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# Identifying the geographical potential of rooftop systems: Space competition and synergy

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ABSTRACT

Urban areas face severe challenges in mitigating and adapting to climate change within limited space. One solution is to develop multifunctional rooftop systems, which use underexploited urban rooftop spaces. Two main options have been to add greenery by installing extensive green roofs (EGRs) or to generate renewable energy by installing photovoltaic panels (PVs). Recently, combining the two systems on one rooftop (EGR-PV) to harvest both benefits has gained attention. Not every rooftop is suitable for such installations, which makes it difficult to estimate the scale of space a city can expect from rooftops to add greenery, renewable energy, or both. This study presents a geographical potential model using building parameters, a building stock layer, and LiDAR data to simultaneously identify the potential for installing EGRs, PVs, and EGR-PVs on rooftops, highlighting the competition and synergy between EGRs and PVs at the building level. As an empirical illustration to support future multifunctional urban rooftop space planning, Amsterdam was used as a case study. The results show that 47 % of rooftops are suitable for EGRs, which could expand the current greenery space by 6 %, and 55 % are suitable for PVs which could sufficiently provide electricity to households by 2030. Moreover, competition exists for 3.2 %, whereas synergy exists for 42 % of the existing rooftops.

## 1. Introduction

Urban areas are suffering from increasing environmental challenges such as heat stress and air pollution (IPCC, 2018) Due to space scarcity, cities have been exploring the extent to which multifunctional rooftops can facilitate climate change adaptation and mitigation measures. In recent years, two technical options have dominated the development of multifunctional rooftop systems. One is the placement of extensive green roofs (EGRs) on existing rooftop spaces to minimise climate stressors such as heat stress, flood risks, and air pollution (Francis & Jensen, 2017; Odli et al., 2016; Shafique et al., 2018; Zhang & He, 2021). The other is installing rooftop photovoltaic panels (PVs) to generate renewable energy, which reduces fossil fuel demand and thus mitigates climate change (Todeschi et al., 2020) Installing rooftop PVs in cities has advantages over implementing them in rural areas, on rooftops or as PV farms in rural, as it puts less stress on power grids owing to the proximity of electricity consumption and production and as it reduces (natural) land use occupation in case of the PV farms. It also lowers the experiences climate injustice when (only) rural areas are made responsible for reducing the climate footprints of cities.

However, technical and climate factors, such as carrying capacity, roof slopes, and orientation, as well as shadings caused by surrounding structures, may make some rooftops less suitable for use in EGRs or PVs. Hence, to support multifunctional rooftop development in cities, it is important to simultaneously evaluate the rooftop potential for EGRs and PVs. This enables the identification of the space that is technically compatible for both systems, whereby spatial competition[1] needs to be addressed by either choosing one system or creating synergy in the form of combining vegetation and PVs on top of each other on existing rooftops (EGR-PV).

This study develops a spatial analysis model that can simultaneously identify the geographical rooftop potential of EGRs and PVs by

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[1] Spatial competition is defined as the competition for rooftop space where roofs have the capacity to install either a green roof or a solar roof.

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examining building properties such as slope, orientation, load-bearing, and shading on the roof (Fakhraian et al., 2021). A spatial analysis for PV suitability of rooftops has been done before (Copper et al., 2017; Melius et al., 2013). Yet, we haven't come across many studies though that combines a spatial analysis of PV suitability, EGR suitability and EGR-PV suitability. Therefore, an empirical study on the municipality of Amsterdam was used to demonstrate the power of the model to appraise the potential synergistic and competitive relationship between EGRs and PVs in the rooftop space of the municipality. Amsterdam is an interesting case because of its wide variety of building types and construction ages. Thus, a wide spectrum of buildings could be identified to demonstrate the functioning of the model. The main research questions were as follows.

1. What are the most relevant parameters to assess the geographical potential of rooftop spaces for the installation of EGRs and PVs?
2. In the case of Amsterdam, to what extent are EGRs and PVs competing in the development of multifunctional rooftop spaces in the city?
3. To what extent can spatial competition be resolved by creating synergy in the form of EGR-PVs?

The remainder of this paper is organised as follows. A literature review is presented in Section 2. A description of the development of the spatial analysis model is provided in Section 3. In Section 4, the use of the model for Amsterdam is demonstrated, followed by a discussion. Section 5 concludes the paper and recommends future research and policy development.

## 2. Literature review

### 2.1. Multifunctional rooftop systems

Over the past decade, two technological options have dominated the development of multifunctional rooftop systems: green roofs and PVs.

Green roofs are commonly referred to as vegetative roofs. EGRs are a type of green roof with a shallow substrate layer on rooftops consisting of small plants, such as sedum, which are mostly resistant to cold and heat (Naranjo et al., 2020). Green roofs can also be intensive, including larger plants such as bushes and trees. Intensive green roofs are often used for urban farming, rooftop gardens, and other societal benefits in urbanised areas (Karteris et al., 2016). Multiple studies have only focused on extensive and semi-intensive green roofs because intensive green roofs are too heavy to apply and are used only in limited specific cases (Karteris et al., 2016). Previous literature has shown that EGRs can significantly help to overcome climate stressors in urban regions, such as reducing heat stress (Francis & Jensen, 2017; Herath et al., 2021; Odli et al., 2016; Zhang et al., 2019), minimizing flood risks (Francis & Jensen, 2017), reducing air pollution (Shafique et al., 2018), replenishing biodiversity (Mayrand & Clergeau, 2018), and insulating residential housing (Peng & Jim, 2013; Todeschi et al., 2020).

In addition to greenery, cities also increasingly need electricity due to urban and economic development and the overall electrification of society. This means a higher demand for oil and gas to be used directly or in power plants, which negatively affects the climate (Shafique et al., 2020). This can be partly solved by relying more on renewable energy sources, among which solar power is the most feasible in cities (Hu et al., 2015). PVs are rooftop systems that are designed to supply renewable energy. In particular, PV installations are increasing significantly. PV systems on residential rooftops have increased 2.5 times compared to 5 years ago.[2] Among the residential houses, 18.8 % had PVs on their roofs.

Recently, growing attention has been given to combined EGR-PV systems. This combined system reduces the energy demand and increases the electricity output owing to the increased efficiency and insulation (Abdalazeem et al., 2022). Environmentally speaking, EGR-PV systems reduce greenhouse gases and simultaneously reduce heat stress around the building. Furthermore, the EGR-PV system increases plant growth, plant duration, and species richness owing to the presence of moisture under PVs (Chemisana & Lamnatou, 2014; ISSO, 2020; Schindler et al., 2018; van der Kolk et al., 2020). According to Van Der Kolk et al. (2020), shading EGR plots (1 $m^2$ area) by PVs provides 6.4 more plants on average on the shaded plots compared to the unshaded plots. Meanwhile, introducing EGRs below PVs can stabilise electricity generation efficiency by evaporating and cooling the ambient temperature of the roof and removing dust particles (Abdalazeem et al., 2022; Shafique et al., 2020). Additionally, enhancing the production of PVs may reduce the maintenance costs of green roof soil and mitigate $CO_2$ emissions (van der Kolk et al., 2020). Thus, there are several beneficial synergies, making it relevant to simultaneously analyse the feasibility of these two urban rooftop functions.

### 2.2. Modelling of multifunctional rooftop systems

Several studies have investigated which parameters can indicate suitability for installing green roofs, particularly EGRs.[3] For example, Silva et al. (2017) suggested a step-by-step approach framework to observe the green roof potential of rooftops in Lisbon. This study examined different aspects of buildings and the environment, such as the slope of the roof, roof support, and dispersed green areas in urban areas. Using these multiple indices helped identify the locations of the green roofs. Other research has focused more on relating the hotspots of ecosystem services to assess where green roofs are actually needed (Gwak et al., 2017; Langemeyer et al., 2020). Another study integrated the building, environmental, and social criteria of green roofs, using deep learning, machine learning, remote sensing, and GIS methods to quantify the potential of green roofs in urban areas (Xu et al., 2020).

Previous research has also been conducted on the potential of urban rooftop spaces for PV installation. This potential can be divided into multiple sub-potentials, namely, physical, geographical, technical, and economic potential (Fakhraian et al., 2021). Physical potential is the amount of potential solar radiation on a rooftop. The limitations are determined based on the amount of energy that the sun can actually provide. The geographical potential is determined by the rooftop geometry, such as the slope of a roof, together with the shading on the rooftop from other buildings or objects such as trees. The economic potential concerns the costs, lifetime of a system, and constraints, together with regulations. Finally, the technical potential determines the output that the PV system can deliver. This study focuses on geographical potential.

Multiple datasets and methodologies have been used to model the geographical potential of rooftop spaces for PVs. LiDAR is a commonly used dataset for assessing the (geographical) potential. For instance, Brito et al. (2011) used LiDAR data to assess the solar radiation using the Solar Analyst extension for ArcGIS in Lisbon (Brito et al., 2011). In Stuttgart, Germany, researchers identified the potential of solar panels using LiDAR, GIS, and 3D models to estimate the slope and orientation of rooftop spaces and to calculate the amount of electricity that can be generated (Strzalka et al., 2012). Other research uses the digital elevation model to evaluate the orientation and slope of buildings and connects this with the electricity demand per household (Mavromatidis et al., 2015). Hong et al. (2017) used the azimuth and altitude to calculate the position of the sun for each month and hour to assess how the shadow behaves during the year and evaluate how much area is not

[2] https://weblog.independer.nl/persbericht/bijna-1-op-de-5-woningen-heeft-zonnepanelen/?referrer=https%3A%2F %2Fwww.google.com %2F&referer=https %3A %2F %2Fwww.google.com %2F.

[3] see Table 1 for further elaboration of the models including parameters that are used

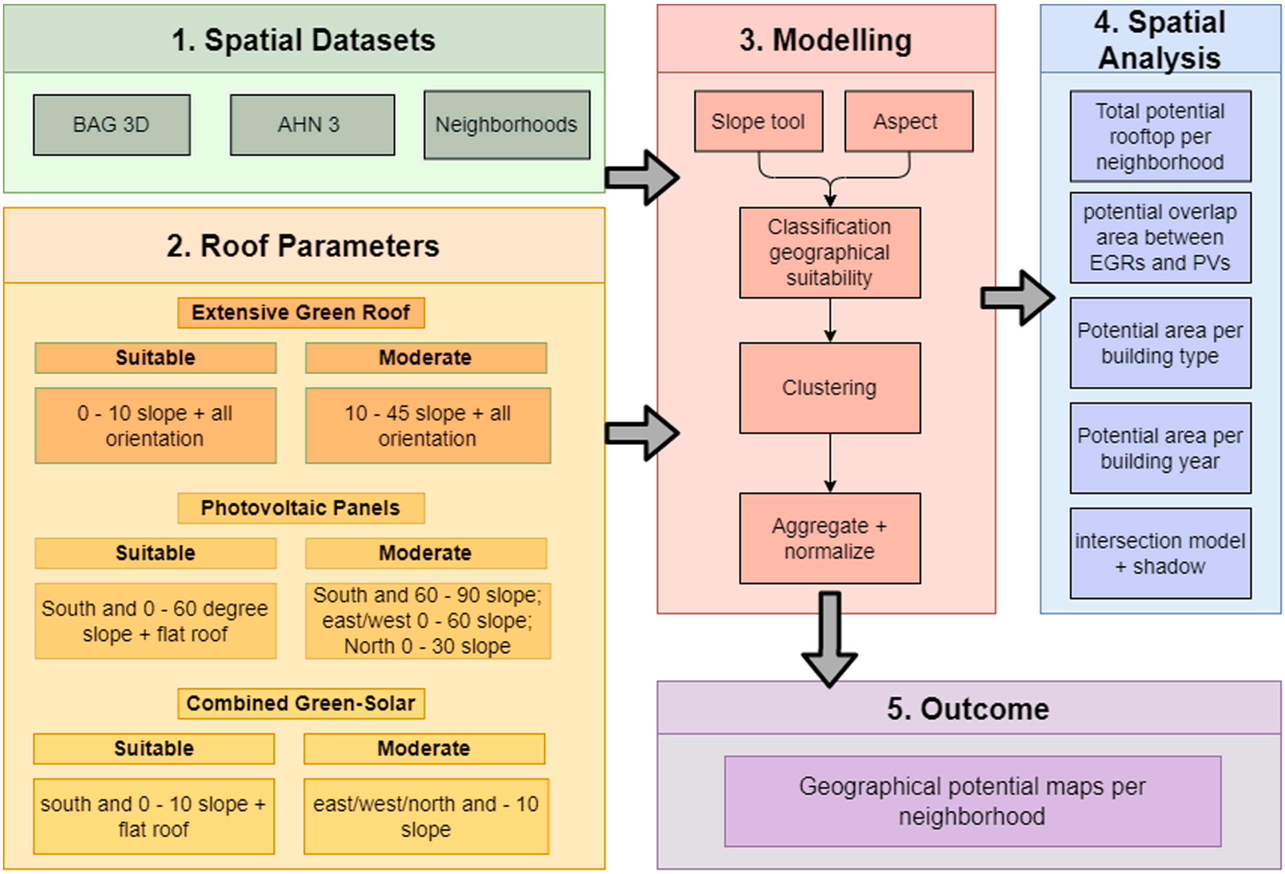


**Fig. 1.** Modelling scheme including the datasets, parameters, modelling, analysis, and outcome (note: GPM = Geographical Potential Model, BAG = Basisregistratie van Adressen en Gebouwen, AHN = Actueel Hoogtebestand Nederland, EGRs = Extensive Green Roofs, PV = Photovoltaic Panel).

in the shaded area (Hong et al., 2017). Notably, for the evaluation of the geographical potential of rooftop space for PV systems, building properties such as slope and orientation, together with the shadings from the surroundings of the building, become prominent.

While the synergy of combining EGRs and PVs is promising, there remains a lack of studies on the geographical potential of rooftop spaces for such multifunctional installations. Therefore, this study aims to fill this knowledge gap by developing a model that can simultaneously evaluate the geographical potential of urban rooftop space for EGRs and PVs, thus providing insights into space competition and synergy between EGRs and PVs.

## 3. Methodology

The geographic potential model (GPM) is built using a spatial analysis approach, where building parameters, a building stock layer, and LiDAR data are used to assess area clusters on rooftops that have the geographical potential to install and maintain one of the three rooftop systems: EGRs, PVs, or EGR-PVs. The modelling scheme is illustrated in Fig. 1, which contains five methodological compartments: 1) spatial datasets, 2) roof parameters, determining the geographical suitability of the rooftop space, 3) modelling, 4) spatial analysis, and 5) outcome, defined in maps.

The model was built with the software ArcGIS 10.6.1, and Python[4] was used to model the datasets on building stocks, building properties, and elevation for the entire Netherlands. The model was adaptable to any desired analysis scale in the Netherlands. In this study, the municipality of Amsterdam was used as an illustrative example to demonstrate the five methodological compartments.

### 3.1. Spatial datasets

To analyse the geographical potential of Dutch rooftop spaces for EGRs and PVs, two types of data were used: elevation and building stock. The elevation data is collected from the 'Actueel Hoogtebestand Nederland 3′ (AHN3) dataset ("PDOK - AHN3 downloads," 2018). The cell size of the data is 0.5 × 0.5 m. Building stock data were assembled from the 'Basisregistratie van Adressen en Gebouwen' (BAG 3D) dataset (tudelft3d, 2017). The neighbourhoods of the Netherlands were gathered from 'buurtenkaart 2021′ (CBS, 2021). The model contains data for all municipalities and neighbourhoods in the Netherlands. Appendix A provides a detailed description of each spatial dataset.

In this study, Amsterdam datasets are presented to illustrate the model as an example. The neighbourhoods, including the location of the historical centre of the municipality, are shown in the appendix in Figure B.1. The Municipality of Amsterdam has approximately 900,000 inhabitants and approximately 400,000 houses[5] that vary in terms of construction years. In 2020, the built environment, which is the second largest CO2 emitter of Amsterdam, was responsible for 27 % of the CO2 emissions in the municipality, directly after the electricity sector, which was responsible for 38 %.

[4] The code is available upon request.

[5] Onderzoek.amsterdam.nl. Last accessed on: 2–6–2022.

**Table 1**
Overview of the parameters determining the geographical potential of rooftop space for the installation of GRs (either intensive or extensive green roofs); GRs (green roofs) and PVs (photovoltaic panels).

| System | Parameters | | | | | Location | Reference |
|---|---|---|---|---|---|---|---|
| | Slope (°) | Orientation | Radiation | Load-bearing | Area ($m^2$) | | |
| GRs | 0 and < 15 | | | Age-based | > 200 | Shenzhen | (Hong et al., 2019) |
| GRs | < 1; 1–5; > 5 | | | | > 100 | Braunschweig | (Grunwald et al., 2017) |
| GRs | Flat; not flat | | | | | Xiamen | (Xu et al., 2020) |
| GRs | < 11; 11–20 | | 3–4 h sunlight | | > 100 | Lisbon | (Santos et al., 2016) |
| GRs | < 3; 3–8.5; 8.5–11; 11–30; > 30 | | | | | Lisbon | (Silva et al., 2017) |
| GRs | Flat; not flat | | | Case-related (China) | | Central Luohe | (Shao et al., 2021) |
| GRs; PVs | 0–11; 11–20; 20–45 | N; NE; E; SE; S; SW; W; NW | > 1200 kWh per year | | GR > 100; PV > 50 | Turin | (Todeschi et al., 2020) |
| GRs | Flat | | | Only EGRs, the others are too heavy | | Thessaloniki | (Karteris et al., 2016) |
| GRs | 0–10 | | | > 20 m concrete; < 20 m steel | > 10 | Liege | (Joshi et al., 2020) |
| GRs | 0–45 | | | | | Hong Kong | (Tian & Jim, 2012) |
| GRs | 2–30 | North on southern hemisphere | | | | Melbourne | (Wilkinson & Reed, 2009) |
| PVs | Flat | | No shadow on rooftop in percentage | | > 33 | Seoul | (Hong et al., 2017) |
| PVs | < 45 | | Annual radiation equal to or greater than 1.68 MWh/$m^2$ | | > 10 | Lisbon | (Santos et al., 2011) |
| PVs | | | Calculate highest solar radiation levels for different areas | | | Auckland | (Suomalainen et al., 2017) |
| PVs | Tilt according to Watt/$m^2$ output (flat = >9.5, not flat = 15) | North excluded (292.5–67.5°) | Annual average insolation of 3.62 kWh/$m^2$ /day | | > 10 | Sydney | (Copper et al., 2017) |
| PVs | 0–20; 20–60 | 135 ≤ aspect ≤ 225 or flat | Shading; no shading | | 20–100 for residential; 100–10000 for commercial | Philadelphia | (Bayrakci Boz et al., 2015) |
| PVs | < 45 | | Calculate solar radiation. Calculates distribution with area and orientation | | In radiation calculation | Lisbon | (Brito et al., 2011) |
| EGRs; EGR-PVs | 0–8 preferred for EGR-PV, > 45 for EGR | All, but south grows better | Not asked | The roof needs to be checked by a constructor | All areas | The Netherlands | Solar Sedum (Personal Communication, 20–4–2021) |
| EGRs | > 20 | Important, but not clear which | | If an adult can stand on the roof | All areas | The Netherlands | Company 2 (Personal Communication, 12–4–2021) |
| EGRs | > 68 if enough support | South requires more water | | Check with constructor | All areas | The Netherlands | Company 3 (Personal Communication, 14–5–2021) |

Note: Blank spaces indicate that the reviewed research or practice did not consider this aspect.

### 3.2. Roof parameters

To determine the geographic potential of the rooftops for EGRs, PVs, and EGR-PVs, two key roof parameters (slope and orientation) were introduced in the model, including their thresholds, to classify the rooftop space into two levels of suitability: suitable and moderate.

The roof parameters were determined through a literature review and interviews with experts from companies that install and maintain EGRs in the Netherlands. Table 1 provides an overview of the roof parameters and their ranges used in EGRs and PVs by researchers and practitioners.

Table 1 shows that the slope is a common parameter that is important for both green roofs and PVs. For instance, Grunwald et al. (2017), Joshi et al. (2020), Santos et al. (2016), Silva et al. (2017), Todeschi et al. (2020), and Xu et al. (2020) considered the slope of green roof systems, and T. Hong et al. (2017), Bayrakci Boz et al. (2015), and Brito et al. (2011) considered the slope for PVs. Based on information from green roof companies in the Netherlands, rooftop space with a slope between 0° and 45° is possible for EGRs and 0–60° is possible for PVs (Bayrakci Boz et al., 2015; Tian & Jim, 2012). The most suitable inclination for EGRs is between 0° and 10° (Karteris et al., 2016; Silva et al., 2017; Tian & Jim, 2012). An elevation of 10° or greater requires more attention than flat roofs. Elevated roofs dry out faster than flat roofs which can damage planted vegetation. In addition, elevated roofs have a higher chance of erosion; therefore, more structural implementation is required, which is technically complex and expensive (ISSO, 2020; Tian & Jim, 2012). Therefore, an elevation between 10° and 45° is considered moderately feasible for implementation on rooftops. The EGR-PVs were set at a maximum elevation of 10°. In practice, EGR-PVs can be applied at 0–5°[6] or approximately 8° (Solar Sedum, Personal Communication, 20–4–2021). Therefore, the maximum elevation was set to 10°. Above this elevation, EGR-PVs are not possible because PVs might block too much natural light from the underneath the EGRs.

Orientation is the most important parameter for PVs and is relevant for EGR-PVs. Bayrakci Boz et al. (2015) and the company Solar Sedum (Personal Communication, 20–4–2021) both identify PVs facing towards

[6] https://www.optigruen.nl/systemen/solargroendak/solar-fkd/. Last accessed on: 13–10–2021

**Table 2**
Classification of geographical suitableness of existing rooftop spaces for EGRs (extensive green roofs), PVs (photovoltaic panels), synergy (EGR-PVs), and competition (either EGRs or PVs) in the Netherlands.

| Geographical suitableness (Classified by slope and orientation) | EGRs | PVs | Synergy (EGR-PVs) | Competition (either EGRs or PVs) |
|---|---|---|---|---|
| Suitable | 0–10° (All) | 0–60° (South) | 0–10° (South) | 10–45° (all directions), mix of moderate EGR and suitable/moderate PVs |
| Moderate | 10–45° (All) | 0–60° (East/west) 60–90° (South) 0–30° (North) | 0–10° (East/West/North) | |

the south (135–225°) as most suitable if the slope of the roof is between 0° and 60°. For moderate implementation, where the maximum potential yield (the annual yield of converted electricity) is lower compared to the suitable inclination and orientation,[7] both east (45–135°) and west (225–315°) are possible up to 60°, and north (315–360°; 0–45°) is included as long as the slope is not > 30°. The south can also be extended further by increasing the slope to 60–90°. This is also considered moderate because the yield is lower than the suitable inclination and orientation. EGRs do not have a preferred orientation. Plant growth in shadows or sunlight depends on the choice of the right plant species. Table 2 shows the parameter overview of all the systems.

Shadows are more important for installing PV and EGR-PV systems because they determine the efficiency of roof panels. Orientation and shadows, including the slope, determine how much solar radiation can potentially be reflected on the rooftop and how much is absorbed by these systems. In our model, the orientation and slope combination for PVs are mainly obtained from PV installation companies that show the relationship between the orientation and slope with the yield of PVs.[8] Shadowing is calculated using the hourly and monthly position of the sun. The position of the sun is subdivided into two important parameters: azimuth and altitude. Both parameters were used to assess shadows using the hillshade tool in ArcGIS and the model of Hong et al. (2017). Using the GPM results, the temporal potential was analysed by including shadows.

Load-bearing of existing building rooftops is the most important parameter for the technical implementation of EGRs, as existing rooftops should withstand the surplus weight of new installations. However, this method is not suitable for estimating this parameter for all buildings. In practice, the load-bearing capacity needs to be checked case by case before installation (Solar Sedum, Personal Communication 25–5–2022). Therefore, this parameter is not included in the model. The purpose of our model is to capture the overall potential of urban rooftop spaces instead of guiding the implementation of individual projects. Furthermore, this study focuses on EGRs, PVs, and EGR-PVs. All three systems are relatively lightweight compared to heavy systems, such as roof gardens, which makes load-bearing relatively less critical (Karteris et al., 2016).

The area of the rooftop space is considered to be an important parameter for EGRs to have a better ecological performance (Wong & Montalto, 2020). Bayrakci Boz et al. (2015) considered space to be important for PV systems. However, geographically speaking, all sizes of rooftop spaces can be used for EGRs and PVs (Solar Sedum, Personal Communication, 20–4–2021). All the cutting values of slope and orientation of the buildings are based on previous literature, and in particular are based on Dutch practices in the Netherlands.

### 3.3. Modelling

To model the geographical potential of EGRs, PVs, and EGR-PVs, the slope was first calculated using the slope tool of ArcGIS. AHN3 data were used as inputs. The model calculates the height difference between the raster cells and returns the slope values in degrees per raster cell. The orientation of the building is calculated using the aspect tool in ArcGIS. These parameters are both in raster format with a resolution of $0.5 \times 0.5$ m.

Second, the geographical suitableness of existing rooftop spaces was classified using the cutting values of the parameters defined in Table 2. Third, suitable and moderate categories are clustered together, where the clusters can consist of neighbouring buildings. All the buildings were identified equally and not separately to visualise the maximum output and implementation of these systems on rooftops. The area of each cluster was 10 $m^2$ or larger to reduce the dispersion of the slope and orientation rasters. Clustering provides more realistic potential for implementing EGRs, PVs, and EGR-PVs.

Finally, all the clusters that were selected were aggregated to each neighbourhood and normalised by dividing it by the total rooftop area from each neighbourhood to identify the geographical potential of each neighbourhood without including the structural load-bearing weight. More details of the GPM are provided in Appendix C.

### 3.4. Spatial analysis

When all three rooftop systems are classified as suitable and moderately applicable, they are illustrated via maps for spatial analysis, including total potential rooftops per neighbourhood, potential overlap areas between EGRs and PVs, shadow analysis, and building type and year analysis.

Analysing the overlap areas between EGRs, PVs, and EGR-PVs is important for identifying potential competition and synergy between EGRs and PVs. Because ERG-PVs have a limit to a slope of 10°, this means that an inclination between 10° and 45° does not enable the installation of EGR-PVs. Suitable EGR potentials and EGR-PVs have the same parameter assessments to define their geographical potential. Therefore, in the competitive space analysis, the moderate EGR potential area was compared to the total PV geographical potential by combining the suitable and moderate potential areas together by merging the two datasets. Both datasets were compared by calculating the overlap between the two datasets. This overlap was then introduced as new data, and this potential area was normalised by dividing it by the total rooftop area per neighbourhood to identify which neighbourhood has the most competition in space.

Subsequently, the model is compared with the hillshade tool to identify how much of this area is in shaded or unshaded areas, similar to the research of Hong et al. (2017). The decision was made to assess them separately because shading is temporally dependent. A single moment in time cannot be used to assess whether it is suitable, however, it is possible to identify which month and time of the day has the highest geographical potential for PVs and EGR-PVs. The azimuth and altitude of the sun are calculated[9] for each hour of sunlight for the 15th day of each month and is compared with the GPM, which is based on the slope and orientation of the building. In this way, we can identify how much of this geographical potential is in shaded and unshaded areas to

[7] http://www.induurzaam.nl/2-energie-opwekken/zonnepanelen/zoninstraling-en-orientatie. Last accessed on 15–5–2022
[8] http://www.induurzaam.nl/2-energie-opwekken/zonnepanelen/zoninstraling-en-orientatie. Last accessed on 15–5–2022

[9] https://www.sunearthtools.com/dp/tools/pos_sun.php. Last accessed on 18–5–2022

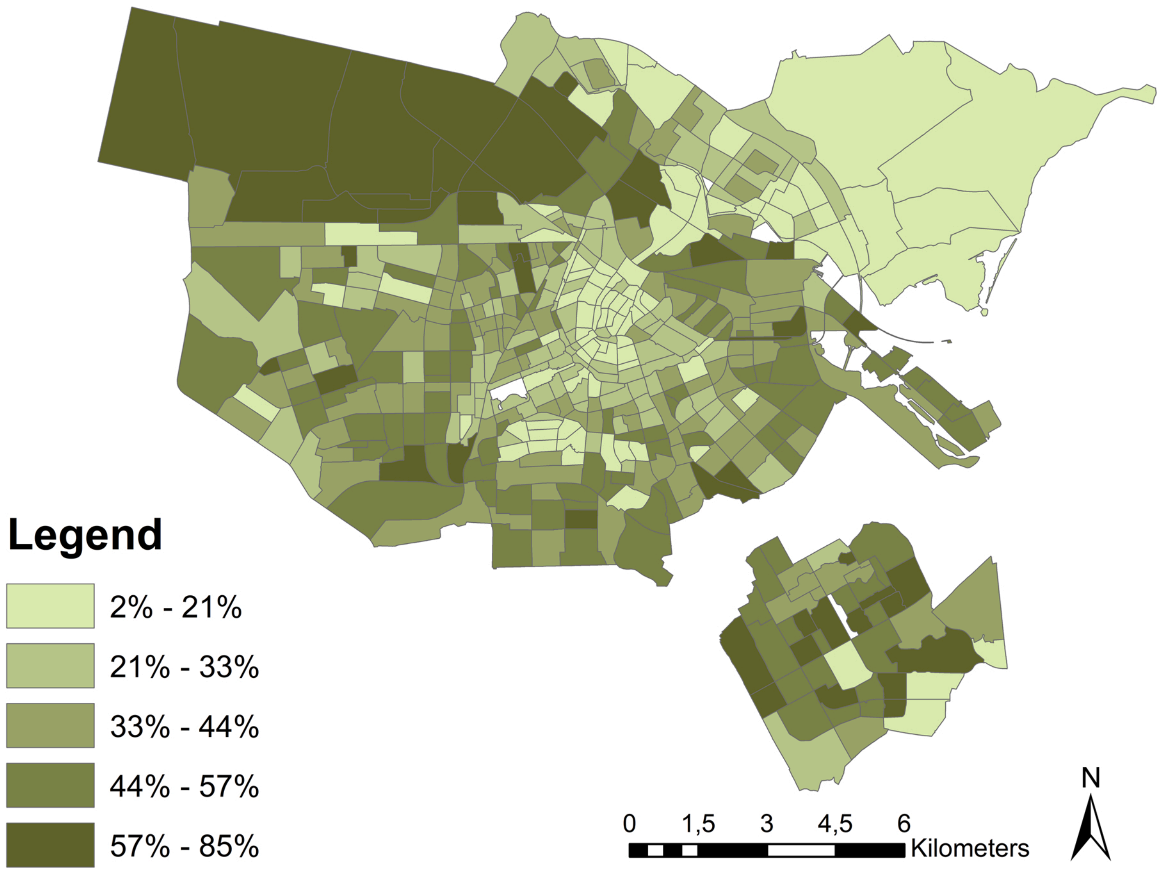


**Fig. 2.** The suitable potential of extensive green roofs per neighbourhood expressed in the percentage of the total rooftop area of each neighbourhood.

understand which month and time of day is most feasible for PVs and EGR-PVs.

Finally, building types and construction years were also introduced to identify the share of geographical potential of the different rooftop systems for different building types, and to understand how the construction year may give an indication of the load-bearing structure of the buildings. For the different building types, all the buildings are categorized into industrial, commercial, service, residential, and other. The share per building type was calculated in a manner similar to space competition analysis. Both building type data intersect with the GPM data and are analysed as the total share for each rooftop type, as well as for each building type. In Appendix E, a table is presented to show the building types defined as the main categories.

## 4. Results of Amsterdam case

In the case of Amsterdam, the GPM estimates that the total rooftop potentials (including suitable and moderate categories) for EGRs, PV systems, and EGR-PVs were 1197 ha, 1404 ha, and 1057 ha, respectively, which were 47 %, 55 %, and 42 %, respectively, of the total rooftop area of the municipality of Amsterdam. Figs. 2 and 3 show the relative suitable potentials per neighbourhood for EGRs and PVs. Areas with moderate EGR and PV potentials are shown in Appendix F.

The amount of green space that can be added to the existing green space in Amsterdam is notable. The EGR potential was 5.5 % of the municipality's total greenery area. As observed in Figure B.2 (appendix B), approximately 35 % of the area of Amsterdam currently has vegetation (Rijksinstituut voor Volksgezondheid en, 2018). Adding EGRs on rooftops could enlarge the area with vegetation from 35 % to approximately 41 % of the city's surface. PV systems contribute to the electricity requirements of cities. The electricity demand of all households in the municipality of Amsterdam is expected to be approximately 0.9 TWh per year in 2030.[10] A yield of approximately 90 % can be achieved by installing suitable PVs on rooftops. If we consider an average output of 350 Watt-peak per PV cell and the size of each cell to be 1.6 $m^2$ (van der Wilt, 2022), then approximately 1.0 TWh can be reached annually. This is sufficient to meet all household electricity demands in Amsterdam. Moderate PV cells have a yield of approximately 70 % and can produce a total of 0.2 TWh annually because the potential moderate area is markedly less than the suitable area of PVs.

As shown in Figs. 2 and 3, both EGRs and PVs have similar patterns, in which the highest potential is located in the municipality of Amsterdam. In particular, both systems have very promising potential in the northwest area, consisting mostly of industrialised buildings with many flat roofs which are very suitable for the implementation of EGRs and PVs. There is also considerable potential in southeast neighbourhoods. These areas are more residential and consist of multiple apartment blocks and flat roofs. The lowest potential of EGRs and PVs is shown in the historic city centre, as the buildings are older and consist of irregular and steep roofs.

### *4.1. Spatial distribution of rooftop space competition and synergies*

The model in this study explores the geographical potential of rooftop space for supplying surplus greenery and producing renewable energy using three rooftop systems. As shown in Table 2, we classify rooftop spaces with a slope of 10° and only have the capacity for one of these systems, and not EGR-PVs. Above a slope of 10°, both EGRs and PVs are still possible but not combined. Therefore, the competition for

[10] https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/duurzaamheid/duurzame-energie/#:~:text=De %20gemeenteraad %20van %20Amsterdam %20heeft,duurzame %20elektriciteit %20op %20te %20wekken

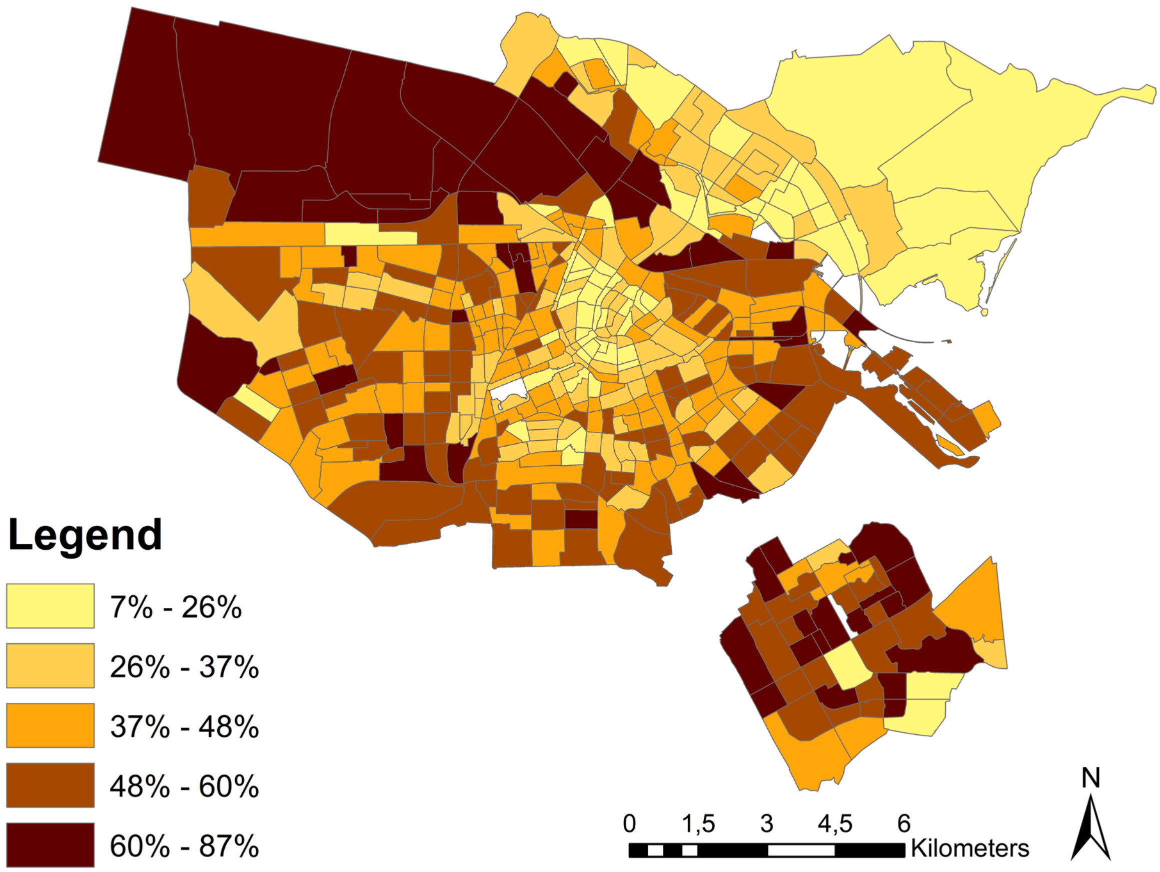


**Fig. 3.** The suitable potential of solar panels per neighbourhood expressed in the percentage of the total rooftop area per neighbourhood.

space between the two systems as well as their synergy were analysed.

*4.1.1. Competition for rooftop space to add greenery and produce energy*

As shown in Fig. 3, certain neighbourhoods have abundant areas suitable for both EGRs and PVs, and both suitable and moderate potentials are combined to show the results of this overlap map. In the GPM, the overlap ranged from 0 % to 32 %. Some neighbourhoods show an overlap between 16 % and 32 %, which requires detailed attention to understand what should be prioritised to have the most optimal outcome for helping to overcome and mitigate climate stressors in urbanised areas. Fig. 4.

*4.1.2. Synergy in space on rooftop to add greenery and produce energy*

It is suitable to install EGRs and PVs between 0° and 10° inclinations. As mentioned above, EGR-PVs can be installed up to 10°, preferably on flat roofs. Otherwise, an insufficient amount of light reaches the EGRs, making it difficult for greenery to grow. In principle, the GPM can identify both the suitable and moderate potentials of EGR-PVs. However, no cluster could be classified between 1° and 10° because all these clusters were smaller than 10 $m^2$. Most clusters were categorised with a flat slope value; therefore, this model is suitable. The geographical potential of the synergy of increasing greenery and simultaneously providing renewable energy on a rooftop for Amsterdam is visualised in Fig. 5. As expected, the synergy potential is the highest in neighbourhoods where the suitable geographical potentials of EGRs and PVs are the highest. Again, the northwest shows significant potential owing to the large number of flat roofs from industrial buildings. EGR-PVs can add approximately 4.8 % of greenery to the total area of Amsterdam. Simultaneously, with an increased efficiency of approximately 3 %, the EGR-PV can facilitate 0.8 TWh annually. This is 90 % of the electricity demand of all the households in Amsterdam.

Previous studies have highlighted that EGR-PVs complement each other's growth (ISSO, 2020; Lamnatou & Chemisana, 2014; Schindler et al., 2018; Shafique et al., 2020; van der Kolk et al., 2020), and it is valuable to install both instead of a single one whenever possible to promote a supply of clean and renewable energy and concurrently increase greenery in dense and grey neighbourhoods. However, the EGR-PV system has a high initial cost (Shafique et al., 2020) and requires more materials than the other systems. Moreover, the system has more weight, which results in a higher burden on the building on which it is installed.

*4.2. Adding shadow to the geographical potential model*

Thus far, the results have identified geographical hotspots in Amsterdam where the three systems can be installed. In addition to the slope and orientation, distinguishing between shaded and unshaded areas can also be important for these systems. Thus, the temporal potential is identified by calculating the extent to which the geographical potential overlaps with the unshaded areas on the rooftops. Calculating for each hour of sunlight, and for the 15th day of each month, Appendix D shows that for all three systems and in the competition for space,[11] during the winter (December–March), most of the potential area is not in unshaded areas, indicating that PVs will have less electricity output. Furthermore, during the afternoon and particularly during the summer months (June–September), most potential is in the unshaded area, which is suitable for PVs and ERG-PVs. EGRs show the same trend, however, because several sedum plants are both cold and heat resistant, it is inconsequential whether they are in shaded or unshaded areas. The shadow analysis for moderate PV and EGR potentials is presented in

[11] Spatial competition is defined as the competition of rooftop space where roofs have the capacity to install either a green or solar roof.

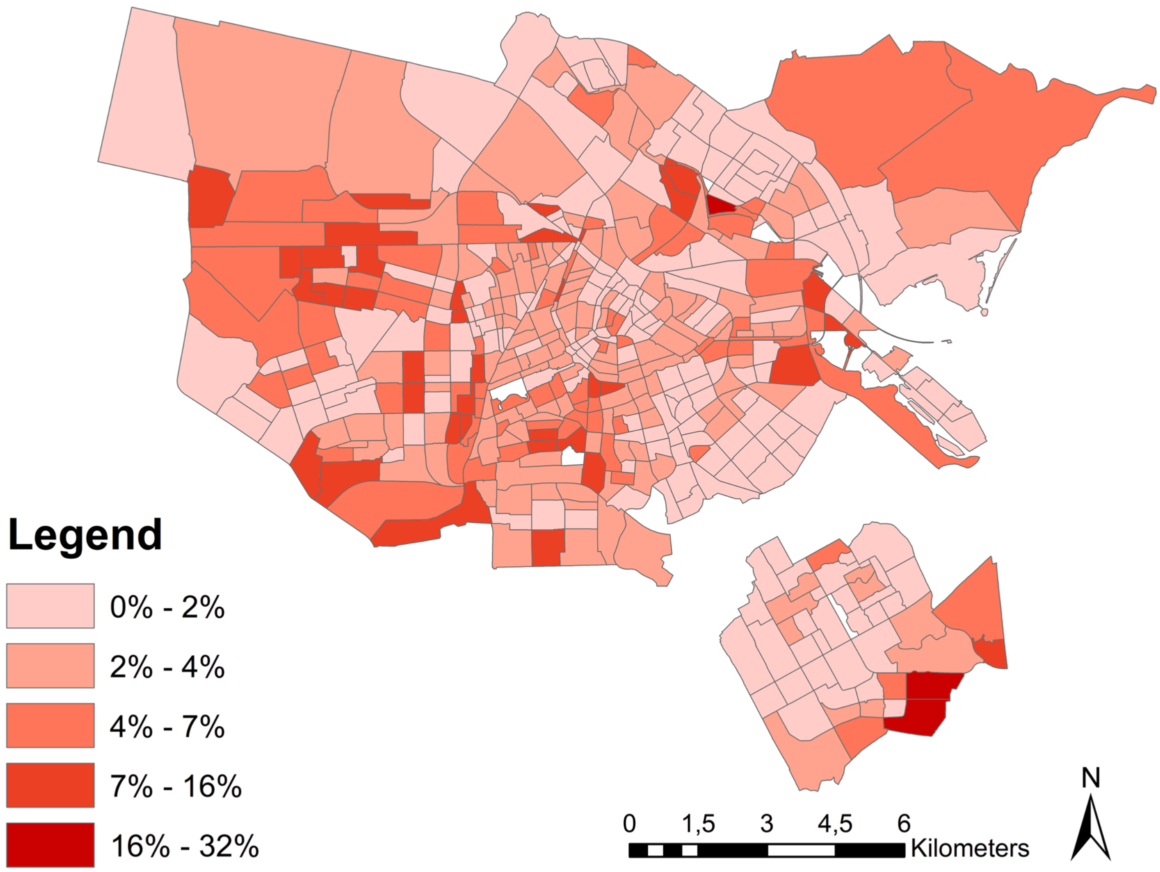


**Fig. 4.** The overlap between extensive green roofs (EGRs) and photovoltaic panels (PVs) per neighbourhood where these systems compete for space. Either EGRs or PVs possible.

Appendix D.

### *4.3. Geographical potential distribution over different building types*

As a complementary analysis, it is insightful to run the GPM for each building type to help inform future policy strategies on which types have the highest potential.

First, the total rooftop area per building type was examined to assess the percentage of the area which has the potential to install one of the three systems. Fig. 6 shows that industrial buildings have the highest potential share of their total rooftop area, followed by services (such as hospitals and sports facilities). Residential buildings are the least suitable for EGRs, PVs, and EGR-PVs. Residential buildings in the Netherlands commonly have steeper roofs, making it difficult to implement these three systems. However, competition for space is highest in residential areas. This is because industrial, commercial, and service buildings have higher shares of flat roofs. However, as shown in Fig. 7, the highest share for each system is residential buildings because residential houses have the highest total rooftop share for the entire municipality of Amsterdam. Looking at the total building share per building type, industrial, residential, commercial, service, and others have shares of 13 %, 45 %, 16 %, 6 %, and 21 %, respectively. This means that, according to the total rooftop area, the residential sector has the largest share in Amsterdam. Appendix G presents the distribution of each building type.

#### *4.3.1. Geographical potential over different building years*

To understand the importance of the construction year, an analysis was conducted comparing the construction year with the geographical potential area.

Fig. 8 shows the distribution of the geographical potential of EGRs, PVs, and EGR-PVs, and the competition for space (excluding the shade) of the building construction years. It is noticeable that most potential is situated around the newer buildings, namely from 1960 onwards. This analysis was added to obtain a proxy measure, as well as to appraise whether different years result in different installation potentials of the three systems. It remains challenging to understand when the load-bearing is sufficient to maintain the weight of the system or when structural change is needed, which makes the suitable areas even more complex and expensive. According to Joshi et al. (2020), before the introduction of the Eurocode (1977), the strength of buildings was overestimated because of less accuracy than after the introduction of the Eurocode (Joshi et al., 2020). If we compare this with our current model, 58 % of the suitable potential for EGR is after 1977, which means that 58 % of the suitable potential area requires more structural adjustments to support its weight on the roof.

## 5. Discussion

The empirical study of Amsterdam demonstrates its high potential in industrialised areas, which consist mostly of buildings with flat roofs. In these areas, both suitable EGRs and PVs are prominent, together with synergy between them. In contrast, competition for space is more prominent in residential areas, which generally consist of steeper roof slopes. This also accounts for the potential of EGRs, PVs, and EGR-PVs. The competition for space is more prominent in residential areas, therefore, more attention should be paid the willingness of people because they are mostly responsible for deciding what to have on their roofs. Because it is a competition for space, both EGRs and PVs cannot simultaneously occur.

There are some limitations to this modelling. First, one of the parameters not included in the GPM is the load-bearing structure on the

 

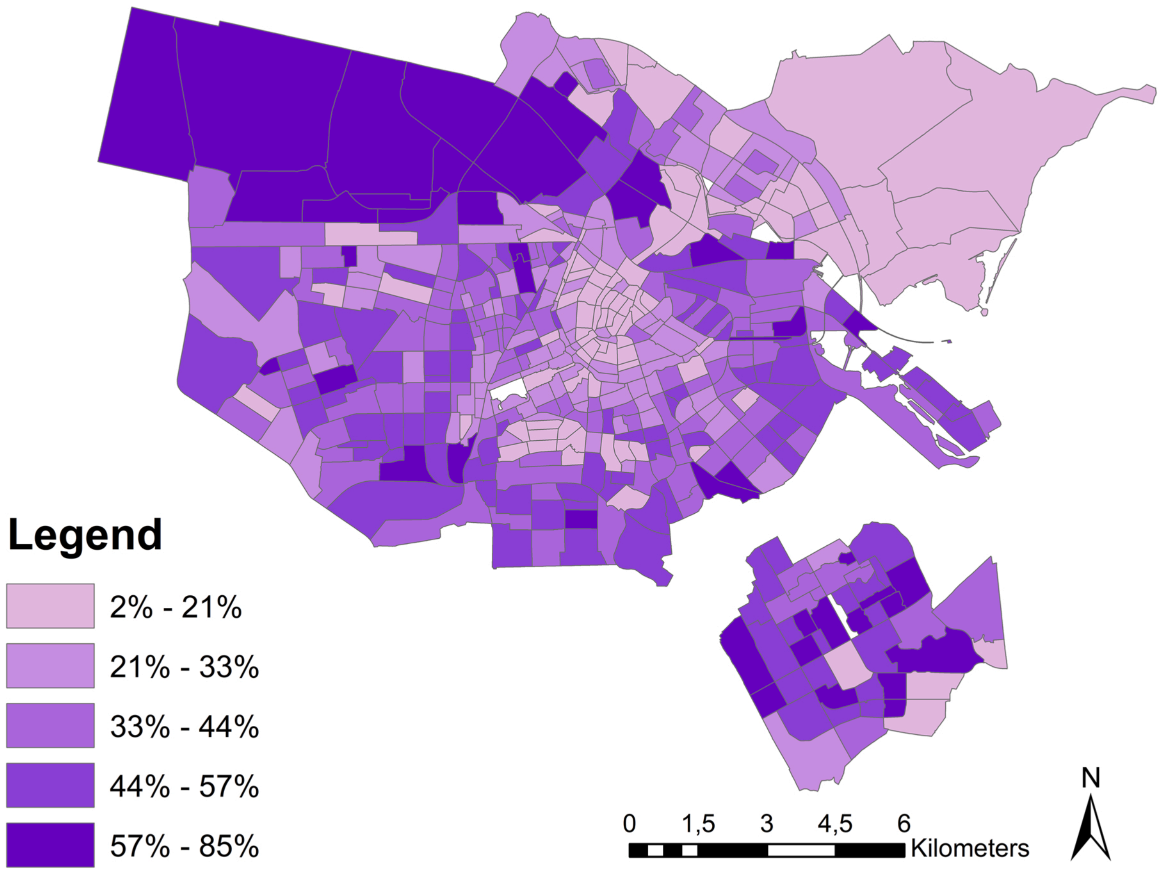


**Fig. 5.** The potential of the EGR-PVs per neighbourhood expressed in the percentage of the total rooftop area per neighbourhood.

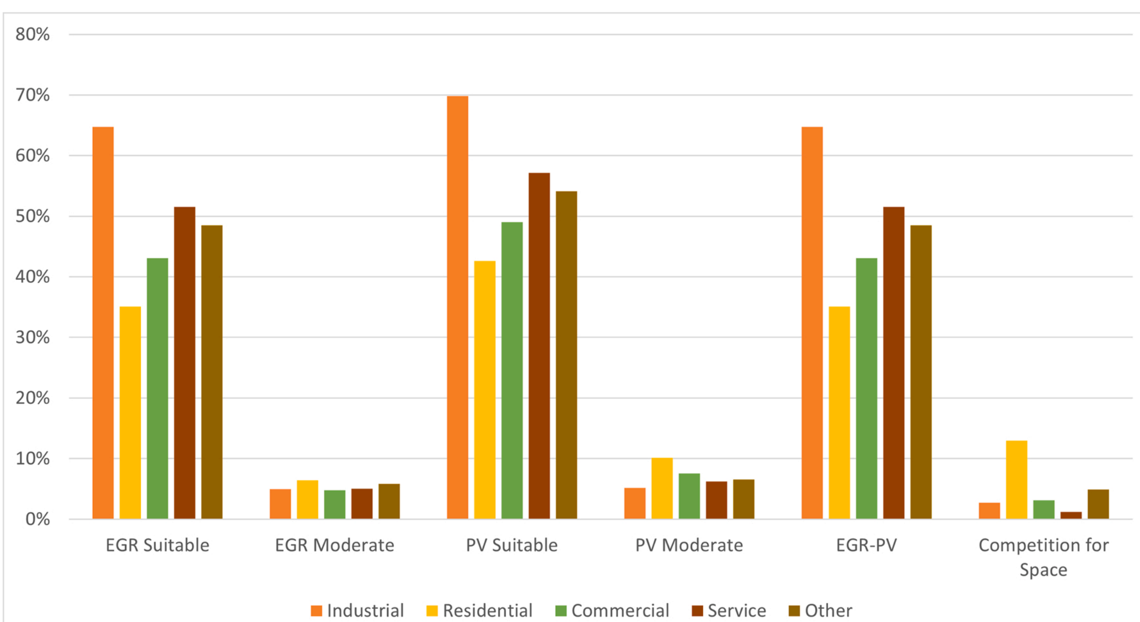


**Fig. 6.** Roof system potential per building type. Expressed in the percentage of the total rooftop area per building type.

surplus weight a roof can withstand. This is a commonly faced limitation because often no data exists that accurately provides the load-bearing structure capability of buildings. However, in our analysis, the year of construction of the buildings was added and then compared with a previous study by Joshi et al. (2020). However, this study was performed and analysed in Belgium. Therefore, it is unclear whether these results will also be accounted for in the Netherlands. Experts in the field, including the company Solar Sedum in the Netherlands, expressed that almost every time they install a green roof, they need to identify the capability for each building individually together with a constructor.

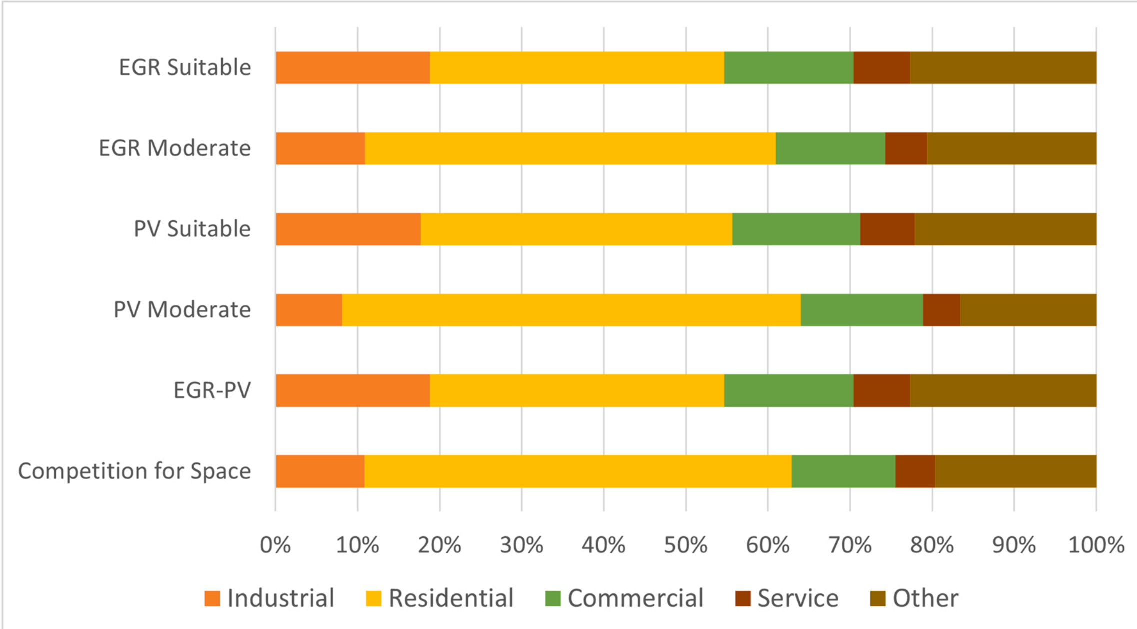


**Fig. 7.** Building type share of total geographical potential of each green roof system.

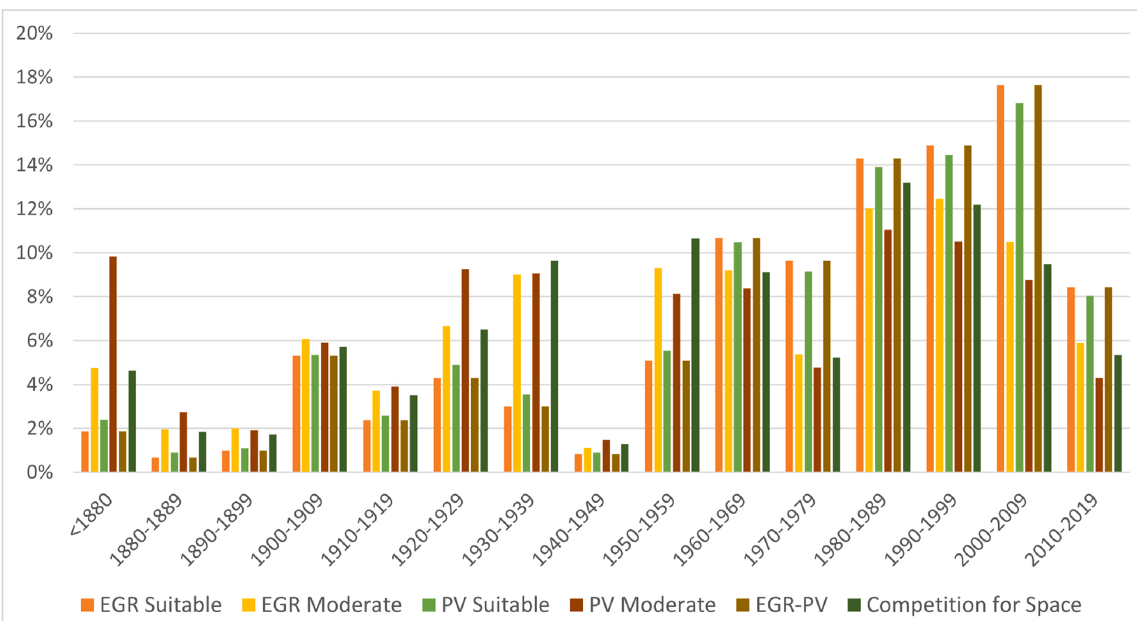


**Fig. 8.** Construction year per rooftop system.

Thus, to complement the construction information of buildings, in practice, it needs to be evaluated (e.g., considering internal changes in homes), which unfortunately is not always done in practice, making it difficult to decide on paper if it would be possible. Installation companies must be careful and always check before installing these systems (Solar Sedum, Personal Communication 25–5–2022).

More research is needed to determine whether there is a correlation between the type of building, the age of the building, and how suitable it is to install EGRs, PVs, or EGR-PVs. If the systems become too substantial for the roof, other lightweight EGRs are possible. Nonetheless, these systems are expensive and reduce the quality of EGR. This trade-off becomes important to the choice of whether installing an EGR is still effective and worth the cost.

Alternatively, reflective white roofs are relatively cheap, easy to implement, and flexible. This roof system is often applied to increase the reflectivity of the roof to increase the albedo and reduce the surrounding heat near the roof and building. However, according to Wang et al. (2020), reflective roofs are most effective in climate zones with more solar radiation, less rainfall, and low wind speeds (Wang et al., 2020). These climate zone characteristics do not align with those of the current Dutch climate. Furthermore, the current focus and willingness for green roof installation in the Netherlands are blue, green, and solar roofs, according to Dutch practitioners (Personal Communication, 10–11–2022). Therefore, this research aligns with the current needs of Dutch society.

This research did not include further building properties such as ownership, monuments, and building safety. This is because this research aims to maximise the installation of these systems in urban areas and indicate how much surplus greenery and energy can be obtained. Further research is needed to observe ownership and regulations for safety to understand where it cannot be installed currently and identify what is required to still be able to install systems such as EGRs, PVs, and EGR-PVs.

In light of some inevitable limitations owing to data availability, particularly the load-bearing structure, a sensitivity check was conducted to validate the model. This was performed using data from existing and installed systems on roofs in Amsterdam (Gemeente, 2020), whereby we can identify the locations of current EGR, PV, or EGR-PV systems. Of all the existing EGRs on roofs in Amsterdam, 99.8 % overlapped with those identified via the GPM. PVs overlapped by 99.8 %, and the EGR-PV system was 100 %. This indicates that the GPM developed in our study accurately identifies where it is possible to install these systems.

As demonstrated by the case study of Amsterdam, the outcomes of the GPM can be valuable for municipalities and policymakers in understanding where rooftop systems can be installed. To complement this information, policymakers can implement financial incentives and other instruments to optimise locations for multifunctional roof systems. Applying roof systems in the most efficient and effective locations can help mitigate climate stressors in cities and surrounding urban and dense areas. In this respect, the distribution of existing greenery can help identify where EGRs should be prioritised. As shown in Figure B.2 (Appendix B), the northwest part of Amsterdam, where the harbour is located, has high potential for EGRs, PVs, and EGR-PVs, and it is clearly visible that these neighbourhoods are less green compared to the other neighbourhoods in Amsterdam. This suggests that there is more potential and necessity to install EGRs.

## 6. Conclusion and recommendations

This study presents a new view on GPM research of rooftop systems by including EGR-PV systems as one of the rooftop systems and identifying the competition for space. This model enables the identification of the slope and orientation of buildings and determines the maximum geographical potential in urbanised areas. In addition, this study presents more insight into the load-bearing structure of buildings and why it is lacking in the literature.

This model has been applied to the municipality of Amsterdam to show how the geographical potential of the rooftop space is in an area that has diverse building types, ranging from historical monuments to an industrial harbour together with high-rise apartments and office buildings. This study provides an important step towards multifunctional rooftop space planning in cities.

The GPM is applicable to the entire Netherlands because it uses a universal approach together with data from the entire country. The strength of the universal approach is that it can be scaled to The Netherlands, and if data allows, it can be scaled up to other countries.

Further research is needed to understand the prioritisation between PVs and EGRs in multifunctional rooftop development, considering space competition and synergy and also environmental benefits and social acceptance to improve the liveability and sustainability of urban areas in the long run.

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Conceptualization: Mike Slootweg, Mingming Hu, Solmaria Halleck Vega, Eveline van Leeuwen, Arnold Tukker; Methodology: Mike Slootweg, Mingming Hu, Solmaria Halleck Vega, Maarten van 't Zelfde, Eveline van Leeuwen, Arnold Tukker; Formal analysis and investigation: Mike Slootweg; Writing - original draft preparation: Mike Slootweg; Writing - review and editing: Mike Slootweg, Mingming Hu, Solmaria Halleck Vega, Maarten van 't Zelfde, Eveline van Leeuwen, Arnold Tukker.

## Declaration of Competing Interest

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

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127816.

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