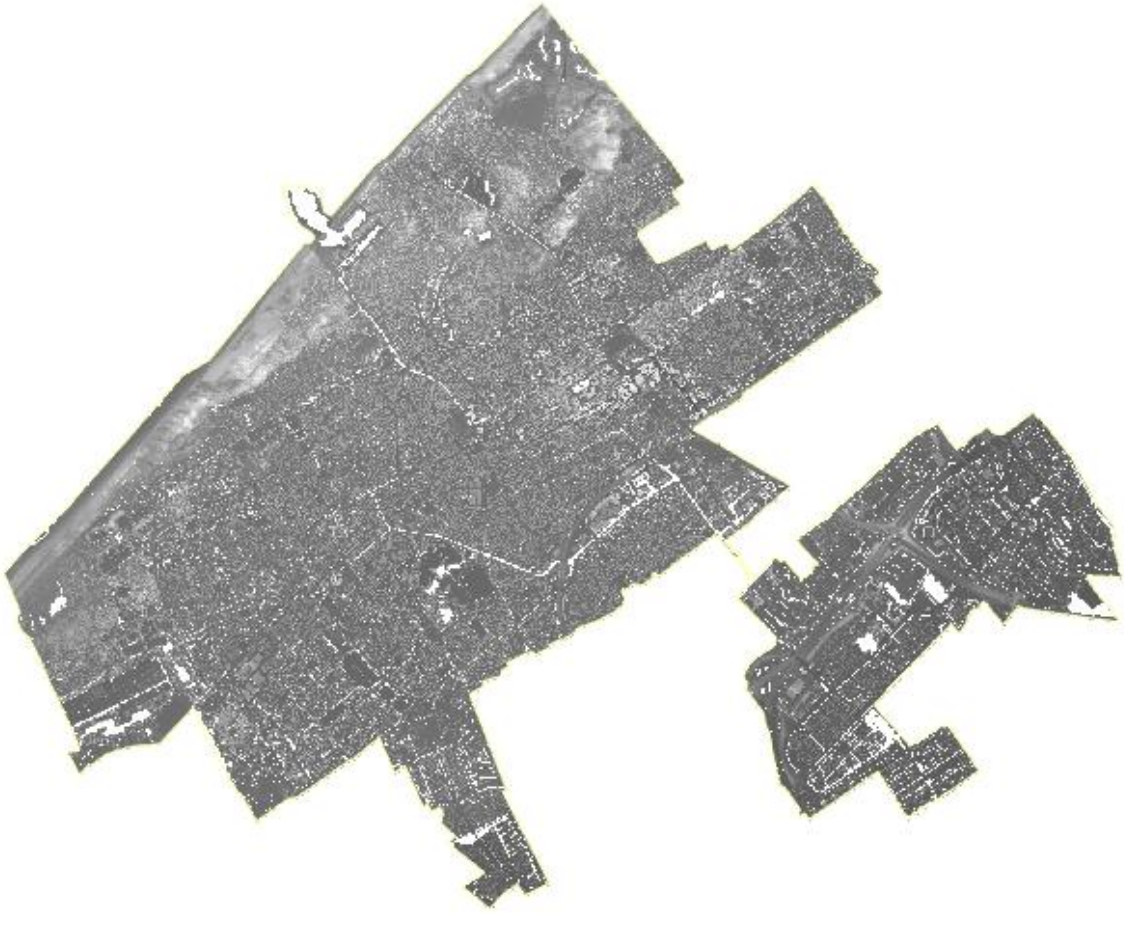

Fig. 3.11. DEM of The Hague municipality.

2) A building footprint layer is added on top of the DEM. This is done in order to differentiate rooftop area from any other type of area, which is essential calculate only the solar PV potential of the areas of interest. Figure 3.12 illustrates the delineation of the rooftop areas when the two data layers are positioned on top each other zoomed in on the neighborhood Willemspark, The Hague. The building footprint layer is represented in yellow to demarcate all separately registered buildings.

Fig. 3.12. DEM of neighborhood Willemspark including building footprint layer represented in yellow.

3.4.3. Model application

As mentioned in the previous section, the model takes a digital elevation model (DEM) in combination with a building footprint layer as main input in order to calculate the solar irradiance and produce an output image in Wh/m^2. Before starting the calculation of incident solar radiation, certain parameters have to be set. These include time configuration, time interval and number of calculation directions. The time configuration is set to 1 year, so the model calculates throughout the time period of one entire year. The time interval is set to 1, so the model calculates the solar radiation once every hour. And the number of calculations directions is set to 16, reduced from a default value of 32. This is done to reduce the computation time. Even though this reduces the accuracy of the calculation, this is not problematic because the results will later be aggregated on a neighborhood scale. When evaluating the incident solar radiation of a single building however, this would not have been desirable.

After the calculation has been performed, a sub selection is made to filter out all areas that are not suitable for the installation of solar PV. Areas can be unsuitable for the installation of solar panels because of multiple reasons. These are:

1) area is too steep for solar panels to be able to be mounted.
2) area does not receive enough solar radiation to reach a minimum radiation threshold.
3) area is north facing (as a consequence will not meet radiation threshold)
4) area on a roof that is too small to install solar panels

Based on these variables a sub selection of all calculated area is made. Only the areas that fulfill all of these requirements remain in the final resulting solar map. The conditions set for these variables are displayed in table 3.5 (ArcGIS, n.d.).

Tab. 3.5. Conditions for the evaluation of rooftops suitable for solar PV (Environmental Protection Agency).

Condition	Value
Maximum rooftop slope	45°
Minimum level of solar insolation	800 kWh/m^2
Azimuth value x	22.5° < x < 337.5°
Minimum rooftop size	25 m^2

When applying these conditions to the solar radiation map, only the rooftops remain that are considered suitable for the installation of solar PV. This results in a map with the incident solar radiation of all suitable rooftops for solar PV of The Hague. The detailed outcomes of this process are presented in appendix A.

To convert incident solar radiation to technical rooftop PV potential, the incident solar radiation will have to be multiplied by a solar PV efficiency coefficient and an installation performance ratio. A solar PV efficiency coefficient is used of 16%, and a performance ratio 86% is applied. These values are based on estimates from the United States Environmental Protection Agency (EPA). This will account for the amount of incoming solar energy that the solar panels are able to convert into electricity and the energy loss induced as the electricity moves through the installation.

3.5. Case

This section will provide contextual information about the case that is used for the socio-spatial analysis and the evaluation of rooftop technical PV potential outlined in the sections above.

3.5.1. General information

Chosen as case for this research is the city of The Hague, Netherlands. The municipality of The Hague is the third largest municipality of The Netherlands measured by population size, with a population of 549000 inhabitants as of 2021 (GDH, 2022), and is located in the mid-western part of the country. Figure 3.13 shows a map of the municipality and its neighborhoods. The list of full neighborhood names corresponding to the neighborhoods is added to appendix C.

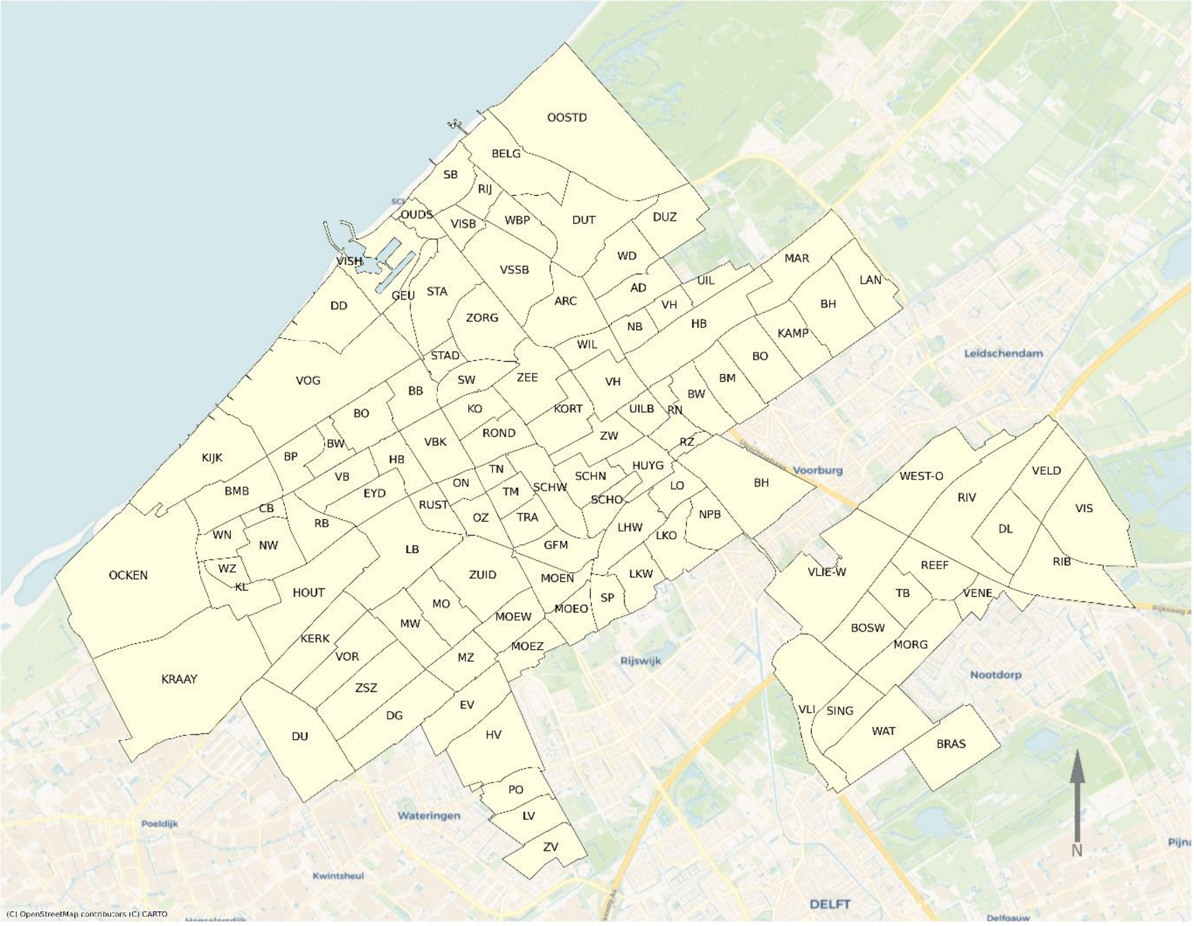

Fig. 3.13. Map of The Hague municipality and the locations of the its respective neighborhoods.

The main driver behind choosing The Hague as case for this research has been the superior data availability regarding many of the indicators describing the city compared to its peers. The city of The Hague provides abundant free open-access data via multiple data outlets, mainly managed by the municipality itself. This data is more easily accessible and covers more areas than data provided by similar cities like Amsterdam and Rotterdam.

Since the research focuses on residential adoption, some neighborhoods will have to be omitted from the socio-spatial analysis outlined above, as they do not qualify as residential neighborhoods. These neighborhoods are either industrial areas, natural parks or neighborhoods with other main functions than providing residence. If these neighborhoods were to be included, this would cause results to be skewed. This could for instance be due to companies on industrial terrains, that have installed large amounts of solar panels on their buildings. When assessing the number of solar panels installed per household in that neighborhood (some industrial terrains also provide limited residential space), the results will be unrealistically high. Figure 3.14 shows a map of The Hague where the neighborhoods that are excluded are displayed in light grey. The reasons for the removal of these specific areas can be found in appendix B.

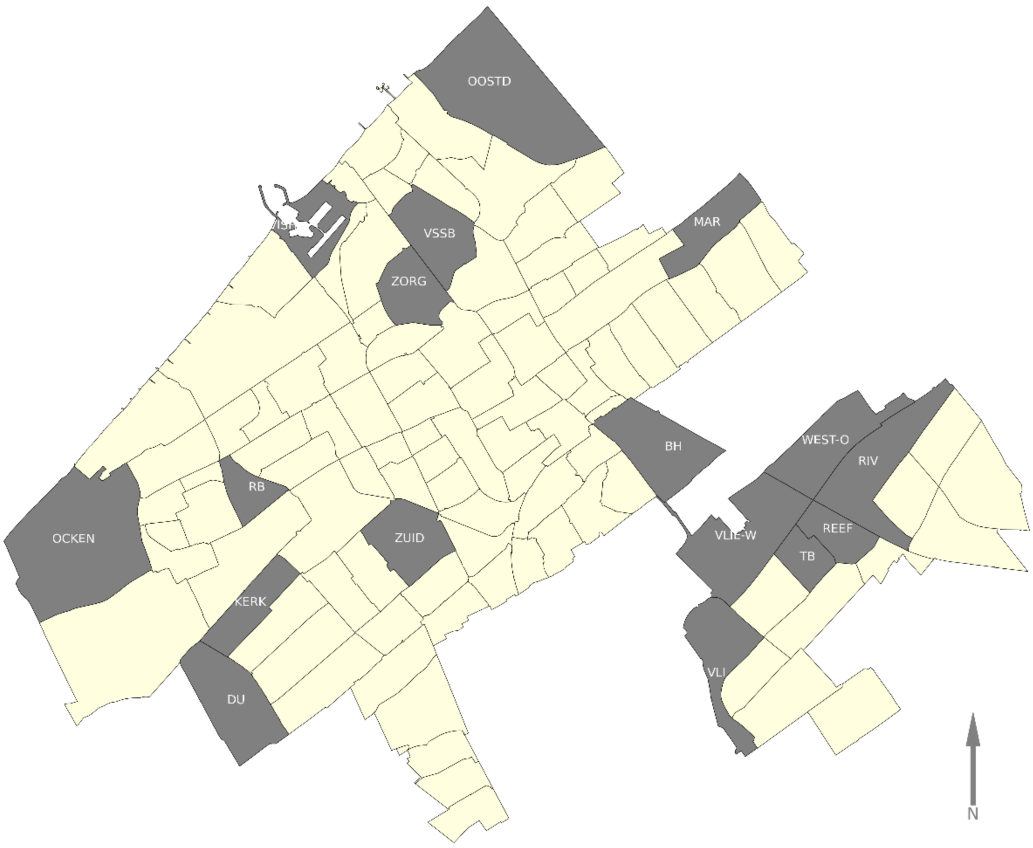

Fig. 3.14. Map of The Hague outlining neighborhoods removed for clustering analysis in grey.

3.5.2. Policy context

To gain understanding of the relevant policy context of the case, this section explores the active policy framework. The development of policy for the municipality of The Hague in light of the renewable energy transition happens on a variety of levels; a national level, a regional energy-strategy level and at the municipal level. The city has developed its strategy towards becoming more sustainable in a variety of documents, eventually leading to the Stedelijk Energieplan (SEP) in early 2021. This is the most recent document outlining the city's plans for becoming a more sustainable city with respect to several different aspects such as food supply, waste processing and energy supply. An overview of how the relevant policy documents regarding the energy strategy are related is in given in figure 3.15.

- On a municipal level relevant documents are the *Den Haag Klimaatpact* (The Hague Climate Pact) and the Den Haag *Duurzaamheidsnota* (The Hague Sustainability Document) from 2019. The *Den Haag Klimaatpact* is a joint undertaking of all political parties represented in the The Hague municipal council stating the future climate ambitions of The Hague of all combined political parties. The *Den Haag Duurzaamheidsnota*, published in 2019, is a more extensive document written by the local municipal government describing in more detail how these ambitions should be realized.
- On a regional level The Hague cooperates with 23 municipalities in the vicinity of The Hague and Rotterdam to form the *Regionale Energiestratgie (RES) regio Rotterdam-Den Haag*. This is a platform where all stakeholders involved cooperate to prepare for and execute sustainability projects within the region (Energiestrategie Rotterdam Den Haag, 2022).

– At a national level the city is bound to the latest *Coalitieakkoord* (Coalition agreement) of the current government and the *Klimaatakkoord* (Climate agreement) published in 2019, setting targets and strategies to be incorporated by municipalities.

The combination of these strategies laid out in these documents has led to the municipality's latest strategy document, called the Stedelijk Energieplan (SEP) presented in 2021. This is the most recent outline of the city's ambitions and approaches to become a more sustainable city. The ambitions and strategies outlined in the SEP are translated into concrete action plans for the neighborhoods of The Hague in the form of *Wijkenergieplannen* (neighborhood energy plans), *Wijkuitvoeringsplannen* (neighborhood execution plans) and the *Transititievisie Warmte* (TVW) (Transition Vision Heat). The TWV is limited to the municipal energy heating system rather than the electricity system. The Wijkuitvoeringsplannen are the final policy measures that translate into concrete actions regarding the energy system within the neighborhoods of The Hague. This structure is highlighted in figure 3.15.

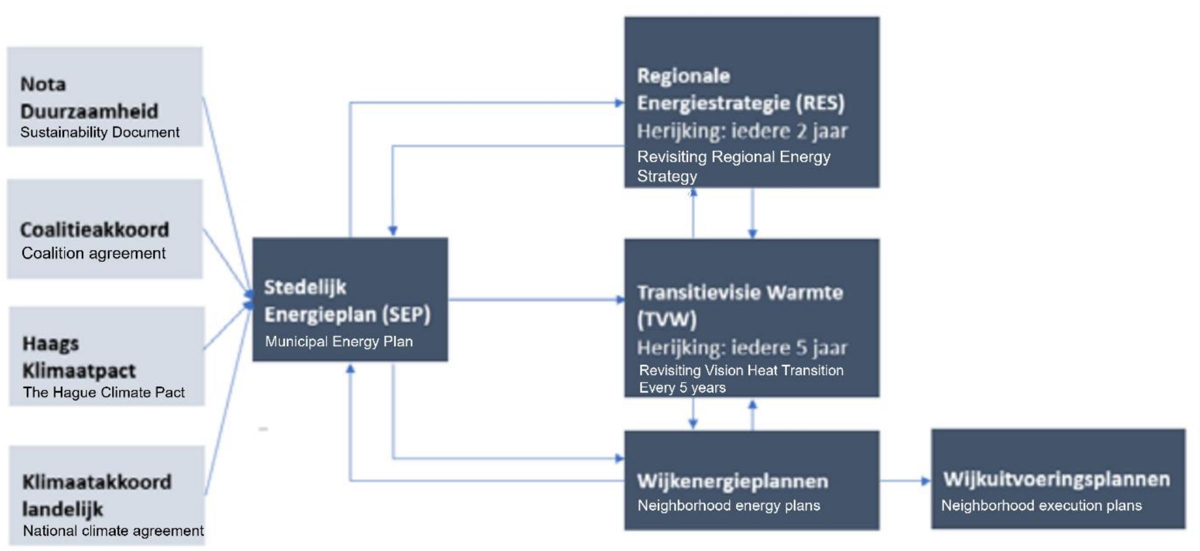

Fig. 3.15. Overview of relevant policy documents The Hague (Stedelijk Energieplan, 2021)

Regarding the residential adoption of solar PV a variety of policy measures are currently put into place. These can be discerned into policy measures active at a national level and policy measures active at a municipal level, the latter being a product from the SEP or similar previous documents. At a national level there are three active policies designed to receive financial benefits from the installation of solar PV (Ministerie van Economische Zaken, 2022). These are:

– Salderingsregeling

The *salderingsregeling* (comparable to a Feed-in-Tarriff (FIT)) allows private owners of solar PV to sell their excess energy generated to the grid for a pre-specified price per kWh depending on their energy contract. The *salderingsregeling* is scheduled to be gradually phased out starting in the year 2025 onwards till 2031 (Milieu Centraal, 2022).

– Belastingteruggave BTW

The belastingteruggave BTW (Tax Return VAT) allows investors in solar PV to have their value-added taxes that are paid with the purchase of solar panels returned, causing a more attractive investment case due to a lower purchase price and therefore shorter payback periods.

– Subsidieregeling coöperatieve energieopwekking (SCE)

The Subsidieregeling cooperative energieopwekking (SCE) (Subsidy Program Cooperative Energy Generation) is designed for owners associations sharing one building and thus sharing one roof. The subsidy is designed to return money to the owners of the project per kWh generated (RVO, 2022). The measure replaces the former Postcoderoosregeling, which allowed investors which formed a small energy corporation to receive a discount on the amount of taxes paid on their energy bills. Due to a recent nationwide discount on energy taxes, small energy corporations falling under this policy have seen their relative benefits been drastically reduced.

On a municipal scale various other instruments exist to support the adoption of solar PV among residential households in The Hague. Within the municipality of The Hague the following measures of policy support exist (Duurzame stad Den Haag, 2022):

– Klimaatfonds Den Haag

The *Klimaatfonds Den Haag* (Climate Fund The Hague) allows the owners of a solar PV project to receive a financial contribution for every ton of induced CO_2 reduction.

– Duurzaamheidsfonds VvE's

The *Duurzaamheidsfonds VVEs* (Sustainability Fund Owners Associations) provides loans to projects within the municipality of The Hague that are aimed improving energy efficiency or decarbonizing energy supply.

The above listed programs give an overview of policy measures designed to support PV adoption among households. They are either applicable at a national level or solely at a municipal level. They are mainly focused on home-owners or owner associations that together share ownership of a building and its roof, and are all financial measures in the forms of beneficial fiscal programs, beneficial loans or subsidies. The analysis of the policy context provides additional insights necessary when interpreting the results at a later stage of the research.

3.5.3. Housing composition The Hague

As different forms of housing situations require different models and processes of solar PV adoption, the distributions of these different situations across The Hague is explored. Although due to lack of explicit spatial available data this distribution can't be analyzed spatially, the shares of these groups within the municipality as a whole can be approximately evaluated. The first category that is explored is the distribution of residential dwellings per property type. As shown in figure 3.16, 43.3% of dwellings in The Hague are owner-occupied, 31.0% is part of social housing (low-rent) and 25.1% falls within the private rental sector.

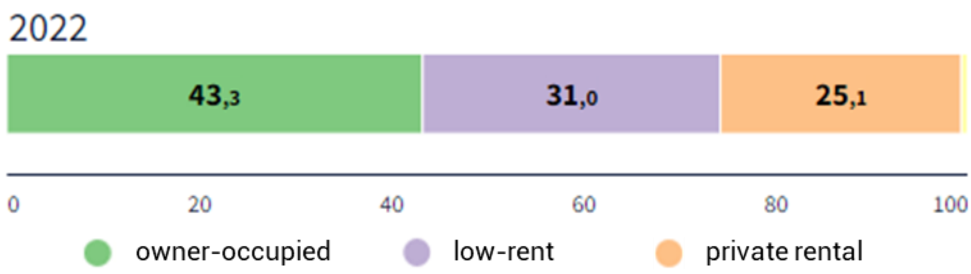

Fig. 3.16. Distribution of dwellings in The Hague per property type.

Another category that is explored is the distribution of housing type across The Hague. Figure 3.17 shows that the vast majority of dwellings in The Hague is made up of apartments, and that approximately only a quarter of its housing stock is made up out of single family homes.

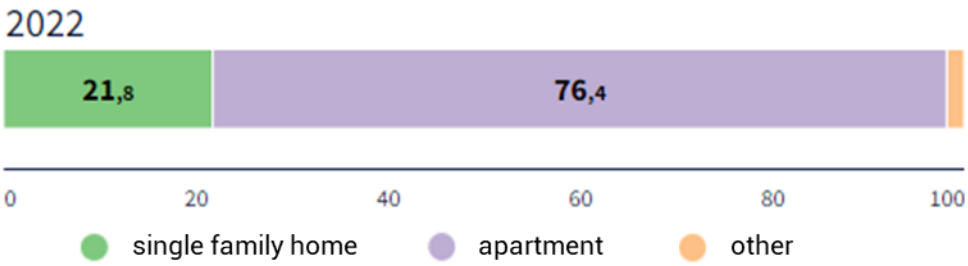

Fig. 3.17. Distribution of dwellings in The Hague per housing type.

Lastly, it is explored what part of dwellings within The Hague is part of either social housing corporations, or an owners association compared to other buildings. This distribution is interesting due to the fact that according to the access to solar framework these groups (social housing and owners associations) are indicated to have poor access to solar PV. It is therefore interesting to get insight into the size of these groups within The Hague. Figure 3.18 indicates that almost 80% of dwellings within The Hague are part of either an owners-association or a social housing corporation. This suggests that the significant majority of dwellings in The Hague does not have sole access to its roof, thus making adoption of solar PV more complicated for these groups.

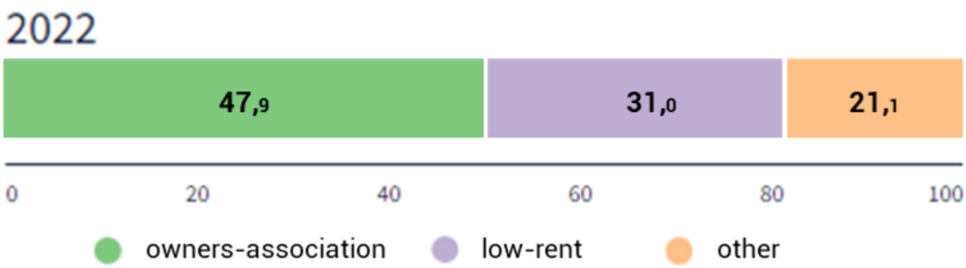

Fig. 3.18. Distribution of dwelling types relevant for solar PV.

4. Results

In this chapter the results of the analyses described in the research design are displayed. Firstly, an overview is given of current solar PV adoption levels among different housing situations. Then, the outcomes of the socio-spatial analysis of the distribution of access to solar PV as described in section 3.3 are introduced. Hereafter, the evaluation of the technical rooftop PV potential across the city is highlighted for different housing situations. And lastly, the results of the intersection of the distribution of *access to solar PV* and the distribution of rooftop technical PV potential are presented.

4.1. Current distribution of solar PV adoption

From the access to solar framework presented in section 3.2 it follows that households in different housing situations do not have equal access to solar PV systems. To see how solar PV systems are currently distributed among different housing situations, the solar PV adoption levels are analyzed for various different types of housing situations. This section presents the results of this analysis.

Table 4.1 shows the adoption levels of solar PV systems among various categories of housing situations. The table shows that the solar panels are installed on nearly 11% of the residential buildings in The Hague. These are all of the buildings that are separately registered with the BAG that are known to the municipality to have a residential function. For all buildings in The Hague registered with the BAG as being owned by social housing corporations, 5,32% have been equipped with solar PV panels. And for all buildings in The Hague that are registered with the BAG as being part of an owners association only 2.95% is equipped with solar panels. Now if we look at the group of residential buildings excluding all social housing and excluding all buildings owned by owners associations, then the adoption rate is even 17.43%. This involves all other housing situations such as owner-occupied buildings and buildings in the private rental sector.

Tab. 4.1. Distribution of solar PV adoption levels for buildings across different residential categories.

	The Hague Total	Social Housing Corporations	Owners Associations (VVE)	Total (excl. Social Housing and VVE)
# of residential buildings per category	88292	21486	18175	48631
# of buildings equipped with solar PV	9683	1143	536	8004
% of buildings with solar per category	*10.97%*	*5.32%*	*2.95%*	*16.46%*

These results indicate that solar PV adoption among social housing corporations and among owners associations is much lower than the average level of solar PV adoption across the Hague. Figure 4.1 shows the distribution across the city of number residential buildings per neighborhood that are equipped with solar PV panels compared to the total number of residential buildings in that neighborhood. The figure demonstrates that the highest levels of solar PV adoption per building are mainly located near the edges of the municipality. Whereas PV adoption per building in the geographical city center is relatively low, as most neighborhoods that fall within the lowest category of solar PV adoption per building are located here.

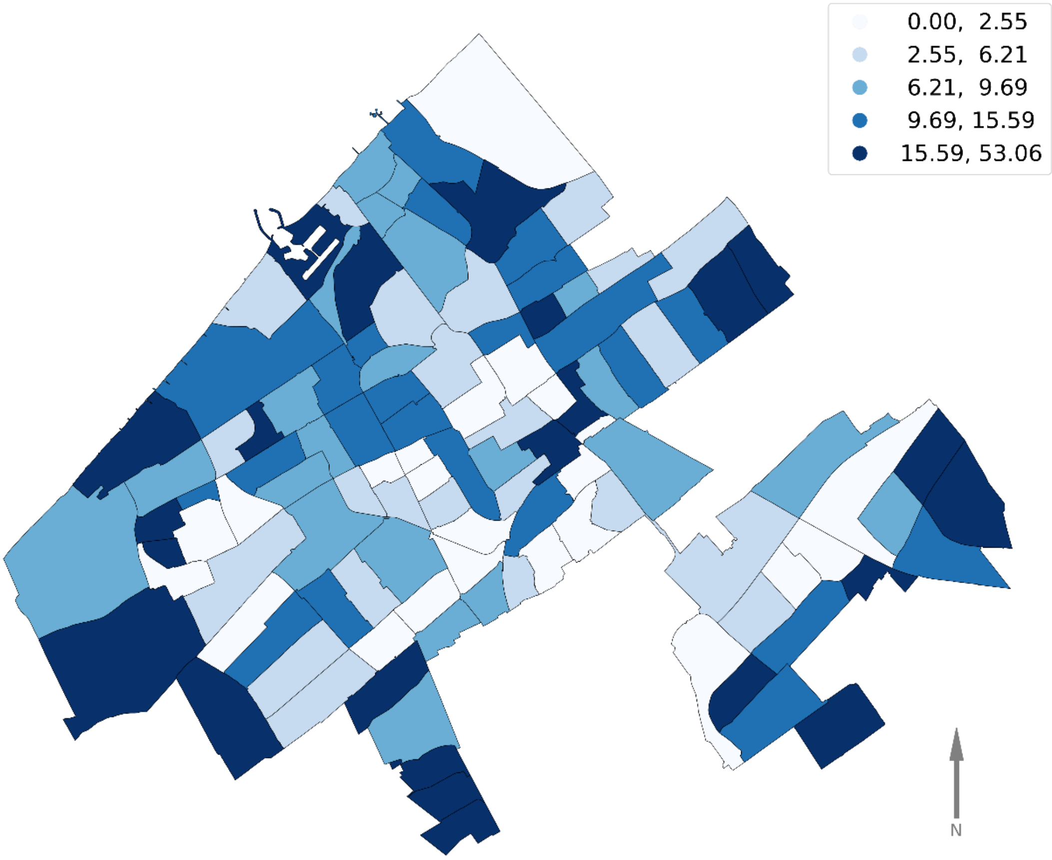

Fig. 4.1. Distribution of percentages of residential buildings equipped with solar panels across all neighborhoods in The Hague in quantiles. The numbers in the legend represent ranges of percentages..

4.2. Socio-spatial analysis of access to solar framework

This section will present the results of the clustering analysis performed as described by section 3.3. By analyzing the variables as operationalized in section 3.3.1, the distribution of access to solar PV across The Hague can be spatially evaluated.

4.2.1. Results of initial clustering set-up

On the basis of the outcomes of the validation analyses, the first clustering analysis is performed with the value of input parameter *k=4.* The input variables for the clustering algorithm are the variables discussed in section 3.3.1, and their spatial distributions are shown in figure 4.2.

Fig. 4.2. Clustering input variables.

The result of running the K-means clustering algorithm with *k=4* is presented in figure 4.3. It can be seen that there is a strong spatial structure present within the clusters, as the clusters are very much concentrated in certain geographic areas. This is remarkable, because the K-means clustering algorithm of itself does not set any spatial restrictions, as opposed to certain other clustering algorithms. The low income cluster is represented in red and is located mainly near the southern part of the municipality along its borders. The average income cluster is represented in beige and is located mostly around the city center. The above-average income cluster is represented in light green and is located mainly north-west of the center and along the shore. And finally, the high income cluster is represented in dark green and is located mostly in the northern part of the city relatively close to the shore. The clusters are named by their cluster averages for income, as this is a relatively easy way to qualify the clusters.

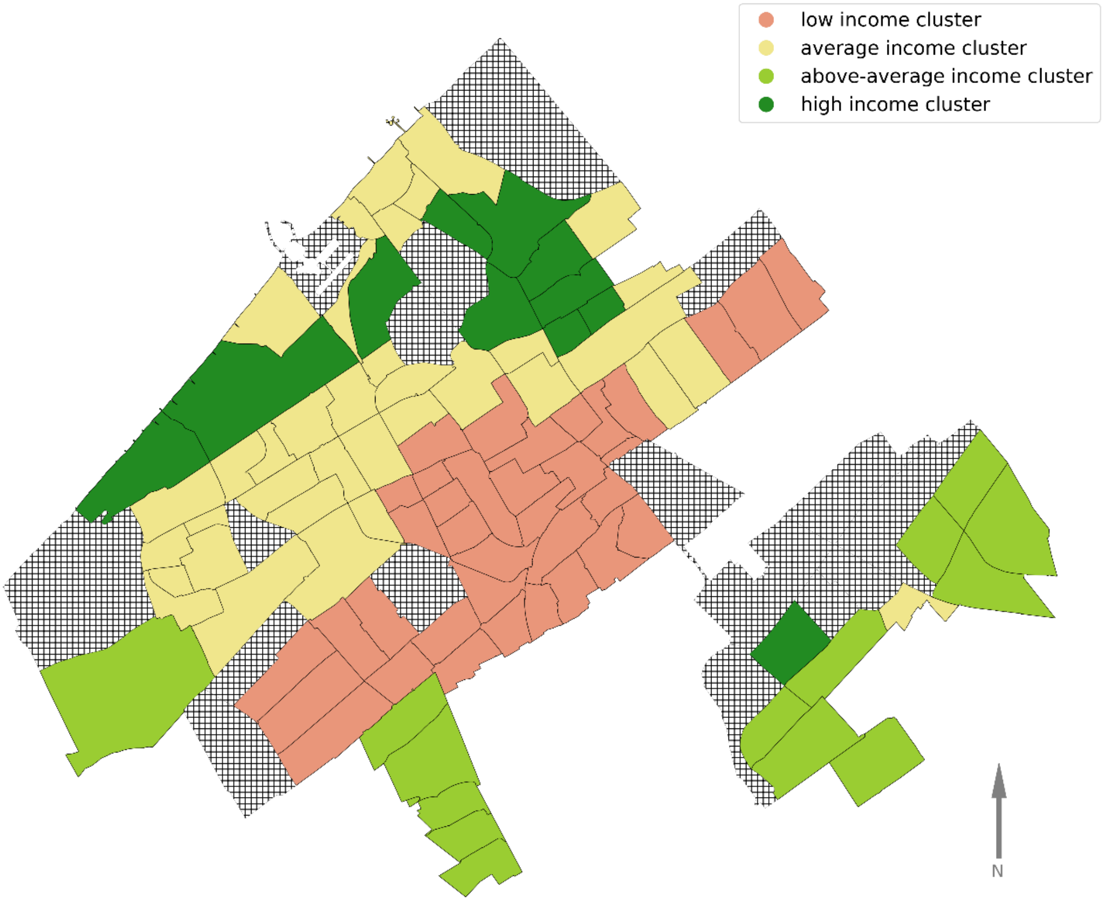

Fig. 4.3. Clustering output (k=4)

Figure 4.3 provides insight on the spatial structure of the formed clusters, but not on what values these clusters actually represent. To get more insight into the characteristics of the respective clusters, table 4.2 shows the mean values for all of the input variables of the clustering algorithm. It displays the different input variables on the rows, and the clusters in the columns.

Tab. 4.2. Mean values of clusters (k=4) for input variables.

	Clusters				
Variables	Low income	Average income	Above-average income	High income	The Hague mean
% owner-occupied homes	26.08	54.76	62.31	71.25	42.7
% apartment buildings	85.67	81.87	25.23	53.50	76.5
% Dutch natives	24.74	60.97	45.93	62.08	43.1
Average yearly household income	32 717	46 422	57 721	91 463	43 075

Table 4.2 characterizes the clusters based on the average values of the input variables. For the purpose of structure in the presentation of results, the clusters are labeled according to their mean income levels.

The low income cluster is characterized by a very high share of apartment buildings and very low values for the variables of income, % of Dutch natives and % of owner-occupied homes. The average income cluster is characterized by a high share of apartment buildings, a relatively high share of Dutch natives and close to mean values for the other variables. The above-average income cluster is characterized by a very low share of apartment buildings, higher than average values for income and percentage of apartment buildings and close to average value for percentage of Dutch natives. The high income cluster is characterized by a relatively low share of apartment buildings and very high values for all other variables.

On the basis of table 4.2 the low-income cluster seems to be the most disadvantaged cluster when considering access to solar PV, and the high-income cluster seems to be the most advantaged cluster. The low-income cluster is characterized by a low share of owner-occupied homes, high share of apartment buildings, low share of Dutch natives and low average household income. These are all characteristics considered to reduce access to solar PV according to the access to solar PV framework. The high-income cluster is the exact opposite to this, and is characterized by high average income, relatively few apartment buildings, high share of owner-occupied homes and high share of Dutch natives. These characteristics are all considered favorable regarding access to solar PV.

To test whether these expectations on access to solar PV are reflected in the distribution of solar PV adoption, the mean solar PV adoption levels are calculated for each cluster. The levels of solar PV adoption are calculated as the average number of solar panels installed per household per neighborhood. The spatial distribution of the number of solar panels per household is shown in figure 4.4.

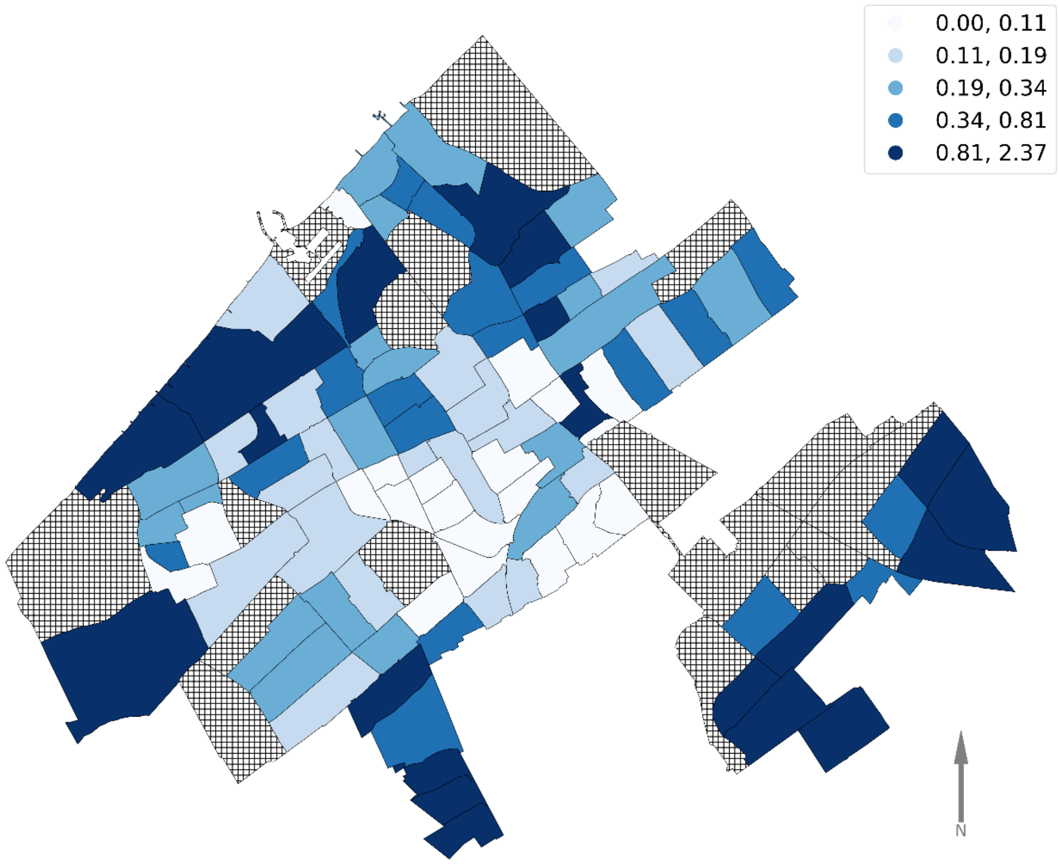

Fig. 4.4. Distribution of number of solar panels installed per household across The Hague..

Figure 4.4 shows that neighborhoods with higher levels of PV adoption are found around the edges of the city, and are almost all found in clusters that were described as advantaged cluster; either the high-income cluster or the above average-income cluster. The areas with lowest level of solar PV adoption are mainly located in the low-income cluster. Table 4.3 shows the average adoption level per cluster of the clustering output in figure 4.3.

Tab. 4.3. Clustering output compared to average solar PV adoption per cluster (k=4)

	Clusters				
Variables	Low income	Average income	Above-average income	High income	The Hague mean
% owner-occupied homes	26.08	54.76	62.31	71.25	42.7
% apartment buildings	85.67	81.87	25.23	53.50	76.5
% Dutch natives	24.74	60.97	45.93	62.08	43.1
Average yearly household income	32 717	46 422	57 721	91 463	43 075
Average number of solar panels per household	0.18	0.27	1.23	0.93	0.35

Calculating the average number of solar panels per household for each of the different clusters allows us to compare level of access to solar PV with actual adoption levels for each cluster, as is displayed in table 4.3. When assessing the average number of solar panels per household for each of the clusters it appears that two clusters have very low adoption levels per household and two clusters have relatively high average adoption levels. The two clusters with the highest level of income, owner-occupied homes and lowest shares of apartment buildings have much higher adoption levels per household than the other two clusters.

One observation that stands out is that there is a large gap in adoption levels between the average income cluster and the above-average income cluster. Even though the values for percentage owner-occupied homes, percentage of Dutch natives and average household income do not differ significantly, there is a substantial difference in the level of installed solar panels per household. This might indicate that the difference in adoption levels between these clusters is largely being driven by the difference in the percentage of apartment buildings.

To add more context to the mean values in table 4.3, the distributions that make up the mean values of the clusters are displayed in figure 4.5. Figure 4.5 shows that the low income cluster in almost all distributions is different from the other clusters and has little overlap. The high income cluster shows to segregate most from the other clusters by its higher income level. As mean values can be very sensitive to outliers, these plots also serve to identify whether the mean values in table 4.3 are heavily influenced by strong outliers. However, none of the distributions of the input variables point to significantly different stories than what can be derived from analyzing the mean values of the cluster variables.

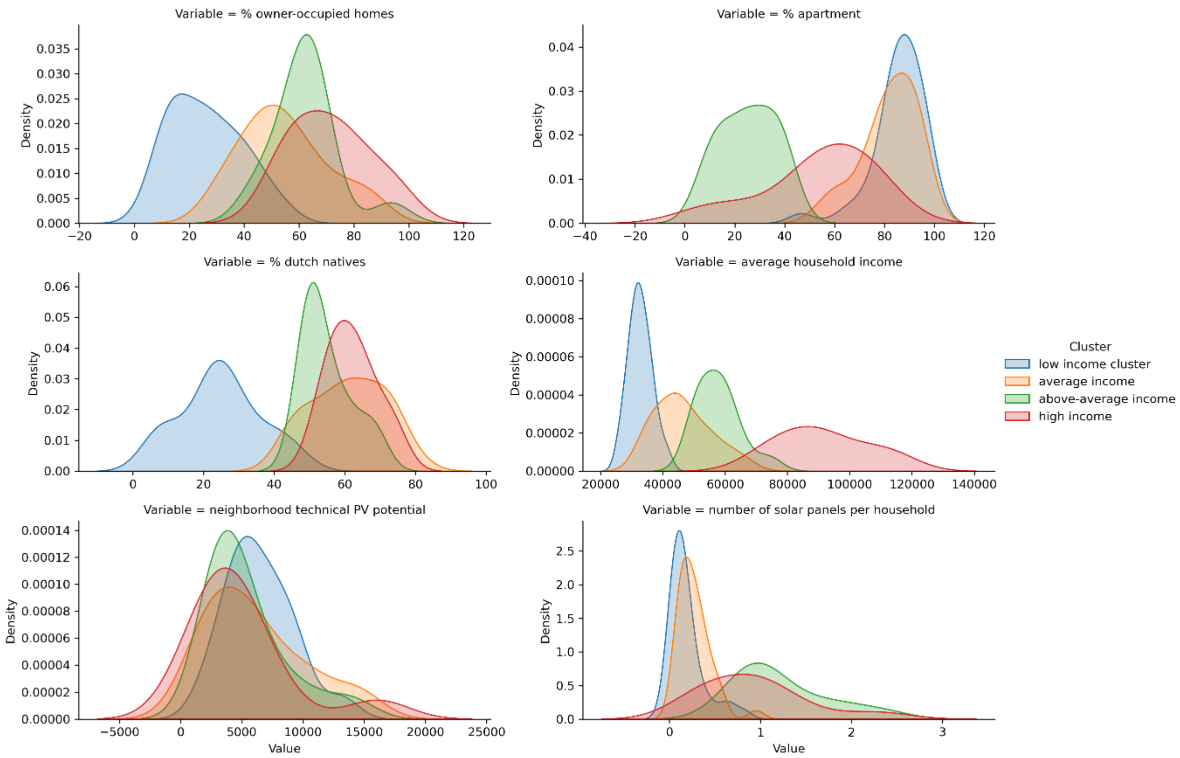

Fig. 4.5. Distributions of cluster values (k=4)

It appears that, for the case of The Hague, the adoption levels of solar PV are in line with the factors that are expected to either positively or negatively influence them. In other words, the clusters for which the input cluster variables indicated lower access to solar PV indeed have relatively low levels of solar PV (low income cluster and average income cluster), and vice versa, clusters for which the cluster variables point to higher levels of access to solar PV have higher adoption levels of solar PV (above-average income cluster and high income cluster).

In appendix E the clustering analysis is repeated for different values of parameter *k* to validate whether the same patterns are observed.

4.3. PV technical potential

In this section the results of the evaluation of rooftop technical PV potential across the city of The Hague for different residential categories will be presented. Firstly, the distribution of rooftop solar PV potential is presented for all rooftops across all buildings in all neighborhoods. Secondly, the rooftop solar PV potential is presented across all residential buildings in only residential neighborhoods. Then, results will be shown for the distribution of rooftop solar PV potential for all buildings part of social housing corporations across all residential neighborhoods. And lastly, the rooftop solar PV potential is evaluated for all buildings part of an owners association (VVE) across all residential neighborhoods.

4.3.1. All buildings

Figure 4.6 shows a map of The Hague municipality and the levels of technical rooftop PV potential per neighborhood. The level of technical PV potential ranges from 200 MWh/year in the lightest green area, to almost 25,000 MWh/year in the darkest green area.

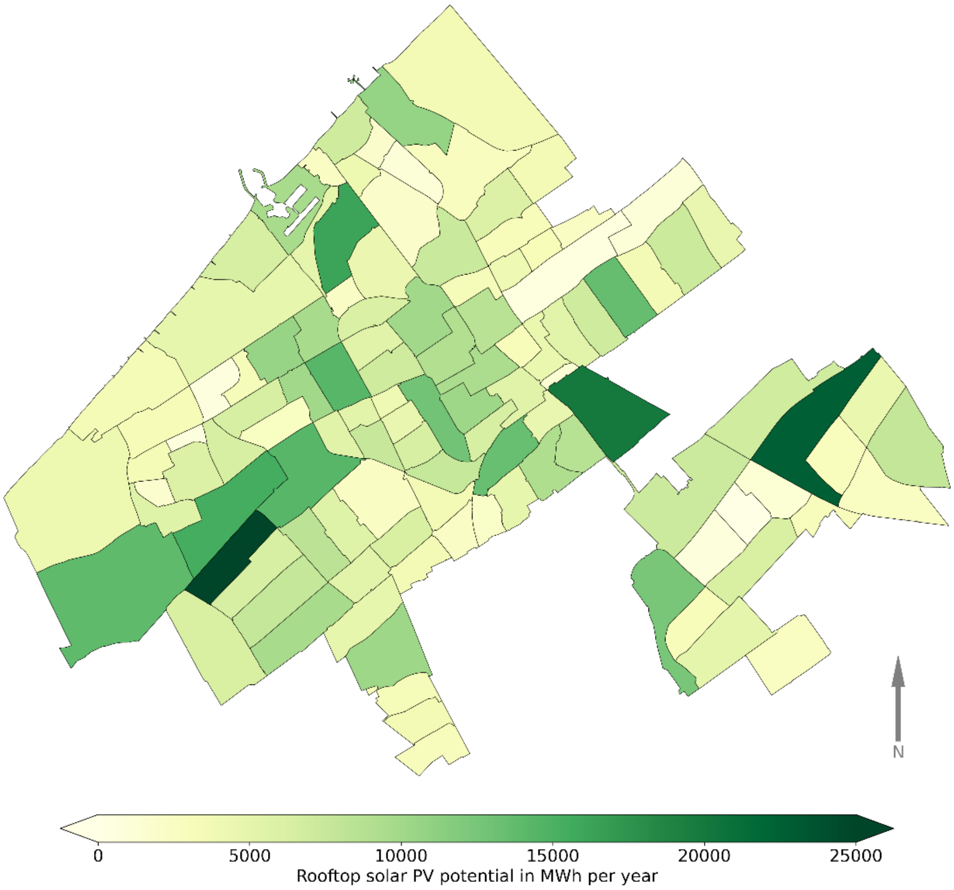

Fig. 4.6. Distribution of technical PV potential across The Hague per neighborhood.

This map includes all neighborhoods of The Hague, also neighborhoods that do not qualify as residential neighborhoods. The areas that color darkest on this map are mainly industrial areas, as they are home to a high amount of roof space due to large industrial and office buildings. When excluding the areas that are not included in the clustering analysis, the map looks as presented in figure 4.7.

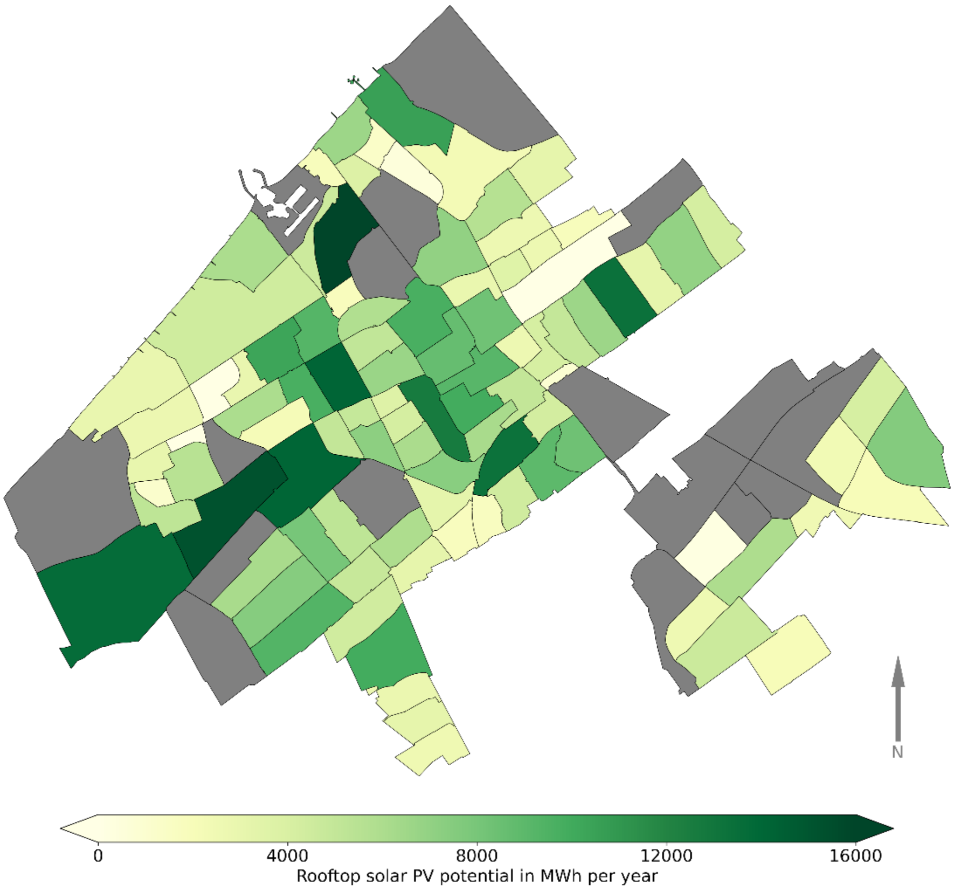

Fig. 4.7. Distribution of technical PV potential of The Hague per neighborhood including only neighborhoods that qualify as residential neighborhoods.

Figure 4.7 displays the distribution of technical PV potential only of residential neighborhoods within the city of The Hague. The technical PV potential ranges from 200 MWh/year to approximately 16,000 MWh/year. By means of visual inspection it can be seen that the highest levels of technical PV potential around the centre of the municipality, and towards the south-western part.

4.3.2. Potential for social housing

Figure 4.8 highlights the distribution of rooftop technical PV potential for buildings owned by social housing corporations across all residential neighborhoods of The Hague. It can be seen that there is a very strong concentration of buildings owned by social housing corporations in the geographical city center, and towards the south-western part of the city. As mentioned in section 3.5.3. 31% of the households in The Hague lives in housing owned by social housing corporations. This is a large group of the population of The Hague that has low access to solar PV since they do not own their own home, generally have lower average incomes and often live in apartment buildings without direct access to a self-owned sun exposed roof. From the evaluation of technical PV potential it can be determined that all buildings owned by social housing corporations together comprise 23.2% of the total rooftop technical PV potential of The Hague.

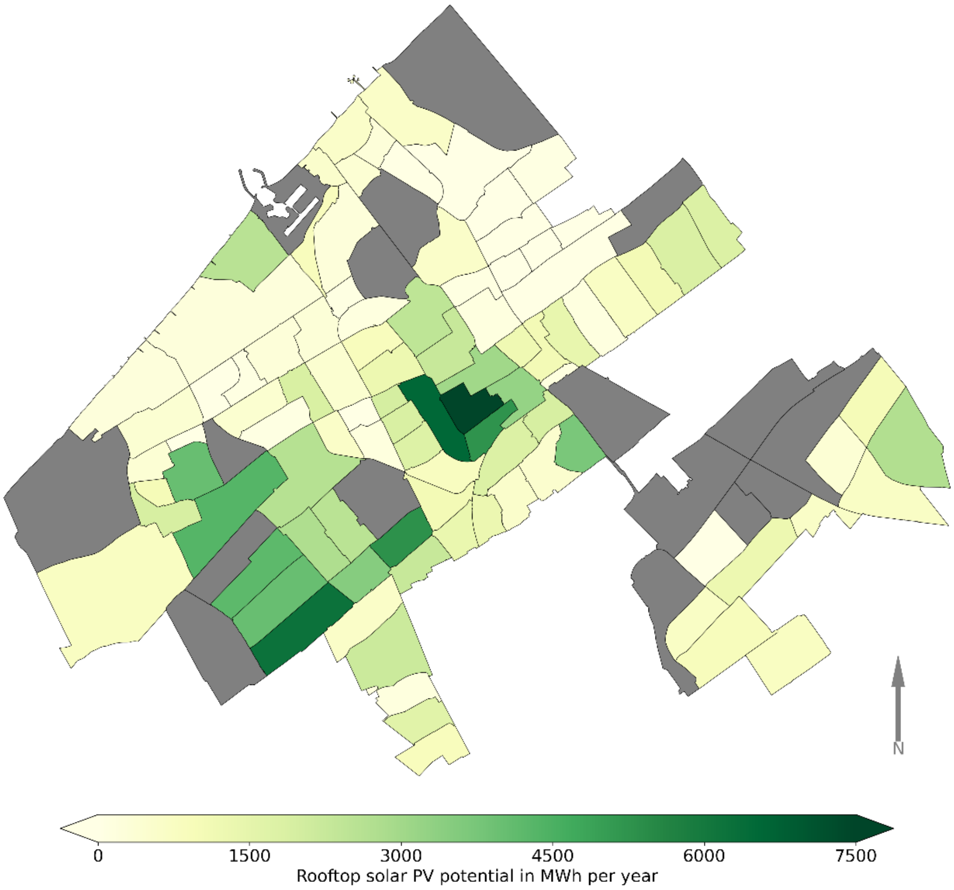

Fig. 4.8. Distribution of rooftop solar PV potential of all buildings owned by social housing corporations across The Hague.

In section 4.1 it was found that the 10.97% of all residential buildings has solar panels installed. The adoption rate of solar PV for all buildings owned by social housing corporations in The Hague is 5.32%. This is thus below the average adoption rate. This means that there still is a large amount of PV potential to be realized by social housing corporations. This is noteworthy due to the fact that these housing corporations provide housing to a group of the population that has generally has low access to solar PV. And secondly, because this group of housing is more easily targeted as they are united in 8 large social housing corporations existent in The Hague.

4.3.3. Potential of buildings from owners associations

Figure 4.9 highlights the distribution of rooftop technical PV potential for buildings owned by owners associations (VVEs) across all residential neighborhoods of The Hague. It can be seen that most of the rooftop solar PV potential is concentrated in and around the geographical center of the city. From the evaluation of technical rooftop PV potential it can be determined that all buildings that are owned by owners associations together make up for 34.1% of the total rooftop solar PV potential of The Hague, while providing housing to 47.9% of the households of The Hague as mentioned in section 3.5.3. Both of these numbers indicate that a large part of buildings and households are part of owners associations. As determined in section 4.1, currently only 2.95% of the buildings that make up is this potential has installed solar PV panels. This is considerably less than the average of 10.97%.

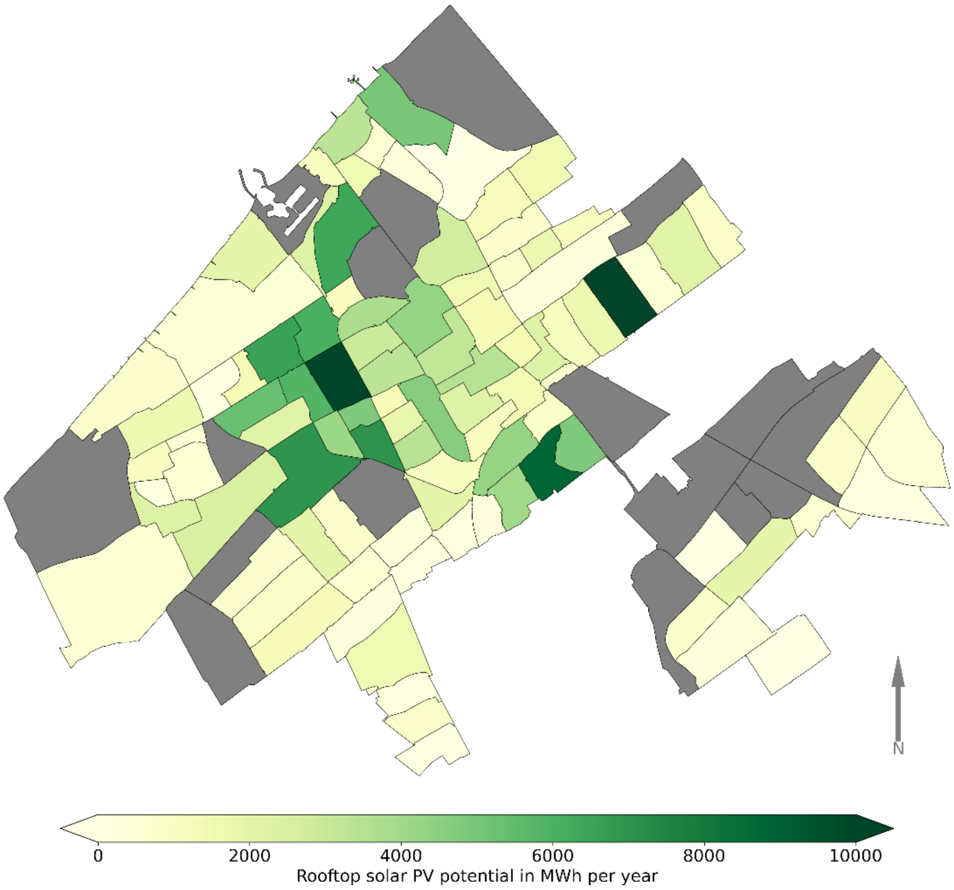

Fig. 4.9. Distribution of rooftop solar PV potential of buildings owned by owners associations across The Hague.

4.4. Intersection of access to solar PV with technical PV potential

As the aim of this research is to evaluate the spatial distribution of accessibility to solar PV and how this intersects with the technical rooftop solar PV potential, this section evaluates how the distributions of access to solar PV and technical solar PV potential spatially compare.

4.4.1. All neighborhoods

Figure 4.10 shows how the spatial distributions of technical solar PV potential compares to the output of the K-means clustering algorithm *(k=4).* The figure shows that many of the areas with high technical rooftop PV potential are located in the low income and average-income cluster, which are the clusters with low adoption levels and inferior access to solar PV.

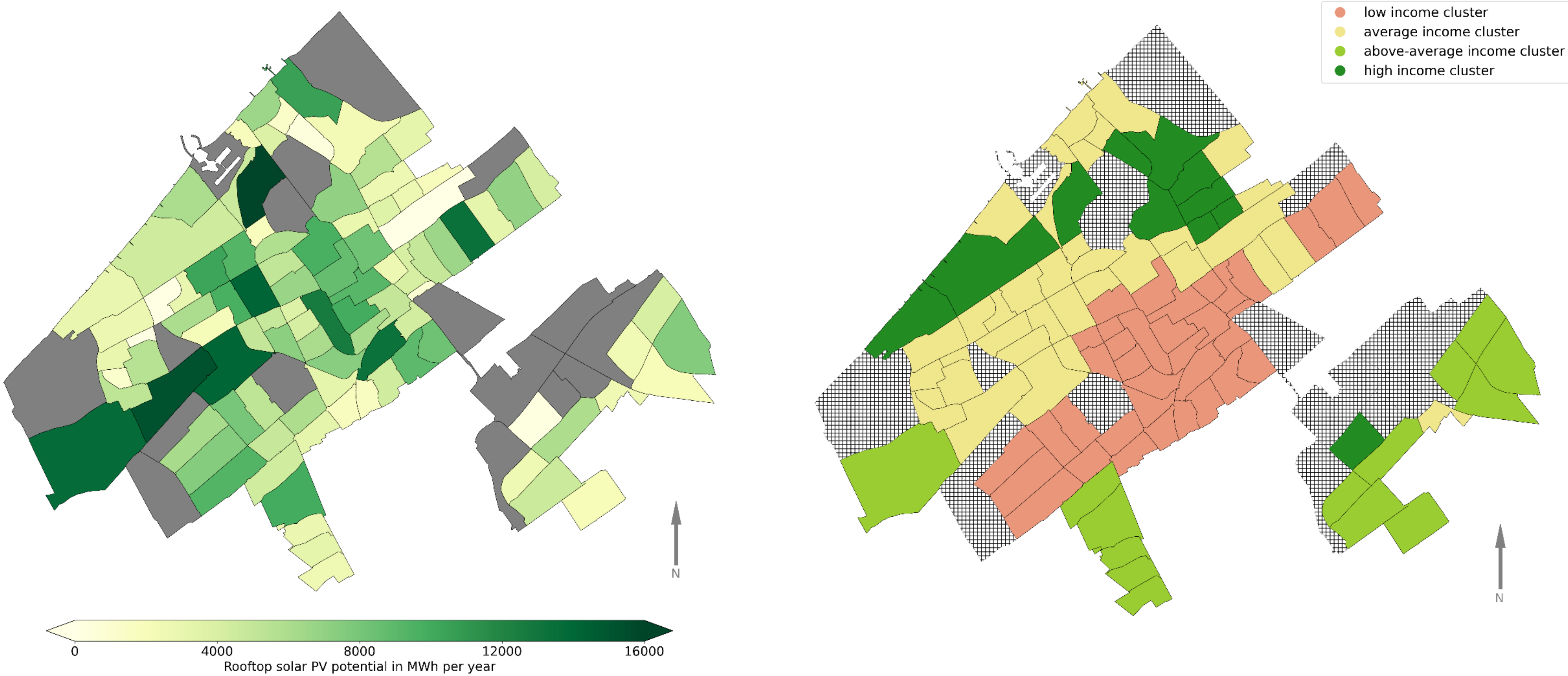

Fig. 4.10. Comparison of rooftop solar PV potential and access to solar PV across The Hague

To verify whether this true, the average technical PV potential per cluster in is calculated. These values are shown in table 4.4.

Tab. 4.4. Average technical PV potential per cluster (k=4)

	Clusters				
Variables	Low income	Average income	Above-average income	High income	The Hague mean
% owner-occupied homes	26.08	54.76	62.31	71.25	42.7
% apartment buildings	85.67	81.87	25.23	53.50	76.5
% Dutch natives	24.74	60.97	45.93	62.08	43.1
Average yearly household income	32 717	46 422	57 721	91 463	43 075
Average number of solar panels per household	0.18	0.27	1.23	0.93	0.35
Average rooftop solar PV potential per neighborhood (MWh/year)	6452	6134	5382	4912	6004

Table 4.4 confirms that neighborhoods with higher levels of technical PV potential are likely to be located in neighborhoods where access to solar PV is lower. This indicates that areas with high technical rooftop PV potential in the urban environment have difficulty exploiting this potential, given their low adoption levels, rather than a lack of actual PV potential. Neighborhoods that in total have more technical PV potential have on average much lower solar PV adoption levels, while neighborhoods that house a lower amount of the technical PV potential have much higher levels of solar PV adoption. To confirm if the average values demonstrated in table 4.4 are representative of the distributions that comprise them, figure 4.11 shows the distribution of technical PV potential throughout the clusters.

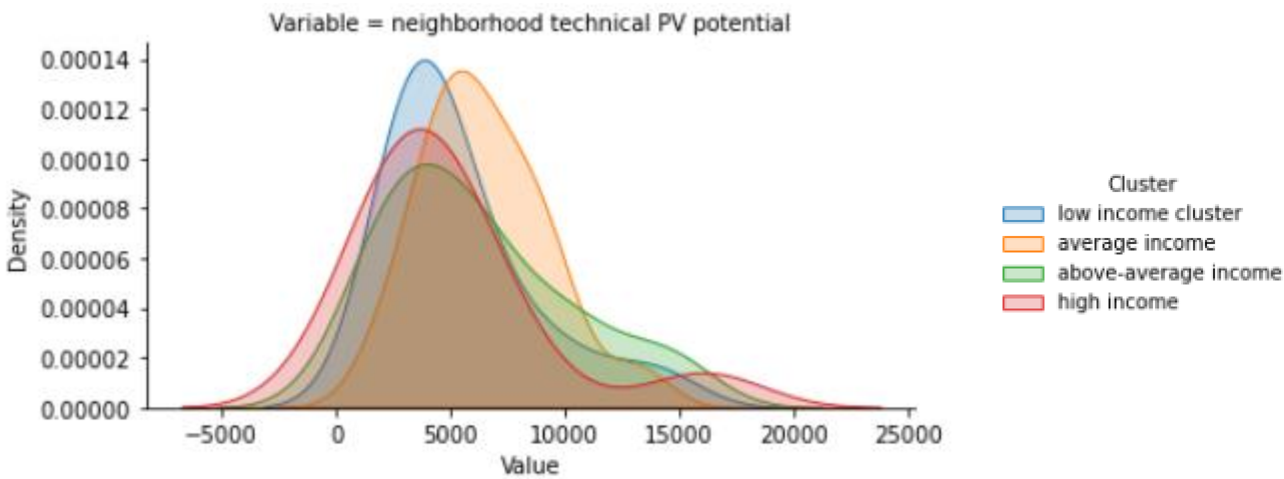

Fig. 4.11. Distribution of cluster output for technical PV potential

When looking at the distributions shown in figure 4.11, it becomes visible that there is a very large amount of overlap between all of the clusters. Meaning that the way in which the results can be interpreted from the average values is not as strongly represented in their respective distributions. Though, the orange distribution representing the low-income cluster does show be shifted more to right indicating a structural level of higher PV potential in this cluster. The average value for the red distribution, representing the high-income cluster, however seems to be most heavily influenced by outliers, due to its flat tail on the right side. This implies that most of the values for the technical PV potential within this cluster are actually lower than its average cluster value.

4.4.1.1. Distribution of solar PV potential across clusters

The clusters where the adoption levels of solar PV are relatively low (low income and average income), are much bigger in population size than the clusters where adoption levels are relatively high (above-average income and high income). Table 4.5 demonstrates that the low income and average income cluster together provide residence to 79.1% of the residents, and to 83% of the households within The Hague. Furthermore, 77.8% of the technical PV potential is situated in these clusters, which are characterized by low levels of solar PV adoption. This means that a very high share of the technical PV potential, almost 80%, is located in neighborhoods that according to this clustering analysis are characterized by very low adoption levels of solar PV and inferior access to solar PV.

Tab. 4.5. Share of residents, households and PV potential per cluster

Cluster	Share of residents	Share of households	Share of PV potential
Low income	43.8	45.6	39.9
Average income	35.3	37.4	37.9
Above-average income	13.9	10.6	12.9
High income	7.0	6.4	9.3

4.4.2. Social housing corporations

In this section the results of the evaluation of technical rooftop PV potential of buildings owned by social housing corporations will be compared to the results of the clustering analysis. Figure 4.12 (see next page) shows almost all of the rooftop solar PV potential of buildings owned by social housing is located in the low income cluster which is characterized by low access to solar PV.

4.4.3. Owners associations

In this section the results of the evaluation of technical rooftop PV potential of buildings owned by owners associations will be compared to the results of the clustering analysis. Figure 4.13 shows the majority of the rooftop solar PV potential of buildings owned by owners associations is located in the average income cluster and the low income cluster, which are characterized by low access to solar PV.

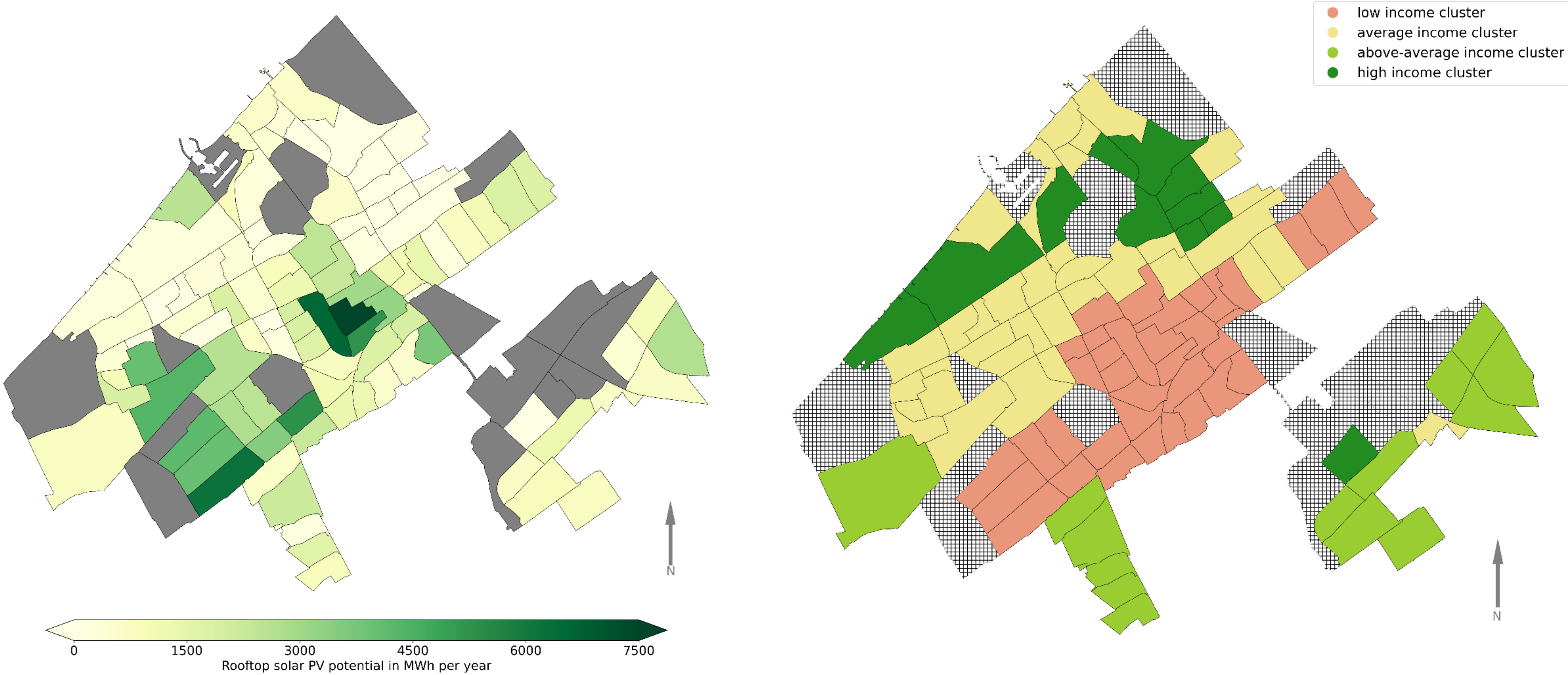

Fig. 4.12. Comparison of rooftop PV potential of social housing corporations and access to solar PV clustering output (k=4)

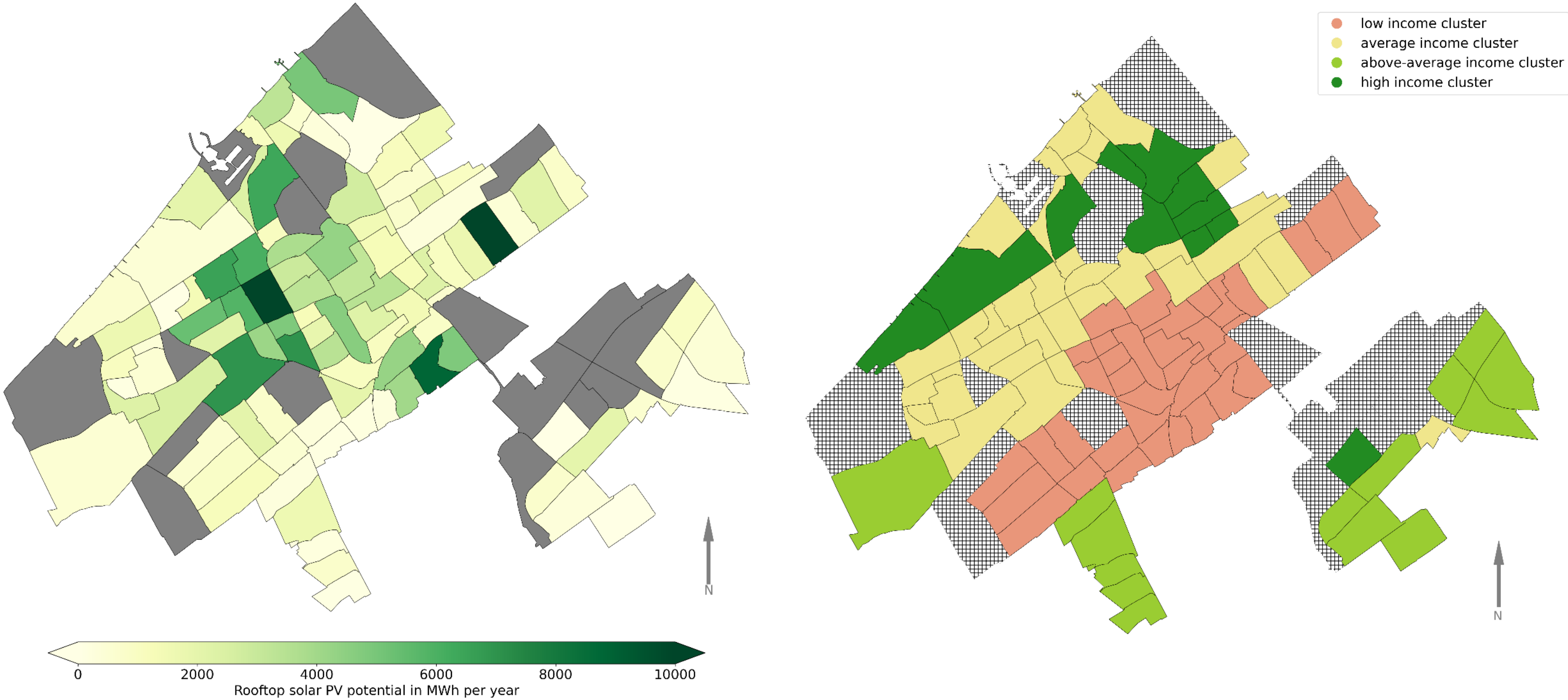

Fig. 4.13. Comparison of rooftop PV potential of buildings owned by owners associations and access to solar PV clustering output (k=4)

5. Discussion

This chapter sheds light on the results that have come forth from the analysis performed in this research. It will present a summary of the key findings and how they provide new insights regarding the research question posed at the beginning of the study. Consequently does it elaborate on where the research fits within literature and how it contributes to it. It will furthermore address limitations of the research and will finalize by commenting on how the research can be relevant for policy design and how future research can advance with the findings of this study.

5.1. Interpretation of main findings

The main research question at the beginning of this research is formulated as: *How can insight into the spatial intersection of access to solar PV and technical solar PV potential contribute to energy policy fostering a just energy transition?* Answering this question involves gaining insight in the two main elements that make up this question. These elements are 1) *access to solar PV* and 2) *technical solar PV potential?* By combining an evaluation of the technical PV potential with a clustering analysis on the basis of the variables defining access to solar PV, new insights have been generated to answer the above mentioned research question.

When assessing the intersection of technical PV potential and accessibility to solar PV it is found that there appears to be a spatial discrepancy between the areas housing a high level of technical PV potential, and the areas characterized by high levels of access to solar PV. This means that areas where solar PV is to a large extent inaccessible to households, provide a great deal of the technical solar PV potential. While areas characterized by good access provide only a small share of the total available technical PV potential. This means that in absolute terms the highest levels of technical PV potential are found in neighborhoods that have difficulty exploiting it. These neighborhoods are characterized by high shares of apartment buildings, low shares of owner-occupied homes, lower average household incomes and low shares of native Dutch population. All barriers that according to literature and practice impair one's access to solar PV.

The finding that adoption levels of solar PV in these more disadvantaged neighborhoods is relatively low is not surprising and in line with previous research done into solar PV adoption in The Netherlands by Vasseur and Kemp (2015) and in Flanders, Belgium by De Groote et al. (2016) and Kwan (2012) in the USA. What is new however, is that this research provides proof that in the urban environment the average neighborhood characterized by poor access to solar PV provides more technical PV potential than neighborhoods characterized by good access to solar PV. When aggregating the levels of technical PV potential for low accessibility neighborhoods, it becomes clear that the vast majority of the technical PV potential for this case, The Hague, is located in neighborhoods where many of the households have difficulty to adopt solar PV either due to living in rental dwellings, not having access to their roof or having difficulty to afford it or perhaps lacking adequate information.

This pattern of low adoption levels among low access neighborhoods is reinforced when looking at social housing corporations and their behavior with regard to the adoption of solar PV. Social housing corporations in The Hague provide housing to 31% of the households, and all suitable roofs of social housing dwellings together form 21% of the technical PV potential. This means that 31% of the households of The Hague are dependent on whether social housing corporations take initiative in the installation of solar PV. So far, realization of solar PV on social housing has been low as the results point out that only 5.5% of the dwellings owned by social housing corporations have been supplied with solar PV, below the average of the city of 10.97%. This indicates that for the case of The Hague, social housing corporations have the potential to 1) exploit a large share of the available technical PV potential, namely 21%, and 2) provide solar PV to a group within the city that otherwise has poor access to solar PV.

Another interesting outcome of this research is that only a minor share of buildings owned by owners associations has been equipped with solar PV, namely 2.95%. This is far lower than the city average of 10.97%. This group however represents 34.1% of the total rooftop solar PV potential, and 48,9% of all households. This finding suggests that it is currently too complicated for owners associations to jointly go through the process of installing solar panels on their building, and thus leaving a large part of the rooftop solar PV potential unexploited. Therefore, besides social housing corporations, owners associations form another group that has ample PV potential but are in need of more effective policy support.

5.2. Positioning in literature

The findings of this research are in line with the general trend in the combined field of energy transition and energy justice literature. The trend that access to energy services is unequally distributed among socioeconomic groups. And that like many other inequalities, unequal access to energy services is also very much a geographical issue. Bouzarovski and Simcock (2017) showed how access to energy end-use is unequally distributed across different places in the UK. Carley and Konisky (2020) mention how access to energy efficient technologies is exclusively seized by higher income households in the US. And Sovacool et al. (2019) show how different low-carbon innovations are being cross-subsidized by low-income groups to higher income groups in Germany and Norway as subsidies introduced for the purchase of electric vehicles or solar PV is paid for by the entire population, but only made use of by higher income households. The results of this research too, point in the direction that access to newer energy-efficient technologies like solar PV is unequally distributed, both among socioeconomic groups and spatially.

This research adds value to the existing body of literature of energy justice and the energy transition in a few different ways. Firstly, the research adds value by attempting to more concretely define the concept of access to solar PV. Throughout the development of the field of energy justice, the concept of access to energy services has been interpreted as a matter of distributional justice. Thus being a matter of fair distribution of ills and benefits of the energy system. Although equal access to energy services is recognized as an important element within the concept of energy justice, current research only seldom defines the factors that determine whether someone has good or poor access to energy services. This research adds value by doing thus for the energy resource solar PV, by distilling which factors or barriers are important when determining whether one has good access to solar PV.

This allows the research to add value to the current body of literature in a second way. This is by providing a method to identify and locate socioeconomic groups within the urban environment that struggle with accessing resources necessary, in this case solar PV, to participate in the energy transition. Although there are various instances of research that indicate that access to solar PV is unequally distributed among socioeconomic, they don’t address the question where these groups are located and to what extent these inequalities exist. Answering this question is important for policymakers to effectively design policy that is able to target these groups at a more local scale. Something which is pointed out to be necessary to alleviate the inequalities that currently exist (Forman, 2017; Reames, 2016).

Lastly, the study provides value by adding insight on the intersection of technical potential of solar PV with the degree of accessibility of households to exploit this potential. The study finds that high levels of technical solar PV potential do not spatially match areas where households have good access to exploit this potential. It shows that the majority of the solar PV potential for the city of The Hague is resided in areas that are only limitedly capable of exploiting this potential in the traditional way; namely being a home-owner privately investing in solar PV on top of a self-owned roof. This demonstrates the need for other innovative models of solar PV adoption to exploit the full solar PV potential in a city like The Hague.

5.3. Policy implications

A secondary aim of this research is to provide insights that support the design of equitable energy policy. The findings of this research show that the conventional way of investing in solar PV by installing solar panels on a roof of your self-owned home is not applicable to many in the urban environment. This research shows, that if not provided with other forms of solar PV adoption, a large part of the technical PV potential in the urban environment is likely to remain unexploited. To tackle this issue, there is a need in the urban environment for policy measures that do not focus solely on the more-advantaged home owner with access to its own roof, in contrast to current policy.

A measure such as the salderingsregeling (FIT) is much more applicable to people that do not face any barriers to invest in solar PV, which are generally wealthier home owners with access to their own roof. This gives an already relatively advantaged group the opportunity to capitalize even more on the benefits of solar PV over those who do not have access to this technology. This same principle applies to a policy measure like the Belastingteruggave BTW (Tax Return VAT) that allows tax benefits on the installation of solar PV. This policy too, is only applicable to those who are in an advantageous position to invest in solar PV with proper access to solar PV. While in an urban environment such as The Hague, this is representative for only a small part of the population.

Therefore, future policy design for the stimulation of solar PV adoption in the urban environment should be more targeted at groups that are currently have little access to solar PV. These are non-home owners, either in the private rental sector or in the low-rent social housing sector, and homeowners part of an owners association. This necessary in order to foster more equal distribution of and more equal access to solar PV resources within the urban environment. In particular, there is the ability to focus on social housing corporations and owners associations as these groups represent a large part of the households and are already united in a corporation or association.

5.4. Limitations of research

The results of this research are the effluent of one the hand exact sciences in the form of mathematical computations, namely the evaluation of technical PV potential, and on the other hand the application of a framework grounded in social science, the assessment of access to solar PV. The answer to the first part of this research can be expressed in straightforward, measurable terms such as kWh or Joules, whereas the latter part of this research lacks this quality. No universal measure or SI-unit exists in which *access to solar PV* is commonly expressed in literature. Although this definitely does not mean the concept is of less importance, it does mean that the definition of the concept might be more debatable.

While trying to define and pin down the concept of access to solar PV, the study thus does not provide a way to measure it in absolute terms, nor does it give weights to factors influencing it. The outcomes of the clustering analysis performed in this research are of categorical nature, and only tell something about the *access to solar PV* in one area or cluster relative to another area or cluster. In an ideal scenario, the research would be able to define access to solar PV as the function of some formula and measure it along some scale. But given the fact that access to solar PV, or any other renewable energy technology, is the result of complex sociotechnical processes, it is the question whether this is even possible. Even though this limits the study in its ability to accurately define access to solar PV, it still provides insights within a given urban environment into which areas need more support relative to other areas in their transition to solar PV based on their access to solar PV. This in order to in the end ensure a more equitable distribution of solar PV resources.

Furthermore does the research assume that a transition away from fossil fuel based energy resources towards solar PV is desirable in many aspects, for which there is abundant proof in literature (Breyer et al., 2017; Sampaio et al., 2017). But it does not consider to what extent this actually feasible. The assumption is made that the infrastructure exists to enable the continued adoption of solar PV within the urban environment. Although in the long term it can be argued that this assumption is reasonable and hopefully is to be true due to the ongoing trend of electrification, in the short term this might prove difficult as there currently is a large strain on the electricity network in The Netherlands. The growing number of solar panels, electric appliances and electric vehicles have caused the electricity network in some areas to be full or overloaded. In the transition towards a v energy system it is essential to have the infrastructure to support it. By indicating the need for policy support among socioeconomic groups that have low access to solar PV, this research assumes the infrastructure exists to enable this. Currently however, this might actually not be the case.

6. Conclusion

In order to accomplish the main objective of this research, a set of different research questions were formulated at the beginning of this research. These research questions will here be revisited.

6.1. Sub-research questions

6.1.1. Sub-research question 1

How is accessibility to solar PV defined?

The concept of accessibility to solar PV is a concept that is not yet clearly defined in literature. This research defines the concept as: 'the freedom of individuals or households to decide whether or not to adopt residential solar PV energy resources, dependent on the existence of one or more barriers.'. This research identifies four factors/barriers to be essential when assessing *access to solar PV*; these are owner-occupation of homes, housing type, affordability and suitable information. By using this definition the concept of *access to solar PV* is the equivalent of the element of behavioral control within the Theory of Planned Behavior (TPB). The combination of this theory and the four identified factors form the basis for the access to solar framework.

Home-ownership is found to be an important factor, as currently little possibilities exist for non-homeowners to adopt solar PV. It proves to be very difficult to split benefits and costs of solar PV adoption to create mutual incentives for both homeowners and renters. The current policy framework relevant to the case used in this research fails to address this situation. This research indicates that areas with higher level of home-ownership tend to have higher adoption levels of solar PV.

Housing type is a second factor that can act as an insurmountable barrier. Households without access to their own roofs, as is often the case for high-rise apartment buildings in the urban environment, have difficulty overcoming the barrier of getting all owners of the buildings incentivized to collectively adopt solar PV. This leads to many apartment buildings, which provide ample technical PV potential, to not be equipped with solar PV. This research shows that areas with high shares of apartment buildings tend to have the lowest level of PV adoption, indicating that this barrier might be very high.

A third factor is affordability. Due to high upfront costs of solar PV systems, solar PV adoption remains unaffordable to less wealthy areas. Even if solar PV is affordable, the investment is often still perceived as too risky. Policy relevant to this case is currently mainly focused on providing financial measures of support to support affordability. The outcomes of this research indicate that PV adoption levels are indeed higher in wealthier areas, as expected.

Lastly, the incapability of attaining suitable information about the adoption of solar PV can too act as a barrier to solar PV adoption. Since solar PV requires what for many is considered a sizeable investment, there is a strong desire for adequate information to guide this process. Especially for households for which this information is not present in their native language, this barrier might be significant. The results of this research do show some proof of this being true, but is not able to confirm this, as areas with higher shares of people with migration backgrounds also tend often to be disadvantaged too with respect to the other factors.

These four factors are recognized as being crucial in determining whether households have *access to solar PV*. It is the synthesis of these four factors that provides insight into whether households have access to solar PV.

6.1.2. Sub-research question 2

How is accessibility to solar PV spatially distributed throughout the urban environment?

This research used applied a k-means clustering algorithm to evaluate the distribution of access to solar PV. The input variables for this analysis followed from the access to solar framework. The results of this analysis show that there are clear signs of spatial structure in the distribution of access to solar PV throughout the case. There is strong spatial clustering of areas with both poor access to solar PV and areas with good access to solar PV. Clusters formed with poor access to solar PV are characterized by high-rise buildings, lack of home-ownership and low affordability. Clusters formed with good access to solar PV are characterized by low-rise buildings, high shares of home-ownership and better affordability. These areas have higher levels of solar PV adoption.

6.1.3. Sub-research question 3

How is the technical rooftop solar PV potential distributed across the urban environment?

To answer this research question the ArcGIS Solar Area Analyst Tool was applied based on a model developed by Fu and Rich (1999). This enabled the research to evaluate the technical solar PV potential for all rooftops of the city of The Hague. The results served as input for later analyses performed in this research. It was found that the majority of the PV potential is located in areas that are characterized by poor access to solar PV. This causes the large parts of technical PV potential within The Hague currently unlikely to be exploited due to inadequate access to solar PV. This holds particularly true for certain residential categories that provide a large part of the rooftop solar PV potential, but currently are unable or inactive in exploiting it. The residential categories are buildings owned by social housing corporations and buildings owned by owners associations.

6.2. Main-research question

How can insight into the spatial intersection of access to solar PV and technical solar PV potential contribute to energy policy fostering a just energy transition?

Based on the answers to the sub-research questions posed in this research it can be concluded that the spatial distribution of access to solar PV in the urban environment does not align with technical PV potential. Areas with poor access to solar PV house a high share of the PV potential, while areas with good access to PV have lower PV potential. As a consequence, the majority of technical PV potential in the urban environment is likely to remain unexploited due to poor access to solar PV within these areas. In this case, policy is currently unable to facilitate these groups in society that lack access to solar PV resources. Solar PV adoption currently is largely restricted to wealthier, more advantaged socioeconomic groups within the city, risking a more unequitable distribution of solar resources as this group is able to capitalize on the benefits provided by solar energy.

To reach a more equitable distribution of solar PV resources in the urban environment, policy is needed that focuses on the groups that have poor access to solar PV. These groups are non-homeowners, home-owners with collective and shared ownership of their roofs and households living in housing provided by social housing corporations. Providing these groups with better means to access solar PV resources can lead to a more equitable distribution of solar PV resources and help to exploit a larger part of the technical PV potential in the urban environment. Something which is desirable in light of the renewable energy transition. This not only is fair and just, but also can act as an enabler of more socially accepted design of the renewable energy transition. The equipment of dwellings of social housing corporations with solar PV in particular, has the potential to alleviate energy costs of a socioeconomic group that generally is more disadvantaged and is already forced to spend a higher share of their income on energy services.

6.3. Further research

As the renewable energy transition gains momentum, the concept of access to renewable energy technologies has started to receive more attention. This attention is important and undoubtedly justified by the need for a more just renewable energy transition. A renewable energy transition that does not solely aim to tackle issues of a deteriorating global climate, which is of course extremely important, but also one that aims to reduce the injustices ingrained in the energy system as we know it today. In this way the renewable energy transition also provides us with an opportunity to restructure patterns and habits that have been incumbent in fossil fuel based energy system.

This research provides evidence that indicates that currently access to solar PV resources is unequally distributed and that new measures of policy are needed to change this. This allows for new research that could focus on designing and evaluating possible measures of energy policy that help improve access to solar PV to socioeconomic groups that currently are unable to seize the potential benefits it provides. At the same time, there is also a need to first more profoundly establish what we understand the concept of access to solar PV or access to renewable energy technologies to be. Although many research in the field of energy justice is of course already being done, it might be beneficial in the long run to first establish a more shared definition of this concept, before trying to improve it. This too lends itself as a pathway for possible future research.

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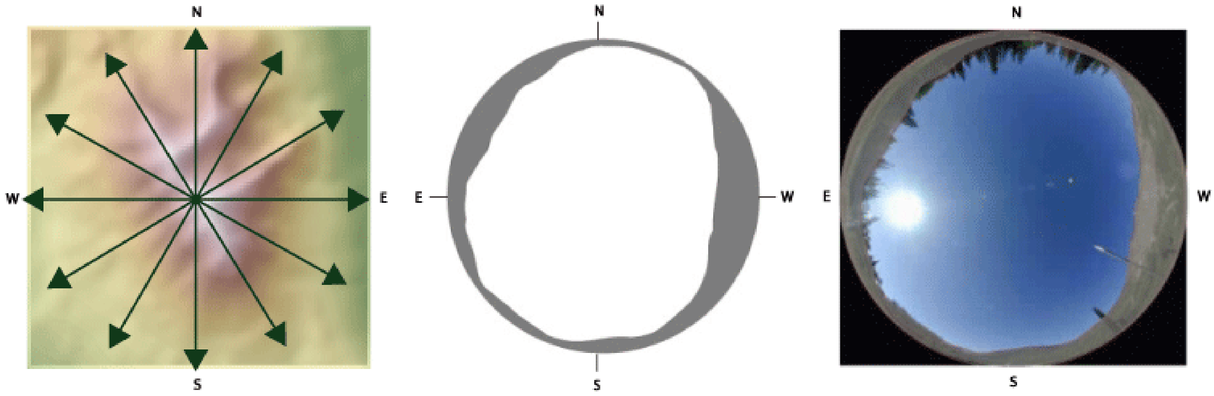
Appendix A

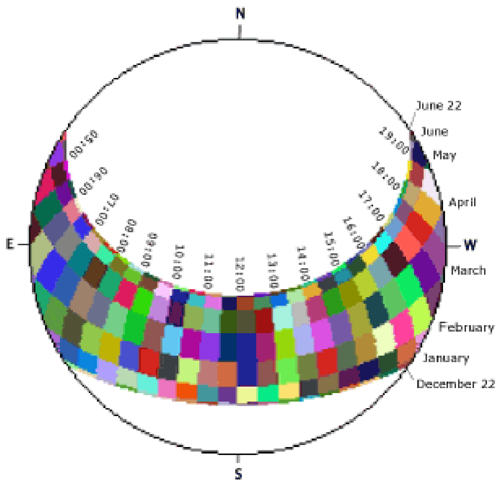
Explanation of Evaluation Method of Technical PV Potential

A key component of the calculation is the creation of an upward-looking hemispherical viewshed. This is similar to an upward looking photograph showing all area for which the sky is visible, see figure A.1. The Area Solar Radiation will evaluate, for a number of pre-specified directions, the maximum angle of sky obstruction. For all directions that are in between the evaluated directions, the model will interpolate the angle of sky obstruction. An example of this process is demonstrated in figure A.1.



Appendix fig. A.1. a) Calculation directions of model b) upward hemispherical viewshed raster derived from fish eye view c) upward hemispherical viewshed (ArcGIS, n.d.)

The direct solar radiation can be calculated by overlaying a sun map on top of each of the created upward-looking hemispherical viewsheds. A sun map displays the position of the sun throughout all hours of the day, and throughout all days of the year. Based on the latitude of the location of interest the sun map is adjusted to cover the right amount of sun hours. Figure A.2 demonstrates an example of a sun map starting from the 21st of December advancing till the 21st of June for a latitude of 45º latitude. Every colored sector represents a different amount of solar radiation originating from for a particular half hour of the day in a certain period of the year, in this case between December 21st and June 21st.



Appendix fig. A.2. Sun map. Every colored sector represents a different amount of solar radiation originating from a particular half hour of the day in a certain period of the year where the sun is located in this position, in this case between December 21st and June 21st.

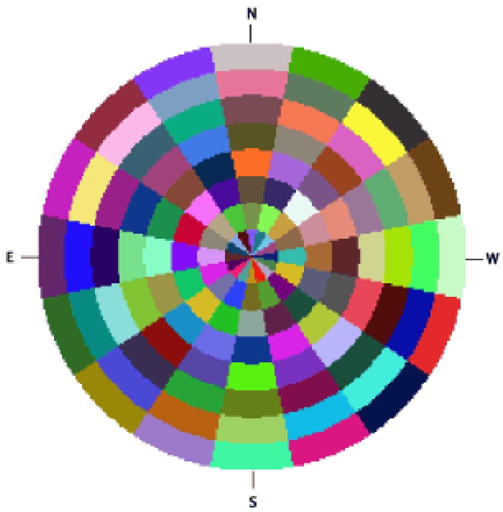
The direct solar radiation for each sector of the sun map can be calculated according equation number A.1. The equation evaluates the direct radiation for each sun map sector by multiplying a solar constant with the transmissivity of the atmosphere for the duration of that sector, corrected for the gap fraction and the angle of incidence. The terms of the equation are clarified below equation A.1.

$$Dir_{\theta,\propto} = S_{const} * \beta^{m(\theta)} * SunDur_{\theta,\propto} * SunGap_{\theta,\propto} * \cos{(AngIn)_{\theta,\propto}} \quad (A.1)$$

where:

- S_{const}– The solar flux outside the atmosphere at the mean earth-distance, known as solar constant.
- $\beta^{m(\theta)}$ – The transmissivity of the earth's atmosphere for a specified path length dependent on the angle of the zenith.
- $SunDur_{\theta,\propto}$ – The time duration represented by each sky sector.
- $SunGap_{\theta,\propto}$ - The gap fraction for each sun sector, proportion of visible sky for the sector.
- $AngIn_{\theta,\propto}$ - The angle of incidence between the centroid of the sky sector and the intercepting surface

To calculate diffuse solar radiation a slightly different map is used, also called a sky map. This is necessary because diffuse radiation can be incident from all directions due to scattering from atmospheric components. Figure A.3 demonstrates a sky map where diffuse radiation is calculated for each sky sector.



Appendix fig. A.3. Sky map (ArcGIS, n.d.). Every colored sector in the sky map represents an amount of incident diffuse solar radiation. The sum of these sectors represents the total amount of incident diffuse solar radiation for the area of study.

For each sky sector, the diffuse radiation is evaluated according to equation A.2. The equation evaluates the amount of incident diffuse radiation per sky map sector, by calculating the diffuse radiation at its centroid, integrating this of the specified time interval, and correcting it by the gap fraction and the angle of incidence.

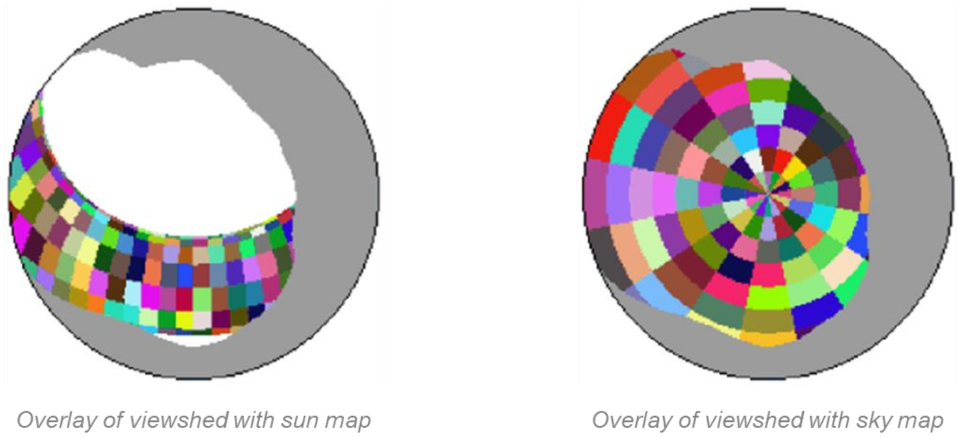
$$Dif_{\theta,\propto} = R_{glb} * P_{dif} * Dur * SkyGap_{\theta,\propto} * Weight_{\theta,\propto} * \cos{(AngIn)_{\theta,\propto}} \quad (A.2)$$

where:

- R_{glb} – The global normal radiation; this is the sum of all incoming direct radiation.

- P_{dif} – The proportion of global normal radiation flux that is diffused.
- Dur – The time interval of analysis.
- $SkyGap_{\theta,\propto}$ - The gap fraction, proportion of visible sky for the sector.
- $Weight_{\theta,\propto}$ - The proportion of diffuse radiation originating in a sky sector relative to all other sectors.
- $\cos AngIn_{\theta,\propto}$ - The angle of incidence between the centroid of the sky sector and the intercepting surface.

By overlaying the sun map and the sky map on the upward-looking viewshed, the model will recognize for which of the directions the direct radiation and diffuse radiation will have to evaluated. A visualization of such overlay is presented in figure A.4. In the figure the grey area represents the obstructed sky directions.



Appendix fig. A.4. Overlay of viewshed (ArcGIS, n.d.) In these pictures the sun map and sky map are overlaid on top of the hemispherical viewshed to determine which sectors from the sun and sky map should be included.

The total global solar radiation per specified area is calculated by summing the amounts of direct and diffuse solar radiation, according to equation A.3.

$$Global_{tot} = Dir_{tot} + Dif_{tot} \quad (A.3)$$

By going through this process for every cell of the DEM an insolation map is produced that provides information on the amount of Wh/m^2 received per cell of the DEM. By limiting this process to strictly the area of interest, in this case the rooftop surface area of the buildings within the municipality of The Hague, the computation time is significantly reduced. This is necessary because the calculation of solar insolation for large geographic areas can be very time consuming. The result of this process is a solar insolation map of all rooftop area of the municipality of The Hague. The insolation map can be used to convert incoming solar insolation into potential electricity generated through solar PV panels on rooftops.

The results of the evaluation of the technical rooftop PV potential in The Hague will be illustrated using the single neighborhood Willemspark. This is done to visualize the results at a higher level of detail. The evaluation of technical PV potential has resulted in the solar map presented in figure A.5. This map stores information for the total amount of incident solar radiation in MWh/year per cell on the map. The blue cells represent areas that receive low levels of solar radiation and the red areas represent cells that receive high levels of solar radiation.

Appendix fig. A.5. Solar radiation map of neighborhood Willemspark.

When applying the corrections as for the conditions specified in section 3.4.3, only the cells remain that fulfill the requirements of installing solar panels, this is displayed in figure A.6. It can be seen that he blue colored cells are removed from the map, and that basically only the red colored cells remain. When aggregating all cells within the pre-specified rooftop boundaries the total amount of solar radiation received for the respective rooftop in MWh/year is calculated. When the size of the rooftop is equal to or larger than 25 m^2, the slope is not too steep, and the total amount of received solar radiation meets the threshold of 800 kWh/m^2, then the rooftop will be included in the technical PV potential.

Appendix fig. A.6. High radiation cells Willemspark.

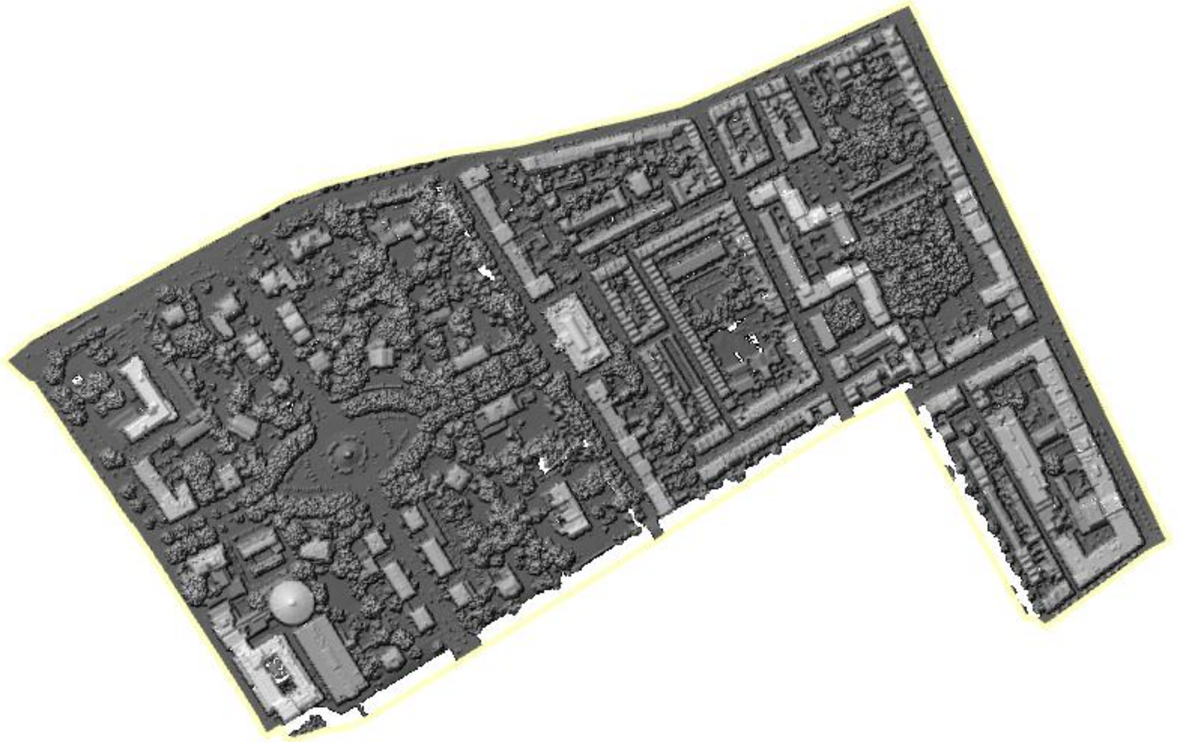
Figure A.7 shows for each rooftop the amount of electricity that could potentially be generated on each rooftop for the neighborhood Willemspark. This is calculated by multiplying the total incoming solar radiation with the solar PV efficiency coefficient and the performance ratio (see section 3.4.3). This results in a number of MWh of electricity that potentially can be generated per year for each building of Willemspark. When aggregating this number for all suitable rooftops per neighborhoods, the technical PV potential can be computed for all neighborhoods across The Hague.

Appendix fig. A.7. Potential electricity produced aggregated per suitable building of Willemspark.

Appendix B

Sample of Hillshade DEM

Figure B.1 shows the effect of adding a 3D hillshade effect to a DEM. By doing this, 3D effects not present in the regular DEM are more adequately visible.



Appendix fig. B.1. Sample of DEM with 3D hillshade effect.

Appendix C

List of full neighborhood names

Appendix tab. C.1. List of full neighborhood names with their respective abbreviations as displayed in figure 3.13.

Name	Abbreviation	Name	Abbreviation	Neighborhood name	Name
Bosweide	BOSW	Transvaalkwartier-Midden	TM	Stadhoudersplantsoen	STAD
Tedingerbroek	TB	Uilennest	UIL	Sweelinckplein e.o.	SW
De Reef	REEF	De Rivieren	RIV	Koningsplein e.o.	KO
Lage Veld	LV	De Lanen	DL	Zeeheldenkwartier	ZEE
Zonne Veld	ZV	De Velden	VELD	Archipelbuurt	ARC
Vlietzoom-West	VLIE-W	De Vissen	VIS	Willemspark	WIL
Vliegeniersbuurt	VLI	Zijden/Steden/Zichten	ZSZ	Rond de Energiecentrale	ROND
Kijkduin	KIJK	Duinzigt	DUZ	Kortenbos	KORT
Bohemen en Meer en Bos	BMB	Waalsdorp	WD	Voorhout	VH
Morgenstond-West	MW	Arendsdorp	AD	Uilebomen	UILB
Morgenstond-Oost	MO	Kerketuinen en Zichtenburg	KERK	Zuidwal	ZW
Ockenburgh	OCKEN	Houtwijk	HOUT	Schildersbuurt-West	SCHW
Componistenbuurt	CB	Venen/Oorden/Raden	VOR	Schildersbuurt-Noord	SCHN
Waldeck-Noord	WN	Dreven en Gaarden	DG	Schildersbuurt-Oost	SCHO
Kom Loosduinen	KL	De Uithof	DU	Huygenspark	HUYG
Van Hoytemastraat e.o.	VH	Kraayenstein en Vroondaal	KRAAY	Marlot	MAR
Morgenstond-Zuid	MZ	Duindorp	DD	Burgen en Horsten	BH
Bosjes van Pex	BP	Erasmus Veld	EV	Oostduinen	OOSTD
Rosenburg	RB	Hoge Veld	HV	Belgisch Park	BELG
Eykenduinen	EYD	Parkbuurt Oosteinde	PO	Rijslag	RIJ
Leyenburg	LB	Landen	LAN	Westbroekpark	WBP
Nassaubuurt	NB	Rivierenbuurt-Zuid	RZ	Duttendel	DUT
Haagse Bos	HB	Rivierenbuurt-Noord	RN	De Venen	VENE
Bloemenbuurt-West	BW	Bezuidenhout-West	BW	Morgenweide	MORG
Bloemenbuurt-Oost	BO	Bezuidenhout-Midden	BM	Singels	SING
Bomenbuurt	BB	Bezuidenhout-Oost	BO	De Bras	BRAS
Vruchtenbuurt	VB	Kampen	KAMP	Rustenburg	RUST
Heesterbuurt	HB	Westvliet-Oost	WEST-O	Oostbroek-Noord	ON
Valkenboskwartier	VBK	Waterbuurt	WAT	Transvaalkwartier-Noord	TN
Binckhorst	BH	Waldeck-Zuid	WZ	Oostbroek-Zuid	OZ
Rietbuurt	RIB	Statenkwartier	STA	Zuiderpark	ZUID
Laakhaven-Oost	LO	Oud Scheveningen	OUDS	Moerwijk-West	MOEW
Moerwijk-Oost	MOEO	Vissershaven	VISH	Moerwijk-Noord	MOEN
Groente- en Fruitmarkt	GFM	Scheveningen Badplaats	SB	Moerwijk-Zuid	MOEZ
Laakhaven-West	LHW	Visserijbuurt	VISB	Nieuw Waldeck	NW
Spoorwijk	SP	Van Stolkpark en Scheveningse Bosjes	VSSB	Zorgvliet	ZORG
Laakkwartier-West	LKW	Geuzenkwartier	GEU		
Laakkwartier-Oost	LKO	Vogelwijk	VOG		

Appendix D

Reasons for removal of neighborhoods from dataset.

Appendix tab. D.1. Reasons for removal of neighborhoods from analysis.

Code	Neighborhood name	Reason for removal
VLI	Vliegeniersbuurt	Business park
TB	Tedingerbroek	Highway area
OOSTD	Oostduinen	Natural park
REEF	De Reef	Incorrect data due to recent construction of new houses with solar PV
RIV	De Rivieren	Industrial area/ business park
KERK	Kerketuinen en Zichtenburg	Industrial area/ business park
BH	De Binckhorst	Incorrect data due to new construction projects
MAR	Marlot	All solar panels installed at Louwman Museum, skews data
ZUID	Zuiderpark	All solar panels installed at Sportcampus, skews data
DU	De Uithof	All solar panels installed at ice skating hall, skews data
ZORG	Zorgvliet	All solar panels installed at Museon-Omniversum
VSSB	Van Stolkpark en Scheveningse Bosjes	All solar panels installed at Madurodam
VLIE-O	Vlietzoom-Oost	Industrial area
VLIE-W	Vlietzoom-West	Industrial area
RB	Rosenburg	Neighborhood with health facilities, not residential area
VISH	Vissershaven	Solar panels installed in harbor skews results
OCKEN	Ockenburgh	Majority is no residential area

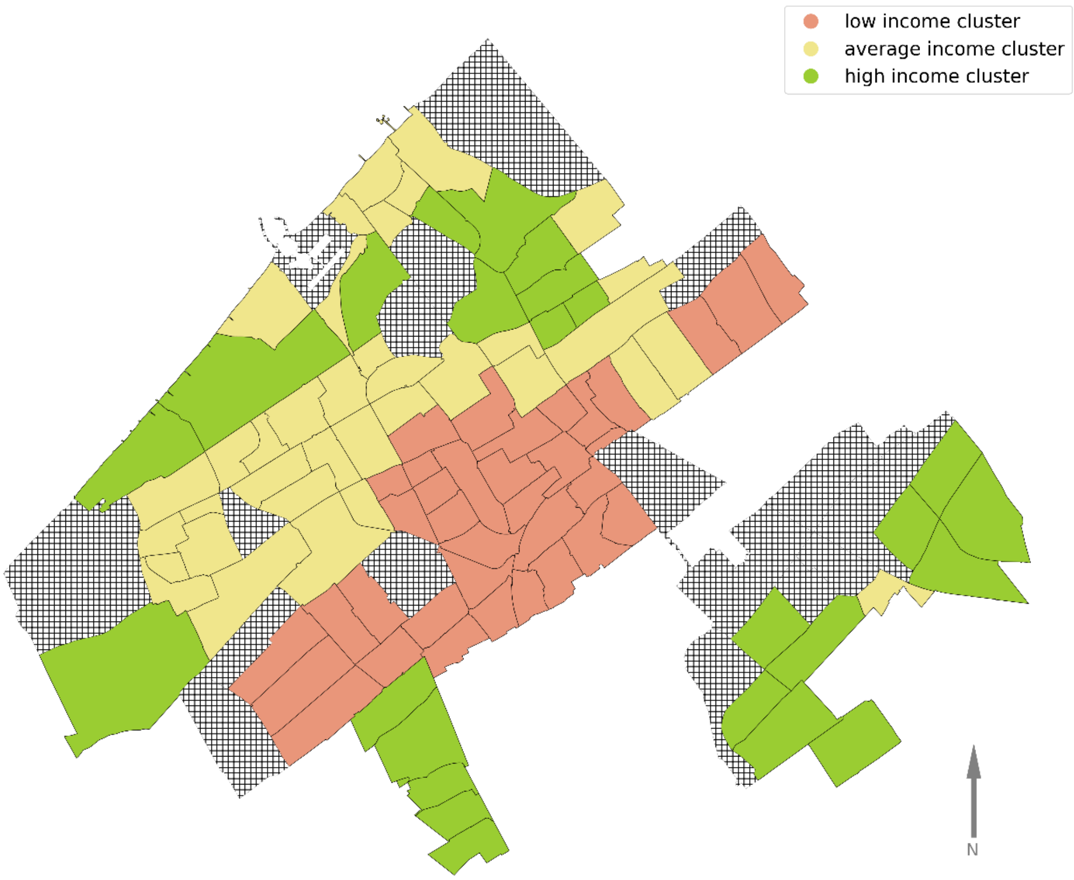
Appendix E

Varying parameter k in clustering analysis

To verify the results of the clustering analysis presented in the previous section, the same analysis is performed for different values of the input parameter *k*. If the results from these analyses demonstrate similar patterns, this would mean that the clustering results from the first analysis are more likely to be part of a structural pattern.

Clustering analysis (k=3)

Figure E.1 presents the results when performing the same clustering analysis for the input parameter *k=3.* When visually comparing the results of this analysis to the initial analysis, it can be seen that the low-income and average-income clusters remain intact compared to the outcome for *k=4* (Fig. 4.3. Clustering output (k=4)). The above-average and high income cluster seem to be merged into one cluster, in order to reduce the number of total clusters from 4 to 3. This indicates that these two clusters are most alike, out of the clusters formed in the initial analysis.



Appendix fig. E.1. Clustering output (k=3)

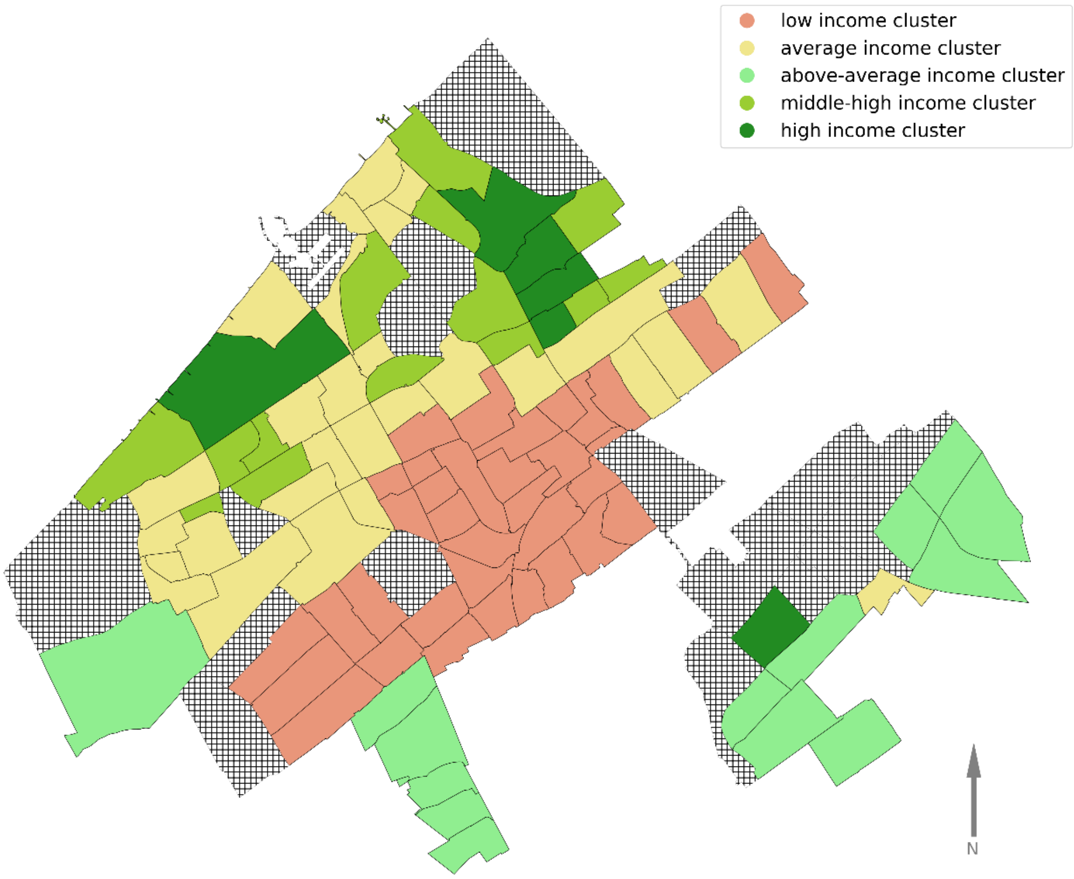
When exploring the mean values of these clusters, the same patterns remain established, as can be seen in table E.1. Two clusters remain with high shares of apartment buildings and both low solar PV adoption levels. Of these two clusters, the average income cluster has a slightly higher average level of adoption, while also having a higher average share of Dutch natives and a higher share of owner-occupied homes. The high income cluster, in this analysis, is the conjunction of the more advantaged clusters determined in the clustering analysis with *k=4*. Its average values indicate better access to solar PV, and its adoption levels are much higher than average.

Appendix tab. E.1. Mean cluster values for (k=3)

	Clusters			
Variables	Low income	Average income	High income	The Hague mean
% owner-occupied homes	26.08	54.76	66.24	*42.7*
% apartment buildings	85.67	81.87	37.67	*76.5*
% Dutch natives	24.74	60.97	58.08	*43.1*
Average household income (€/year)	32 717	46 422	72 568	*43075*
Average # of solar panels per household	0.18	0.27	1.1	*0.35*

Clustering analysis (k=5)

Figure E.2 presents the output when performing the clustering analysis for setting *k=5.* Again the same patterns can be observed. The low income cluster and the average income cluster as determined in figure E.1 remain relatively intact, though it can be seen that the high income cluster falls apart into three smaller separate clusters.



Appendix fig. E.2. Clustering output (k=5)

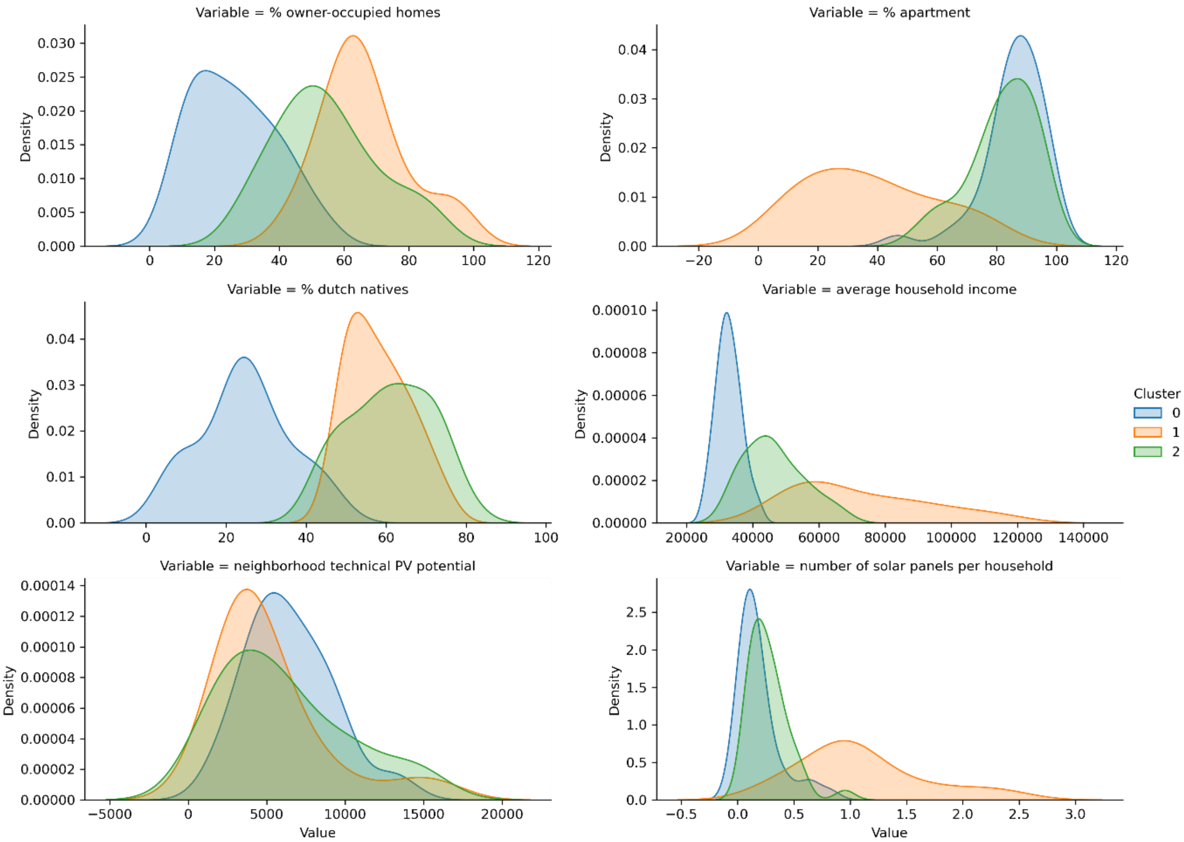
Table E.2 shows the mean values for each cluster. It can again be observed that adoption levels per household are specifically low in the clusters that have high shares of apartment buildings, and vice versa.

Appendix tab. E.2. Mean cluster values for (k=5)

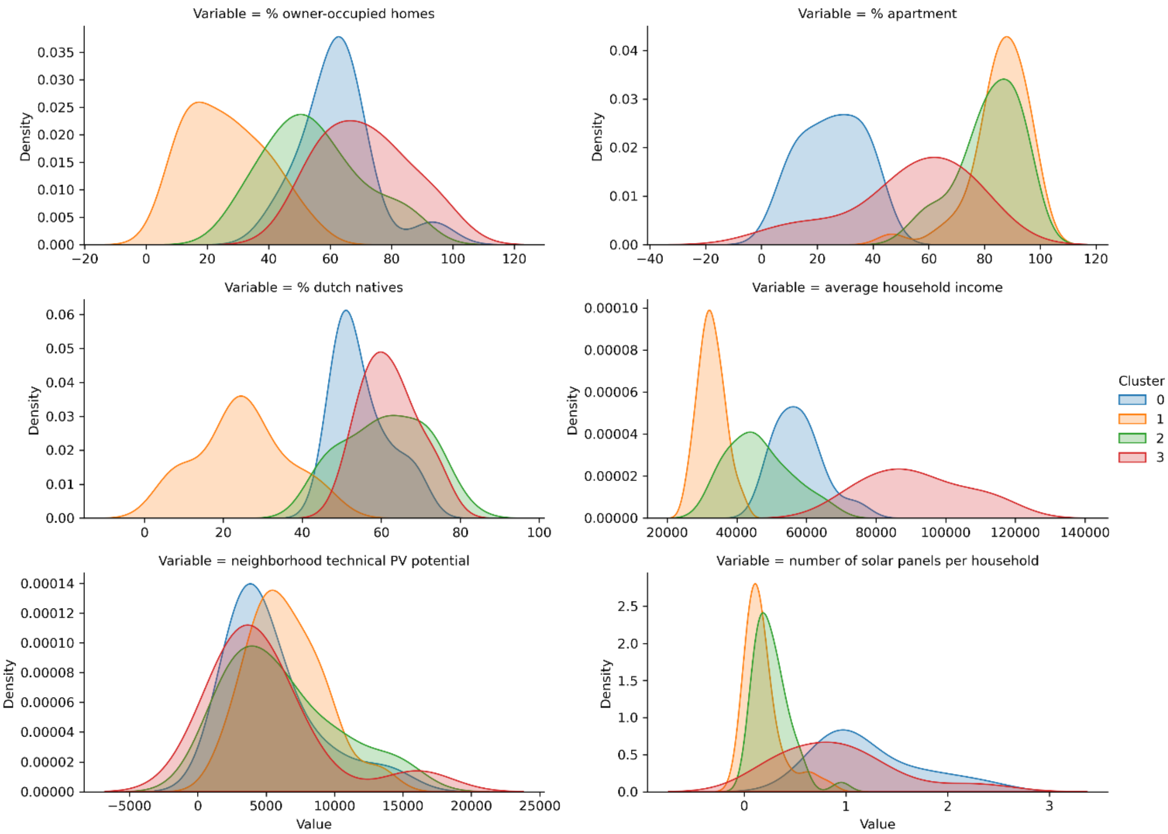
	Clusters					
Variables	Low income	Average income	Above-average income	Middle-high income	High income	The Hague mean
% owner-occupied homes	25.72	48.83	62.31	68.00	79.05	*42.7*
% apartment buildings	85.61	82.47	25.23	76.70	40.13	*76.5*
% Dutch natives	24.11	59.54	54.93	63.07	62.43	*43.1*
Average yearly household income	32 651	42 350	57 721	65 450	101 700	*43075*
Average # of solar panels per household	0.18	0.24	1.23	0.46	1.18	*0.35*

Appendix F

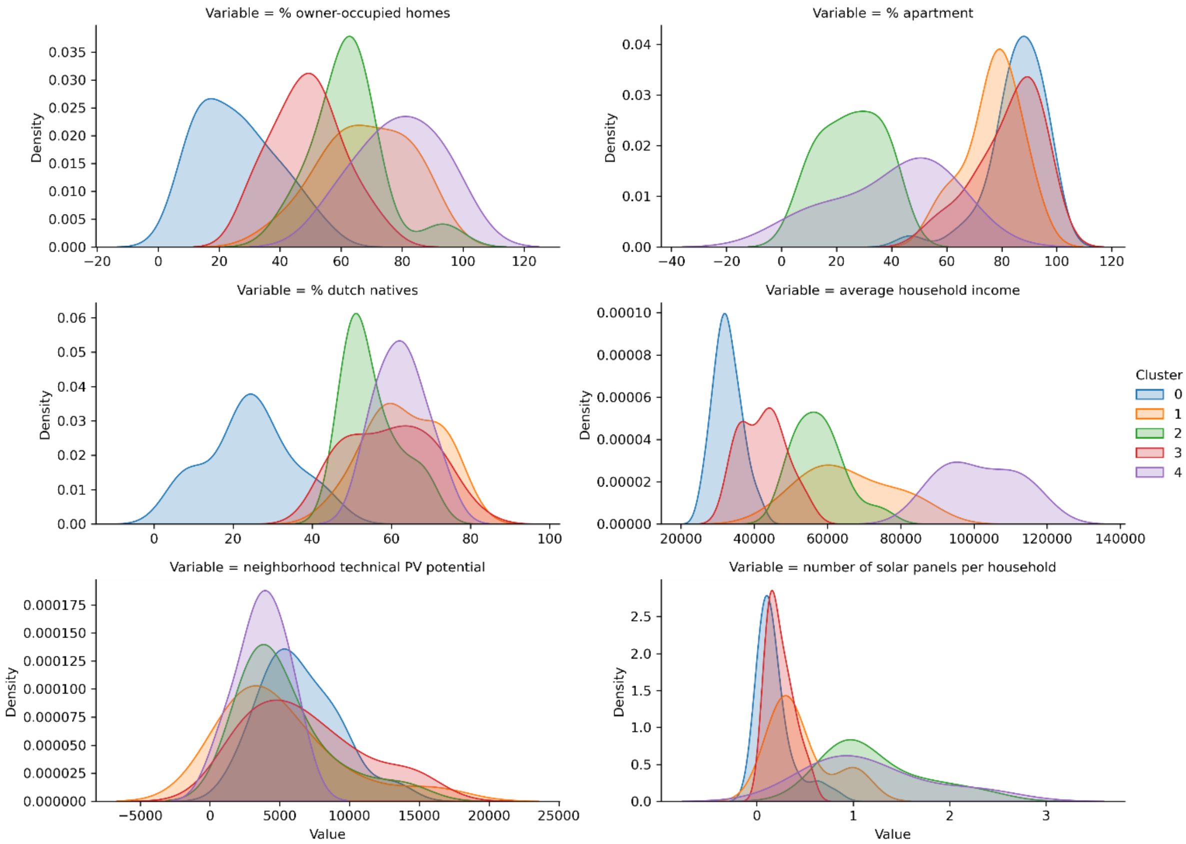
Clustering output distributions



Appendix fig. F.1. Distributions for clustering output k=3.



Appendix fig. F.2. Distributions of clustering output k=4



Appendix fig. F.3. Distributions for clustering output k=5.