

## Article

# Namares—A Surface Inventory and Intervention Assessment Model for Urban Resource Management

Elias Naber <sup>1,\*</sup>, Rebekka Volk <sup>1</sup>, Kai Mörmann <sup>2</sup>, Denise Boehnke <sup>3</sup>, Thomas Lützkendorf <sup>2</sup>  
and Frank Schultmann <sup>1</sup>

- <sup>1</sup> Institute for Industrial Production, Karlsruhe Institute of Technology, 76187 Karlsruhe, Germany; rebekka.volk@kit.edu (R.V.); frank.schultmann@kit.edu (F.S.)
- <sup>2</sup> Institute of Sustainable Management of Housing and Real Estate, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany; kai.moermann@kit.edu (K.M.); thomas.luetzkendorf@kit.edu (T.L.)
- <sup>3</sup> Division 4—Natural and Built Environment, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany; denise.boehnke@kit.edu
- \* Correspondence: elias.naber@kit.edu

**Abstract:** Densely built-up areas are challenged by reduced biodiversity, high volumes of runoff water, reduced evaporation, and heat accumulation. Such phenomena are associated with imperviousness and low, unsustainable utilisation of land and exterior building surfaces. Local authorities have multiple objectives when (re-)developing future-proof districts. Hence, exploiting local potentials to mitigate adverse anthropogenic effects and managing the resource of urban land/surfaces have become key priorities. Accordingly, a five-level hierarchy for a land-sensitive urban development strategy was derived. To support the operationalisation of the hierarchy, we present the model Namares, a highly resolved GIS-based approach to enable spatially explicit identification and techno-economic and environmental assessment of intervention measures for advantageous utilisation of available surfaces per land parcel. It uses existing data and covers the management of economic, natural, and technical resources. Nine intervention measures are implemented to identify potentials, estimate investments and annual costs, and assess the appeal of existing subsidies. The approach was applied to a case study redevelopment area in a large city in Germany. The results provide spatially explicit information on greening potentials, estimated investments, subsidy demand, and other quantified benefits. The case study results show the limited potential for additional unsealing of impervious surfaces by transforming ca. 10% of sealed ground surface area into new urban gardens. At the same time, up to 47% of roof and 30% of facade surfaces could be utilised for greening and energy harvesting. The approach enables a comprehensive localisation and quantitative assessment of intervention potentials to enhance decision support in land-sensitive urban development strategies.

**Keywords:** urban surfaces; geographic information system; assessment; soil; facade; roof; plot-level; potential; techno-economic; climate change adaptation; namares



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## 1. Introduction

Increasing service demands and the influx of population into urban areas put pressure on maintaining access to basic needs and the quality of life in cities [1–4]. Not only do urbanisation and urban lifestyles increase the demand for resources from energy, water, land-use, and product consumption perspectives [1,5,6], but also climate-change-induced and observable unfavourable conditions, such as urban heat islands, will become more severe and intense in densely built-up areas [1,7]. Partly on that account, international principles [8] (such as the Sustainable Development Goals [9]) and national legislation call for impactful and sustainable improvements [10] in order to mitigate and counteract the mentioned problems and other accompanying adverse environmental impacts, such as biodiversity loss [1,11–15], disturbed water balances and flows [1,16,17], harmful emissions [18–20], and soil loss [1,15,21]. Therefore, authorities are challenged to cope with

tasks beyond their current formal purview of governance, quickly gain practical experience, and develop competencies for managing local resources to mitigate anthropogenic impacts, adapt to climate change, and future-proof cities [22–28]. Accordingly, systems for location-specific information handling are needed to provide data-driven science-to-policy integration [29,30]. In this context, (re-)development strategies for densely built-up environments comprise a wide field of actions that focus on the resources of land/surfaces, which can be categorised into vegetation, water, built form, and materials [31]. Intervention strategies for vegetation, water surfaces, and materials deal with surface features that are variable/adjustable. On the contrary, the built form possesses fewer variable or adjustable features [31].

Indeed, built-up areas feature surfaces with different levels of utilisation. On the one hand, the soil surfaces are highly utilised, high in demand, finite, and can be unsealed or sealed [32–34]. Furthermore, available surfaces are subject to diverse and diverging utilisation goals and pressures. Consequently, managing urban soils has been identified as a (wicked) problem [35]. On the other hand, fewer or completely unutilised (fabricated/artificial) surfaces on buildings and other infrastructures offer exploitable surface areas and deliver considerable benefits when used [34,36–39]. Hence, vital elements of sustainable urban development strategies are land-use change, surface greening, and proactive management of available surfaces [40–42]. Accordingly, land/soil surfaces are an essential resource that should be used efficiently and sparingly. Remaining (fabricated) surfaces can be used to conserve land, compensate for the local consequences of changes in land use, and add value to ecosystem services.

Thus, we derived a five-level hierarchy for a land-sensitive urban development strategy (Section 2). Furthermore, based on the literature review in Section 1.1, we developed a highly practical and resolved GIS-based approach (Sections 3.1 and 3.2) for creating a complete inventory of surfaces in a district to enable spatially explicit identification and techno-economic and environmental assessment of nine intervention measures (Sections 3.3 and 3.4) for advantageous utilisation of available surfaces per land parcel.

### 1.1. State of the Art

Regarding specific intervention measures, many studies and reviews highlight the social, ecological and economic benefits and downsides of (technical) ecosystem-based adaptations, nature-based solutions, and green infrastructures (roof or facade greening, urban gardens, etc.) [43–47]. Therefore, this section focuses on relevant strategy development and related challenges.

The meta-review of O’Riordan et al. [48] presents literature on eco-services of urban soils and the impacts of impervious surfaces. This and other reviews point out the gaps regarding neglected aspects, such as biomass, material fluxes, and cultural services, and the need for better geographical representation and interconnection of research and practitioners (q.v. next paragraph). Veerkamp et al. [49] reviewed assessment studies on green and blue infrastructure. Based on their comprehensive review, the authors concluded that small-scale measures are less explored, and that there is high heterogeneity in assessment methods and a wide variety of indicators. Accordingly, comparability and uncertainty in measure evaluation are recurrent issues. Hanna and Comín [50] investigated the relation of the assessments to the Sustainable Development Goals and determined that most studies focus on goals 11, 13, 15, and 16. However, they observed that most studies focus only on particular aspects of these goals. Therefore, they reasoned that research in this field is in an early stage.

Concerning measure sizes and location, less literature can be found. Browning et al. [51] reviewed and investigated the locations of and distances to green spaces and found that the nearness of green spaces matters in urban settings. Particularly, health benefits were observed for smaller buffer radii of less than 500 m from green spaces. Beninde et al. [52] stated the importance of soil green area size and corridors regarding size and species richness. Depending on the conservation objective, species richness declines rapidly for

green-space patches below 27 ha within urban landscapes, 4.4 ha for urban-adaptor species, and 53.4 ha for urban-avoider species (*ibid.*). These requirements are substantial in urban redevelopment and suggest the expansion of available and large green spaces or the provision of green corridors. However, Goddard et al. [11], Dewaelheyns et al. [33], O'Brien et al. [53], Amorim et al. [54] and Ring et al. [55] pointed out the significant role of smaller green patches or private gardens. At the same time, they flagged their negative impacts and disservices, which can arise if non-native biotopes are created or if the opportunities for synergy are not utilised. In conclusion, the authors argued for viewing private gardens or small green spaces collectively as interconnected patches and networks instead of separate entities. Accordingly, considering small-scale fragmented surfaces and surface patches is necessary for urban development planning (which is less explored [49]).

In most literature, the development of green spaces is regarded as a solution for more sustainable, healthy, and higher quality-of-life cities. In comparison, disservices and possible management challenges are underrepresented. Lyytimäki and Sipilä [56] discussed disservices to the ecological, socio-ecological, and social systems; and concluded that minor disservices triggered by smell, cleaning/care hassle, and damages to structures can have high negative impacts on acceptance. Hence, they emphasise the need to consider local knowledge and the affected social system. Säumel et al. [57] presented urban green services and disservices for urban streets and concluded that trade-offs must be considered. Based on experts' assessments, Campagne et al. [58] stated that the perception of (dis-)services varies among the different stakeholders and agents. Accordingly, they emphasised the importance of implementing explicit management of ecosystems to develop services and limit disservices. In accordance with this, the review of Ignatieva et al. [59] on urban lawns as nature-based solutions emphasises the necessity to engineer urban lawns ecologically or to diversify soil-based solutions to maximise benefits and limit disadvantages. In addition to Goddard et al. [11], Lyytimäki and Sipilä [56], and Säumel et al. [57], Gaertner et al. [60] discussed 17 papers on non-native species in urban environments and called for more research in this area. In the risk assessment study of von Döhren and Haase [61] on street trees, the authors discussed the lack of data on particular vegetation performances, which was also observed by reviews focused on urban green services, e.g., [49], and disservices, e.g., [58].

Xing et al. [62] reviewed the implementation of green infrastructures and design decisions. They subdivided design decisions into vegetation selection, supporting infrastructures, and operations (irrigation and maintenance). Moreover, they identified the need for respective models and data. The contributions to benefits, trade-offs, possible disservices, and assessment or management tools call for a better understanding and representation of location, onsite, and operative decisions. Regarding this, a multitude of tools has been developed [28]. Voskamp et al. [28] provided an overview of 43 tools that support the planning of nature-based solutions for urban climate adaptation. The review identified well-acknowledged challenges, such as expertise and building competencies, along with less-acknowledged challenges, such as financial planning and governance of urban development. Concerning the latter, spatially explicit approaches are rare. Hence, there is an academic and practical void in assisted, measure-based financial planning that enables an integrated and collaborative approach to urban planning and governance. Despite the large sample reviewed by Voskamp et al. [28], many additional conceptual and applied approaches can be found in the literature. As a compliment to the comprehensive review of Voskamp et al. [28], missing aspects are raised in the following.

For planning and assessing nature-based solutions, commercial and academic analytical and simulation engines exist, which were unmentioned by Voskamp et al. [28]. For example, ENVI-met [63] and PALM4U [64] are often used to assess urban fabric and the microclimatic effects of greening but require a high level of expertise and are computationally intensive. Additionally, distinguishing between internal (in-house) and external (outsourcing) assessments and planning is missing, which would indicate the competencies required and the scenarios of application. The same applies to national/regional meteorological

services offered to help authorities invest in adaptation measures [65]. However, many of these services tend to be generic, or cannot be modified for specific goals or locations, nor repeated at will. Besides, many small and medium enterprises offer urban green infrastructure assessment services, and authorities use these services in one-off investigations or confined projects that lack continuity and standardisation.

Popular approaches for detection of potentials or prioritisation of actions are descriptive statistics or geographic statistics. To identify trade-offs and synergies, Sylla et al. [66] used Getis-Ord for spatial hot-spot analysis and principal component analysis. Grunwald et al. [67] proposed a data-based approach and defined specific metrics to assess measures, which other studies have adopted (e.g., [68]). However, this approach was limited to roof areas and did not quantify expected benefits. Ring et al. [55] identified a lack of tools on the plot-level. Thus, they conceptualised a methodology to account for plot-level urban green infrastructure evaluation. They calculated different metrics and performed utility analysis based on expert evaluations. Norton et al. [38] proposed another framework for prioritising urban green infrastructure measures and concluded that the skills needed to perform data handling, preprocessing, and analysis may not be available in local governments. In essence, many approaches offer assessments of inventories but do not quantify exploitable potentials or provide guidance for prioritisation. Moreover, Selmi et al. [69] and Jayasooriya et al. [70] indicated that data of different quality levels, spatial levels, and scales often have to be used, which introduces uncertainties and makes it difficult to perform a consistent plot-based prioritisation.

A commonality between all reviewed papers is the identification of modelling and data challenges. Mainly, these challenges are related to availability, validity, comprehensiveness, spatial and temporal resolution, and accuracy (e.g., [71–74]). In this regard, many studies are limited concerning the surface inventory data. In addition, assessment input data and model parametrisation are also limited. Hence, many studies apply various methods for data acquisition. The inventory of city objects (e.g., surfaces) can be compiled via cadastral surveying (onsite measurements/classification by experts) and remote sensing (mainly through airborne or satellite surveys). Typical remote sensing data are thermal infrared, light detection and ranging (Lidar), hyper-spectral, multi-spectral, synthetic aperture radar, stereo imaging, and digital photogrammetry. Although these remote acquisition approaches yield promising and much-needed data—e.g., airborne remote sensing can easily achieve sub-meter resolutions, whereas satellite-based measurements are often much coarser [74]—the conversion to a detailed object or surface inventory is often restricted by the achievable resolution, the capabilities of classification algorithms, and the availability of resources to process, obtain, or buy data. Input parameters are predominately collected through empirical studies, from the literature, using statistics, or by applying parameterised models. A major challenge is to ensure the transferability of observed, computed, or researched data. Additionally, comparability of inputs and assumptions has to be ensured to enable fair, reproducible, and objective assessment of different measures.

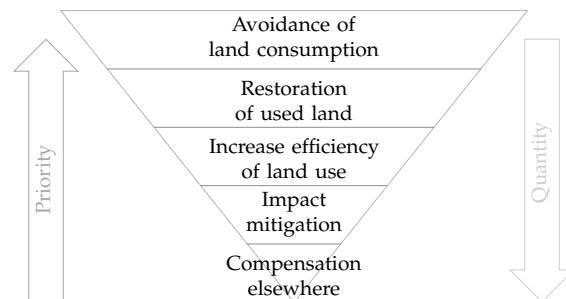
In order to facilitate proper management and consider an appropriate set of measures on various urban surfaces to mitigate anthropogenic impacts, adapt to climate change, and future-proof cities, the following section address the requirements for assessments on city and sub-city scales. A key element of the sustainable use of urban surfaces is a detailed overview of potentials and possible measures on the neighbourhood, district, or city scale [28]. The presented overview strongly indicates the need to develop tools that can be easily and repeatedly implemented in urban planning procedures.

## 2. Challenges and Proposal

Based on the land take hierarchy of the Soil Strategy of the European Union 2030 [8] and waste management principles according to the §6 German Circular Economy Act [75] and Federal Nature Conservation Act [76], a five-level hierarchy (Figure 1) was developed to guide a land-sensitive urban development approach: (1) Avoidance of additional land consumption or creation of impervious surfaces. (2) Restoration of used and no longer used

surfaces to a natural or a quasi-natural state. (3) More efficient (re-)use of already used land. (4) Mitigation of impacts caused by land consumption. (5) Compensation of unavoidable land consumption elsewhere, e.g., via removal of impervious surfaces and restoration.

Accordingly, applying this hierarchy implies avoiding additional land use as much as possible and minimising the loss of ecosystem services if land use is unavoidable.



**Figure 1.** Five-level hierarchy for a land-sensitive urban development strategy. Avoiding land consumption is the ultimate goal and should be most commonly adopted. Compensating for land use should be the last resort and rarely adopted.

Motivated by the identified shortcomings and lack of tools to identify high-level land-use potentials and strategies, we developed a GIS-based model to enable administration-oriented assessments of cities. The developed modelling approach allows for the inventory of most urban surfaces in high granularity and enables a comprehensive assessment of urban redevelopment focused on utilising different surfaces. Hence, the approach focuses on levels 2–5 of the guiding hierarchy of land-sensitive urban development.

Thus, the following key requirements were identified for an urban development assessment methodology:

- Accounting for all available urban surfaces: soils and surfaces on buildings and infrastructures.
- A comprehensive inventory of urban features from easily accessible and regularly updated data.
- Appropriate reference units to allow for considering interdisciplinary aspects.
- Practicability for use in municipal administrations (e.g., based on existing procedures, data models, resources, and data management).
- Modular expandability.
- Wide system compatibility.
- Transferability to different scales and locations.
- Identification of theoretical and technical potentials of measures.
- Financial assessment.
- Technical and environmental assessment.
- Social assessment.

The main objectives were to comply with the derived requirements and apply the approach to a case study district to demonstrate its utility (Section 3.5).

For this, a data management and computation approach was implemented in PostgreSQL 13.4 (The PostgreSQL Global Development Group, Berkeley, CA, USA) with the GIS extensions of PostGIS, -Raster, and -SCFGAL. For 3D cityGML data management, the 3DCityDB (Version 4.3.0 (2021-04-28), Chair of Geoinformation, TU Munich, Munich, Germany) software was used. The main benefits of this configuration are the use of highly deployable, open-source, or free software with extensive support through comprehensive documentation, a vast developer and user community, and regular updates.

### 3. Materials and Methods

#### 3.1. Data Model

The data model is designed to handle readily available municipal spatially referenced data. Despite good data of good quality, our analysis for this contribution is restricted by data privacy (e.g., socio-demographic data could only be provided aggregated at the neighbourhood level; data regarding contaminated soils could not be considered). Hence, not all officially recorded data could be used. Therefore, and for demonstration purposes, targeted onsite surveys were conducted to allow for necessary data enrichment [77,78]. However, in an internal municipal deployment scenario, much more (and sensitive or classified) data can be considered, and the presented approach allows for easy integration. The following minimal data inputs on the plot and building levels were used to run the developed model:

- Cadastral data, such as from the Authoritative Real Estate Cadastre Information System (ALKIS®);
- Building and infrastructure data such as, 3D level of detail 2 (LOD2) CityGML data;
- Surface sealing materials, such as from sewer-service/runoff water charge surveys (surveying and mapping of impervious surfaces by the local authorities or airborne remote sensing surveys);
- Preservation, historic interest, or other plot/building data which cover constraints for (re-)development activities;
- Socio-demographic data such as building occupation, ownership or other census data;
- Administrative zoning or other region of interest break down relevant for the investigation, e.g., assisted areas or survey units;
- Weather data on irradiation, precipitation, etc.

A detailed description of the used data is presented in Table 1. The use of raw satellite or similar raw remote sensing data is not considered, as accurate and suitable data sets are available. If they are not available, remote sensing data could be used to create necessary datasets.

**Table 1.** Minimal data inputs, case study data sources, and descriptions.

Data Set ( <i>Symbol</i> )	Brief Description or Meta Data Source	Source
Buildings and infrastructure ( <i>B</i> )	Cadastral building and infrastructure footprints <sup>i</sup> with building use-type, (sub-)surface classification, name, address, ID information and other.	[79]
3D LOD2 CityGML ( <i>GML</i> )	Geodata of solids and multi-surface building representations with standardised roof types. High position accuracy <sup>ii</sup> and object-IDs allow one to join and intersect with other data.	[79]
Land parcel ( <i>L</i> )	Cadastral land parcels with address, ID information.	[79]
Nameres survey ( <i>N</i> )	Building survey for building archetype classification and individual building units/apartments count.	self-provided
Ownership ( <i>O</i> )	Geodata of land parcels with public/municipal ownership.	[79]
Precipitation ( <i>P</i> )	Local and long-term data on precipitation (annual and monthly).	[80]
Preservation and conservation interest ( <i>PC</i> )	Status regarding preservation, conservation, monument or other historic interest.	[81,82]
Solar irradiation ( <i>SI</i> )	Local statistical long-term data on solar irradiation, heating degree days and temperatures (annual and monthly).	[83]
Surface material ( <i>SM</i> )	Geodata on surface sealing and materials classification in high resolution (runoff water charge data <sup>iii</sup> ).	[79]
Zoning ( <i>Z</i> )	Aggregation layers for generating aggregated results.	self-provided

<sup>i</sup> The cadastral data's accuracy is below 3 cm for border points. <sup>ii</sup> The representations are based on the cadastral building and infrastructure footprints <sup>i</sup> and light detection and ranging (Lidar). The accuracy of the LOD2 data for height information is between 20 and 30 cm, 10 cm for the other dimensions. <sup>iii</sup> The polygon data is based on cadastral building and infrastructure footprints <sup>i</sup> and measurements [84].

In Germany, many of the listed data sets are standardised and regularly updated, yet the currentness of data has to be ensured. Similar datasets for other countries can be found.

Regarding the 3D building data, the LOD2 data provides the minimum feature resolution and is widely and readily available in Germany. However, many features, such as building apertures, cantilevers, and other small surface features, are not captured by the LOD2 data. Hence, study area inspections, expert knowledge, and additional data sources are needed to account for the shortcomings, e.g., via reduction factors for window surfaces (Section 3.3).

For the case study area (Section 3.5), additional data were surveyed to provide retained or not recorded characteristics, and assess data quality and survey expenditure. For example, this applies to unit/apartment number per building. The data quality assessment of selected characteristics was evaluated alongside this survey. Regarding most of the characteristics, data quality was found to be suitable for a granular assessment on a sub-land plot level and acceptably up-to-date. Some classifications were outdated regarding the types of use of the surveyed buildings, but this did not affect this study. Other analysis-specific data sources and default parameters are presented in Section 3.4.

### 3.2. GIS-Analyses

The aggregated data were processed in the database scheme and spatially analysed. Mostly standard PostGIS functions were used, e.g., area/geometry calculation, intersections, difference, union, and buffering. However, the available 3D-LOD2 CityGML model of the case study district had geometry artefacts. Therefore, the freeware FZKViewer 6.3 (Build 2170) [85] was used to determine necessary characteristics, and the results were fed into the respective database tables. Except for the in-depth 3D-LOD2 surface analysis, all analysis steps were carried out in PostgreSQL/PostGIS.

The primary GIS-analysis (carried out in PostgreSQL/PostGIS) creates the urban surface elements, enabling the sub-parcel impervious surfaces' calculation and assessment. These geometries are created via the spatial intersection  $INT^A$  of the *land parcel*  $L \cap SM$  *surface sealing*, and spatial intersection  $INT^B$  of the *buildings and infrastructure*  $B \cap SM$  *surface sealing* geometries. The respective intersections are then inserted into the final database ( $E = INT^A \wedge INT^B$ ). The resulting database consists of highly granular data of all surface elements ( $e \in E$ ), the respective intersection geometries, and the intersected data's original IDs. After that, the urban surface elements, the 3D-LOD2 CityGML model, and the 3D analysis results are combined and further enriched via spatial joins (e.g., with zoning data) and relational joins (preservation and historic interest data, etc.). These analyses yielded multiple fundamental surface properties, which are summarised in Tables 2 and 3. The surface material  $SM_m$  is used to create the surface cover types SCT (Table 4).

**Table 2.** Spatial properties and identifiers of  $e \in E$ .

Property ( <i>Symbol</i> )	Value Description	Type <sup>iv</sup>	Source
<b>IDs</b>			
<b>Identifiers</b>			
Urban surface element ID ( $i$ )	Unique primary analysis unit/element ID	Integer	$E_i \subseteq E$
Zoning ID ( $z_i$ )	Unique aggregation and statistical unit ID	Integer	$Z_i \subseteq Z$
Land parcel ID ( $l_i$ )	Unique land lot or plot or parcel ID	Integer	$L_i \subseteq L$
Building address ( $ba$ )	Fixed format postal address	String	$B_a \subseteq B$
Building ID ( $b_i$ )	Unique building ID	Integer	$B_i \subseteq B$
Building element ID ( $gmli$ )	Unique identifiers for roof, facade, footprint elements	Integer	$GML_i \subseteq GML$
Preservation/conservation ID ( $pci$ )	Unique ID	Integer	$PC_i \subseteq PC$
Surface material ID ( $smi$ )	Unique identifiers for roof and sealed soil surfaces	Integer	$SM_i \subseteq SM$
<b>Geometries</b>			
<b>Spatial data type</b>			
Urban surface element ( $u_g$ )	Polygon, multipolygon	Geom	$E_g \subseteq E$
Zoning ( $z_g$ )	Polygon, multipolygon	Geom	$Z_g \subseteq Z$
Land parcel ( $l_g$ )	Multipolygon	Geom	$L_g \subseteq L$
Building ( $b_g$ )	Polyhedral surface	Geom	$B_g \subseteq B$
Building element ( $gmli_g$ )	Polyhedral surface, polygon	Geom	$GML_g \subseteq GML$
Preservation/conservation ( $pcg$ )	Point, line, polygon	Geom	$PC_g \subseteq PC$
Surface material ( $smg$ )	Multipolygon	Geom	$SM_g \subseteq SM$

<sup>iv</sup> Geom: Geometry**Table 3.** Non-spatial properties of  $e \in E$ .

Property ( <i>Symbol</i> )	Value Description	Type	Source
<b>Parcel features</b>			
<b>Non-spatial data type</b>			
Cistern ( $smc$ )	States the presence of a rainwater cistern	Boolean	$SM_c \subseteq SM$
<b>Building features</b>			
<b>Non-spatial data type</b>			
Building typology class ( $nbt$ )	50 Episcopo/Tabula residential building archetypes and more than 230 use-types (use-types according to ALKIS® classification)	String	$N_{bt} \subseteq N, B_{bt} \subseteq B$
Superstructure volume ( $gmlv$ )	Enclosed volume by the building envelope	Double	$GML_v \subseteq GML$
Apartments/units ( $nau$ )	Number of units in the building	Integer	$N_{au} \subseteq N$
Building passage ( $bp$ )	Special feature which is not part of the 3D LOD2 model	Boolean	$B_p \subseteq B$
Arcade ( $ba$ )	Special feature which is not part of the 3D LOD2 model	Boolean	$B_a \subseteq B$
Cantilever or recessing facade ( $bc$ )	Special feature which is not part of the 3D LOD2 model	Boolean	$B_c \subseteq B$
<b>Element features</b>			
<b>Non-spatial data type</b>			
Surface type ( $s$ )	Surface type typology $s \in S = \{roof, facade, ground\}$	String	$E_s \subseteq E$
Surface cover type ( $sct$ )	Surface cover typology $sct \in SCT = \{imp1, imp2, imp3, p, sol1, sol2, eg, ig\}$ derived from $E_{smm} \subseteq E$ (Table 4)	String	$E_c \subseteq E$
Orientation ( $o$ )	Surface normal which provides the azimuth	Double	$GML_o \subseteq GML$
Tilt ( $tilt$ )	Surface tilt; Slope/pitch of a roof	Double	$GML_{tilt} \subseteq GML$
Volume ( $ve$ )	Element volume based on assumed thickness or material	Long	$GML_{ve} \subseteq GML$
Area ( $a$ )	Element area	Long	$E_a \subseteq E$
Perimeter ( $per$ )	Element perimeter	Long	$E_{per} \subseteq E$
x,y,z dimensions ( $dim$ )	Point or vector information and length	Points	$E_{dim} \subseteq E$
Solar irradiation ( $si,tp$ )	Annual and monthly azimuth and inclination dependent solar irradiation/global horizontal irradiation with $tp \in TP = \{annual, jan, feb, mar, apr, mai, jun, jul, aug, sep, oct, nov, dec\}$	Long	$SI_{tp} \subseteq SI$
Precipitation ( $p,tp$ )	Annual and monthly long-term precipitation with $tp \in TP$	Long	$P_{tp} \subseteq P$
Relative location to ground ( $gcon$ )	Elements position with regard to whether adjacent to the ground	Boolean	$E_{gcon} \subseteq E$
Relative location to neighbouring features ( $ncon$ )	Elements position with regard to whether adjacent to other features, e.g., for party walls	Boolean	$E_{ncon} \subseteq E$
Shape index ( $shpi$ )	Ratio of perimeter and area for element shape description and artefact detection	Double	$E_{shpi} \subseteq E$



**Table 4.** Surface cover types (SCT) of the initial state and surface material relations.

Surface Cover Type $SCT$	Surface Material Material $SM_m$
Impervious 1 ( $imp1$ )	Asphalt, concrete, paving with joint grouting
Impervious 2 ( $imp2$ )	Paving, slabs, interlocking stones
Impervious 3 ( $imp3$ )	Grass paving
Pervious ( $p$ )	Soil/urban green
Solid 1 ( $sol1$ )	Solid walls
Solid 2 ( $sol2$ )	Solid roofs
Extensive green ( $eg$ )	Extensive roof greening <30 cm substrate thickness
Intensive green ( $ig$ )	Intensive roof greening >30 cm substrate thickness

### 3.3. Measures and Potentials

The results of the GIS-analyses were used to localise the respective potentials for a multitude of measures ( $t \in T = \{erg, irg, uprg, rmpv, pvr, gbf, wbf, fmpv, sdg\}$ ; see Table 5) that were calculated on the individual element level ( $e \in E$ ). Thus, different aggregates can be defined, i.e., from a single element of a building or a backyard to buildings, building blocks, neighbourhoods, or other aggregation sets. For this work, ground, roof, and facade surface potentials were considered ( $s \in S = \{roof, facade, ground\}$ ).

As an initial descriptive result, a complete inventory of surfaces was created (Section 4.1). This inventory can be interpreted as the **theoretical potential** and was the basic information for the technical assessment of the considered measures:

- Extensive roof greening ( $erg$ ): roof greening with 10 cm substrate thickness, short grass, or sedum plants;
- Intensive roof greening ( $irg$ ): ground-level greening with >25 cm substrate thickness, short grass, and herbaceous plants (1:1);
- Underground parking roof greening ( $uprg$ ): roof greening with >35 cm substrate thickness, short grass, herbaceous plants, and deciduous trees (2:1:1);
- Roof-mounted photovoltaics ( $rmpv$ ): installation of photovoltaic (PV) modules;
- Photovoltaics and roof greening ( $pvr$ ): installation of mono-crystalline solar panels and roof greening with 10 cm substrate thickness, short grass, or sedum;
- Ground-based facade greening ( $gbf$ ): planting climbing plants, plants with and without climbing support;
- Wall-based facade greening ( $wbf$ ): prefabricated vegetation elements/mats, short grass, or herbaceous plants;
- Facade-mounted photovoltaics ( $fmpv$ ): installation of PV modules;
- Soil unsealing/domestic garden ( $sdg$ ): unsealing and plot-specific multi-use configuration of porous plaster, partially greened grids (1:1 short grass, impervious), and domestic garden (1:1:1 short grass, herbaceous plants and deciduous trees) areas in a plot.

Except for soil unsealing/domestic garden ( $sdg$ ), all measures are single-component measures. Hence, these are uniform and do not consider partitions of the surface element under consideration. In the case of  $sdg$ , different surface cover materials and partitions of surfaces are possible and enable multi-use configurations within a plot ( $e_i \subset E$ ). The configuration is dependent on the current use of the identified surface, such as for parking, passageways, or utility spaces (e.g., for bicycle parking, emergency areas, or waste bins). The cadastral data identify the current use based on the type of use and building part classification. The minimum need for multi-use configuration is estimated by the current use or the apartment/unit count ( $e_{nau}$ ) associated with the plot (<=5 units: 20 m<sup>2</sup>; >5 units: 30 m<sup>2</sup>, for porous plaster).










Photovoltaic and roof greening ( $pvr$ ) is a combination of  $erg$  and  $rmpv$  for flat roofs. Thus, the respective assessment procedures apply.

For the **technical potential**, each of the measures is associated with a set of same level of detail indicators (Section 3.4), constraints (Table 5), and reduction factors (Table 6).The

constraints are measure-specific and determined by the technical implementation and operational characteristics with respect to its element selection  $\sigma_{\varphi}(E)$  (Table 5). The reduction factors are determined by site inspections, empirical knowledge, and expert knowledge.

The **economic potential** (see Section 3.4) is based on the **technical potential**. Here, scenario considerations stipulate the selection or assessment scope (e.g., mix of measures or specific aggregates, such as public or private ownership).

**Table 5.** Surface element selection for the technical potential assessment of measures  $t \in T = \{erg, irg, uprg, rmpv, pvr, gbfg, wbf, fmpv, sdg\}$ .

Measure ( $t$ )	Element Selection ( $\sigma_{\varphi}(E)$ ) <sup>v</sup>	Measure ( $t$ )	Element Selection ( $\sigma_{\varphi}(E)$ ) <sup>v</sup>
 Extensive roof greening ( <i>erg</i> )	$\sigma_{s=roof} \wedge a \geq 10 \wedge tilt < 45$ $\wedge green=0 \wedge cons=0(E)$	 Intensive roof greening ( <i>irg</i> )	$\sigma_{s=roof} \wedge a \geq 10^{ii} \wedge tilt \leq 5$ $\wedge green=0 \wedge cons=0(E)$
 Underground parking roof greening ( <i>uprg</i> )	$\sigma_{s=ground} \wedge a \geq 5 \wedge green=0$ $\wedge cons=0(E)$	 Roof mounted photovoltaics ( <i>rmpv</i> )	$\sigma_{s=roof} \wedge a \geq 25 \wedge tilt \leq 5$ $\wedge green=0 \wedge cons=0(E)$ $\vee$ $\sigma_{s=roof} \wedge a \geq 10 \wedge tilt > 5$ $\wedge green=0 \wedge cons=0(E)$
 Photovoltaics and roof greening ( <i>pvr</i> )	$\sigma_{s=roof} \wedge a \geq 25 \wedge tilt < 5$ $\wedge green=0 \wedge cons=0(E)$	 Ground-based facade greening ( <i>gbfg</i> )	$\sigma_{s=facade} \wedge a \geq 10 \wedge$ $intersec=1 \wedge cons=0 \wedge pw=0(E)$
 Wall-based facade greening ( <i>wbf</i> )	$\sigma_{s=facade} \wedge a \geq 10 \wedge$ $intersec=0 \wedge cons=0 \wedge pw=0(E)$	 Facade mounted photovoltaics ( <i>fmpv</i> )	$\sigma_{s=facade} \wedge a \geq 10 \wedge cons=0$ $\wedge pw=0(E)$
 Soil desealing/ greening ( <i>sdg</i> )	$\sigma_{s=ground} \wedge a \geq 1 \wedge green=0(E)$		

<sup>v</sup> If not indicated otherwise, selection criteria are assumptions based on technical restrictions and on [37,39,67,86, 87].

**Table 6.** Technical potential input parameter  $r_m^{s,t} \in R$  with  $m \in M = \{obs, sho, util, pv, eff\}$  for surface type (s) and measure (t) scope of implementation determination (based on [88–91]). The reduction factors account for obstruction (obs), shadowing (sho), utilisation (util), pv (pv), efficiency (eff), and performance ratio (pr).

Parameter ( $r_m^{s,t}$ )	erg	irg	uprg	rmpv <sup>vi</sup>	purg	gbfg	wbfg	fmpv	sdg
$r_{obs}^{roof,t}$	{0.6}	{0.6}	{0.6}	{0.6,0.6}	{0.6}	{1}	{1}	{1}	{1}
$r_{obs}^{facade,t}$	{1}	{1}	{1}	{1}	{1}	{0.7}	{0.7}	{0.7}	{1}
$r_{m}^{ground,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}
$r_{sho}^{roof,t}$	{1}	{1}	{1}	{0.9,0.9}	{0.9}	{1}	{1}	{1}	{1}
$r_{sho}^{facade,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{0.8}	{1}
$r_{sho}^{ground,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}
$r_{util}^{roof,t}$	{1}	{1}	{1}	{0.9,0.4}	{1,0.4} <sup>vii</sup>	{1}	{1}	{1}	{1}
$r_{util}^{facade,t}$	{1}	{1}	{1}	{1}	{1}	{0.8}	{0.8}	{0.8}	{1}
$r_{util}^{ground,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}
$r_{eff}^{roof,t}$	{1}	{1}	{1}	{0.19,0.19}	{0.19}	{1}	{1}	{1}	{1}
$r_{eff}^{facade,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{0.15}	{1}
$r_{eff}^{ground,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}
$r_{pr}^{roof,t}$	{1}	{1}	{1}	{0.8,0.8}	{0.8}	{1}	{1}	{1}	{1}
$r_{pr}^{facade,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{0.8}	{1}
$r_{pr}^{ground,t}$	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}

<sup>vi</sup> pitched roof, flat roof. <sup>vii</sup> vegetation, PV.

### 3.4. Assessment and Key Performance Indicator Calculation

The indicators were compiled according to the case study requirements, which required considering the resources of area, water, material flows, eco-services, and energy. The presented assessments consider a set of developed and selected indicators summarised in Tables 8, 9 and 10.

For the measure set (T), the measure sizes are the effective measure areas ( $e_{ma}$  with Equation (1)). This effective area is determined by deducing not usable areas via surface (s) and measure (t) type-dependent reduction factors (obstructions  $r_{obs}^{s,t}$ , shading  $r_{sho}^{s,t}$ , and utilisation factor  $r_{util}^{s,t}$  Table 6) from the area of the considered urban surface element ( $e_a$ ). The selection  $\sigma_\varphi(E)$  determines the suitable surface elements  $e \in E$  according to Table 5. This effective measure area represents the presumed surface area on an element that could be potentially occupied by the measure and is the main reference value for the assessments.

$$e_{ma} = \begin{cases} e_a \cdot \prod_M r_m^{s,t} & , \text{ if } \prod_M r_m^{s,t} \neq \{ \} \quad \forall r \in R \setminus \{1\} \\ e_a & , \text{ if } \prod_M r_m^{s,t} = \{ \} \quad \forall r \in R \setminus \{1\} \end{cases} \quad (1)$$

For the economic assessment, empirical investment/capital expenditure (CAPEX) and maintenance/operational expenditure (OPEX) data from different sources, such as field manuals, expert interviews, and cost databases [37,92–98], were analysed and summarised in Table 7. The CAPEX data include all item costs to completion (construction steps CS, e.g., unsealing, other works, and final works). The OPEX data included annual maintenance costs (excluding irrigation). A major requirement was to account for the scale of the implementation (measure size) to account for effects such as economies of scale, and to distinguish between fixed and variable cost components. For all measures except for roof-mounted PV, the  $e_{ma}$  was used as a reference value for the economic assessment. The nominal installation capacity ( $cap^t$ ) was used for PV installations and was dependent on effective measure area ( $e_{ma}$ ) and standard test conditions' efficiency ( $r_{pv}^t$ ) (Equation (2)).

$$cap^t = e_{ma}^t \cdot r_{pv}^t \quad \forall \quad t \in \{rmpv, fmpv\} \quad (2)$$

**Table 7.** Input data for the economical assessment. Data were based on [37,84,92–98]. *inv*: CAPEX; *cost*: OPEX; *base*: rates specific for a particular implementation size; *fix*: fixed part; *var*: variable part; *el*: electricity; *maint*: maintenance; *fee*: fees and charges for services; *sc*: self-consumption; *feed-in*: compensation for electricity fed into the grid.

Parameter	Value	Parameter	Value
$c_{sdg,removal\ solid\ surface}^{inv,base}$	23.7 $\frac{\text{€}}{\text{m}^2}$	<i>making ground-b. facade greening</i>	35 $\frac{\text{€}}{\text{m}^2}$
$c_{sdg,removal\ fixed\ tiled\ surface}^{inv,base}$	7 $\frac{\text{€}}{\text{m}^2}$	$c_{roof\ pv}^{inv,fix}$	1000 €
$c_{sdg,removal\ loose\ tiled\ surface}^{inv,base}$	5 $\frac{\text{€}}{\text{m}^2}$	$c_{roof\ pv}^{inv,var}$	1400 $\frac{\text{€}}{\text{kW}_p}$
$c_{sdg,semi-loose\ surfaces}^{inv,base}$	4.9 $\frac{\text{€}}{\text{m}^2}$	$c_{grid}^{cost,el}$	0.35 $\frac{\text{€}}{\text{kWh}}$
$c_{sdg,basic\ desealing\ operations}^{inv,base}$	40 $\frac{\text{€}}{\text{m}^2}$	$c_{surface\ runoff}^{cost,fee}$	0.299 $\frac{\text{€}}{\text{m}^2 \cdot \text{a}}$
$c_{sdg,making\ porous\ paver}^{inv,base}$	55 $\frac{\text{€}}{\text{m}^2}$	$c_{pv}^{cost,maint}$	0.02 $\frac{\text{CAPEX}}{\text{a}}$
$c_{sdg,making\ grass\ paver}^{inv,base}$	35 $\frac{\text{€}}{\text{m}^2}$	$c_{sdg}^{cost,maint}$	5 $\frac{\text{€}}{\text{m}^2 \cdot \text{a}}$
$c_{sdg,making\ basic\ garden}^{inv,base}$	17 $\frac{\text{€}}{\text{m}^2}$	$c_{erg,extensive\ green\ roof}^{cost,maint}$	3 $\frac{\text{€}}{\text{m}^2 \cdot \text{a}}$
$c_{sdg,planting\ mid-sized\ tree}^{inv,base}$	575 $\frac{\text{€}}{\text{m}^2}$	$c_{irg,intensive\ green\ roof}^{cost,maint}$	4 $\frac{\text{€}}{\text{m}^2 \cdot \text{a}}$
$c_{erg,making\ extensive\ green\ roof}^{inv,base}$	75 $\frac{\text{€}}{\text{m}^2}$	$c_{uprg,ugp.\ roof\ greening}^{cost,maint}$	4 $\frac{\text{€}}{\text{m}^2 \cdot \text{a}}$
$c_{irg,making\ intensive\ green\ roof}^{inv,base}$	125 $\frac{\text{€}}{\text{m}^2}$	$c_{wbfg,wall-b.\ facade\ greening}^{cost,maint}$	40 $\frac{\text{€}}{\text{m}^2 \cdot \text{a}}$
$c_{making\ ugp.\ roof\ greening}^{inv,base}$	125 $\frac{\text{€}}{\text{m}^2}$	$c_{gbfg,ground-b.\ facade\ greening}^{cost,maint}$	15 $\frac{\text{€}}{\text{m}^2 \cdot \text{a}}$
$c_{wbfg,making\ wall-b.\ facade\ greening}^{inv,base}$	400 $\frac{\text{€}}{\text{m}^2}$	$c_{facade\ pv}^{inv,var}$	500 $\frac{\text{€}}{\text{m}^2}$
$c_{pv}^{sc}$	30%	$c_{cost,feed-in(\leq 10\ \text{kW}_{peak})}^{pv}$	0.0663 $\frac{\text{€}}{\text{kWh}_{el}}$
$c_{cost,feed-in(>10\leq 40\ \text{kW}_{peak})}^{pv}$	0.0643 $\frac{\text{€}}{\text{kWh}_{el}}$	$c_{cost,feed-in(>40\leq 100\ \text{kW}_{peak})}^{pv}$	0.0495 $\frac{\text{€}}{\text{kWh}_{el}}$

The CAPEX data (Equation (3)) have three cases, whereas the OPEX data (Equation (4)) have two cases. In the *rmpv* case, CAPEX was calculated with a technology/material (*t*)-dependent fixed component ( $c_{inv,fix}^{t,cs}$ ) and a variable component ( $c_{inv,var}^{t,cs}$ ) that depends on the nominal installation capacity ( $cap^{t,cs}$ ) in  $\text{kW}_{peak}$ . The parameters were derived from the literature (Table 7). The *fmpv* CAPEX was dependent on the area size, and the area size-specific rates were nominal-installation-capacity-dependent. The calculation of these rates was based on [99]. For soil unsealing/greening (*sdg*), extensive roof greening (*erg*), intensive roof greening (*irg*), underground parking roof greening (*uprg*), ground-based facade greening (*gbfg*), and wall-based facade greening (*wbfg*), mainly area discrete rates were found, which did not sufficiently allow for assessing implementation-area-dependent CAPEX or OPEX. Consequently, individual area-specific rate functions were derived from empirical data based on [37,92–98] (Figure 2). The functions in Figure 2 were used to compute CAPEX and OPEX based on rates for surface areas of implementation of 20  $\text{m}^2$  as a base value, except for soil unsealing/greening, where the base value relates to surface areas of implementation of 500  $\text{m}^2$ . The exponential functions were fitted via non-linear regression with high weights for observations close to the base value. These functions output area dependent factors in percent for converting area-specific costs between implementation areas between 0 and 5,000  $\text{m}^2$ . The functions use the CAPEX and OPEX calculation for each measure as  $f_{adap,CAPEX}^t$  or  $f_{adap,OPEX}^t$  in Equations (3) and (4). The results of these analyses are summarised in Figure 2. The base values are given in Table 7. Depending on the base

year of the data, the building industry price index and the regional price index were used to adjust for the current year and region of interest.

$$CAPEX = \begin{cases} \sum_{cs=1}^{CS} (c_{inv,fix}^{t,cs} + c_{inv,var}^{t,cs} \cdot cap^{t,cs}) & \forall t \in \{rmpv\} \\ \sum_{cs=1}^{CS} (-5 \ln(cap^{t,cs}) + c_{inv,base}^{t,cs} \cdot e_{ma}^{t,cs}) & \forall t \in \{fmpv\} \\ \sum_{cs=1}^{CS} (c_{inv,base}^{t,cs} \cdot f_{adap,CAPEX}^t(e_{ma}^{t,cs}) \cdot e_{ma}^{t,cs}) & \forall t \in T \setminus \{rmpv, fmpv\} \end{cases} \quad (3)$$

Regarding OPEX, a similar procedure was adopted (Equation (4)). For the PV surfaces, a proportion of the respective CAPEX was calculated. All other annual OPEX costs were computed with an effective-area ( $e_{ma}$ )-dependent function (Figure 2) and respective base values for OPEX (Table 7). Concerning the adaptation factor for the OPEX for  $sdg$ , the function of  $uprg$  was applied, as a similar curve was assumed.

$$OPEX = \begin{cases} CAPEX \cdot c_{cost,maint}^{pv} & \forall t \in \{rmpv, fmpv\} \\ c_{cost,maint}^{t,cs} \cdot f_{adap,OPEX}^t(e_{ma}^{t,cs}) \cdot e_{ma}^{t,cs} & \forall t \in T \setminus \{rmpv, fmpv\} \end{cases} \quad (4)$$

Other economic cash flows ( $cf$ ) were calculated for profits from selling or consuming PV electricity  $Q_{el}$  (Equations (5)–(7)) or for reduced drainage fees (Equation 8). Concerning electricity generation via PV, the cash flows resulted from savings from self-consumption of an assumed 30% of the yield (Equation (6)) and 70% grid feed-in (Equation (7)) with input parameters summarised in Table 7 and Figure A2.

$$Q_{el} = e_{si,annual} \cdot e_{ma} \cdot r_{pv}^t \cdot r_{pr}^t \quad \forall t \in \{rmpv, fmpv\} \quad (5)$$

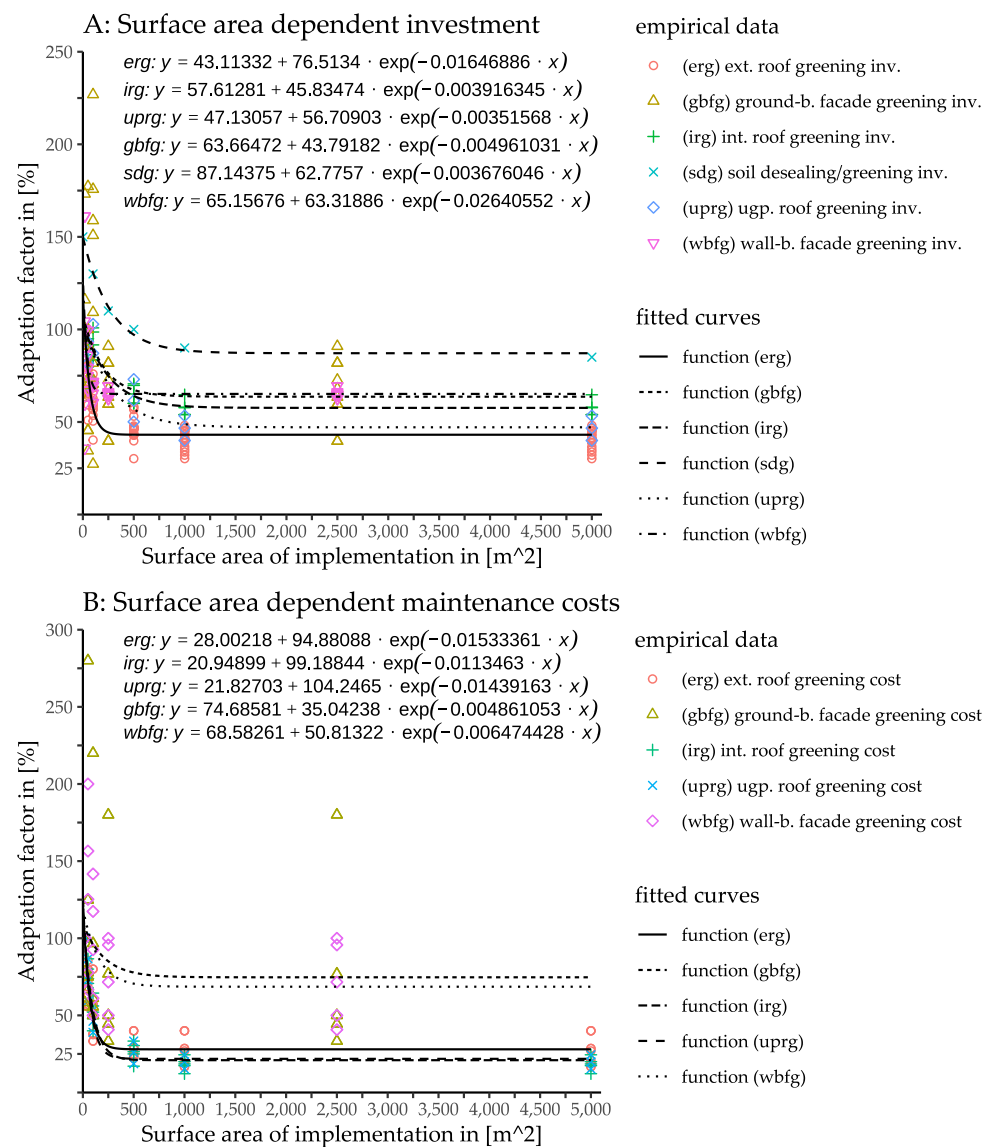
$$cf_{self-consumption} = Q_{el} \cdot c_{sc}^{pv} \cdot c_{cost,el}^{grid} \quad \forall t \in \{rmpv, fmpv\} \quad (6)$$

$$cf_{feed-in} = Q_{el} \cdot (1 - c_{cost,sc}^{pv}) \cdot c_{cost,el}^{feedin} (kWp) \quad \forall t \in \{rmpv, fmpv\} \quad (7)$$

$$cf_{drainage\ charge} = e_a^{t,s} \cdot c_{cost,fee}^{surface\ runoff} \cdot ind_{factor\ drainage\ charge}^{t,s} \quad \forall t \in T \quad (8)$$

Additionally, and in accordance with the case study requirements (Section 3.5), two subsidy schemes were implemented following the funding scheme in the analysed urban district.

The input parameters for the technical and environmental assessment were based on empirical observations, measure or product data sheets, norms, guidelines, or scientific studies (Tables 8 and 9). Again, the primary reference unit is the effective measure area ( $e_{ma}$ ) except for measures that include PV, where energy-related yields (e.g., air pollutants mitigation) use the reference unit of produced energy in kWh. For all measures without PV, the indicators are the results of multiplying the effective area of a measure and the remaining element area by the indicator input parameters for the measure and initial state (ratio indicators are normalised by the area). For PV, the air pollutants and energy-related yields are calculated with the energy yield instead of the area. The initial state values are summarised in Table 9. This simplified assessment approach is used to keep input requirements comparable and straightforward. Furthermore, detailed simulations were not feasible due to missing data or computational performance requirements (e.g., both apply for spatiotemporal simulations of urban atmospheric dynamics for urban heat island quantification). All measures except for  $gbfg$  were assumed to be fully completed at the time of implementation. For  $gbfg$ , the facade greening grew to the extent of the implementation area with an annual growth rate of  $\frac{2.5m^2}{a}$  per plant, and one plant was assumed for every 4 m of facade width (based on [37]).



**Figure 2.** Investment (CAPEX) and maintenance (OPEX) of economy of scale (EOS) of six and five alternatives for urban surfaces (re-)development in Germany. (A) shows the EOS factors in percent for investment. (B) shows the EOS factors in percent for maintenance other than irrigation.

Greening alternatives with limited biomass growth potentials (bounded by available surface area and substrate thickness) were assumed to have constant total  $\text{CO}_2$  sequestration potentials. In contrast, trees in the *sdg* measure provided  $\text{CO}_2$  sequestration potentials over time. Hence, except for *sdg*, all greening alternatives had constant  $\text{CO}_2$  sequestration, and *sdg* had an additional annual  $\text{CO}_2$  mitigation potential of  $10 \frac{\text{kg}}{\text{tree a}}$  (based on [100]: oak 0–20 years with 1000 trees per ha). For the analysis in this work and *gbfg*, the  $\text{CO}_2$  sequestration of the fully covered potential area was considered. The abatement of air pollutants was based on the modelling of Yang et al. [101]. Evapotranspiration was calculated according to Harlaß [102] with annual precipitation of  $816 \frac{\text{mm}}{\text{a}}$  (for the case study district and based on [80]). Runoff was calculated according to [103]. The ecoscore represents a metric that originates from the German environmental impact assessment and scores biotopes according to their ecoservices. Boehnke et al. [77] modified the utilised scoring to reflect biotope and habitat quality and its frequency of occurrence in urban centres. The biodiversity indicator reflects the possible count of small animal and insect populations (based on [37]). The levelised cost of energy (LCOE) was calculated for all measures, including PV

(Equation (9)), for  $i = 0.05$ , by linear depreciation for the residual value based on a service life of 25 years and for  $T = 20$  years.

$$LCOE = \frac{\sum_{t=0}^T \frac{CAPEX + OPEX - residual\ value}{(1+i)^t}}{\sum_{t=0}^T \frac{Q_{el}}{(1+i)^t}} \quad (9)$$

**Table 8.** Assessment indicators  $ind \in Ind$ , units, and the respective parameters for the considered measures. Values are rounded and represent defaults and literature values.

Parameter ( $ind$ )	Unit	$erg$	$irg$ <sup>viii</sup>	$uprg$ <sup>ix</sup>	$rmpv$	$gbfg$	$wbfg$	$fmpv$	$sdg$ <sup>x</sup>
<i>Albedo</i>	—	0.2	0.2	0.2	0.2	0.17	0.2	0.2	{0.2, 0.23, 0.19}
<i>Peakrunoff coefficient</i> <sup>xi</sup>	—	{0.4, 0.7}	0.2	0.2	1	—	—	—	{0.4, 0.4, 0.2}
<i>Avg.runoff coefficient</i> <sup>xi</sup>	—	{0.2, 0.4}	0.1	0.1	0.9	—	—	—	{0.25, 0.2, 0.1}
<i>factor drainage charge</i> <sup>xii</sup>	—	0.5	0	0	0.5	—	—	—	0
<i>Evapotranspiration</i> <sup>xiii</sup>	$\frac{mm}{a}$	391	506	547	138	500	300	0	{147, 277, 580}
<i>Biodiversity</i> <sup>xiv</sup>	$\frac{n}{m^2}$	10.6	12	12	0.6	13	10.6	0.6	{0.6, 5.3, 13}
$CO_{2,eq}^{mit}$	$\frac{kg}{m^2 \cdot a}$	0	0	0	0.428 <sup>xv</sup>	0	0	0.428 <sup>xv</sup>	$10 \frac{kg}{tree}$ <sup>xvi</sup>
$CO_{2,eq}^{fix}$ <sup>xvii</sup>	$\frac{kg}{m^2 \cdot a}$	0.8	2.4	2.4	0	1.2 <sup>xviii</sup>	1.2 <sup>xv,xvi</sup>	0	{0, 0.65, 2.4}
<i>Green waste</i> <sup>xiv</sup>	$\frac{kg}{m^2 \cdot a}$	0.1	0.44	1.35	0	0.3	0.15	0	{0, 0.05, 2} <sup>xix</sup>
$NO_2^{mit}$ <sup>xx</sup>	$\frac{g}{m^2 \cdot a}$	2.33	2.635	2.793	0 <sup>xv</sup>	3.57	2.33	0 <sup>xv</sup>	{0, 1.17, 2.946}
$SO_2^{mit}$ <sup>xx</sup>	$\frac{g}{m^2 \cdot a}$	0.65	0.74	0.785	0.0001 <sup>xv</sup>	1.01	0.65	0.0001 <sup>xv</sup>	{0, 0.33, 0.83}
$O_3^{mit}$ <sup>xx</sup>	$\frac{g}{m^2 \cdot a}$	4.49	5.15	5.49	0 <sup>xv</sup>	7.17	4.49	0 <sup>xv</sup>	{0, 2.25, 5.82}
$PM_{10}$ <sup>xx</sup>	$\frac{g}{m^2 \cdot a}$	1.12	1.32	1.48	0.1 <sup>xv</sup>	2.16	1.12	0.1 <sup>xv</sup>	{0.1, 0.56, 1.6}
<i>Impervious</i>	—	1	1	1	1	—	—	—	{1, 1, 0}
<i>Ecoscore</i> <sup>xxi</sup>	pt	4	5	6	1	4	4	1	{1, 3, 6}

<sup>viii</sup> Short grass and herbaceous plants (1:1). <sup>ix</sup> Short grass, herbaceous plants and deciduous trees (2:1:1). <sup>x</sup> Configuration of porous plaster, green pavers (1:1 short grass, impervious) and domestic garden (1:1:1 short grass, herbaceous plants and deciduous trees). <sup>xi</sup> [103]. <sup>xii</sup> Based on [84]. <sup>xiii</sup> Based on [102]. <sup>xiv</sup> [37]. <sup>xv</sup> Per kWh and based on [104,105]. <sup>xvi</sup> Estimation based on [100] oak 0–20 years with 1000 trees per ha. <sup>xvii</sup> [106] <sup>xviii</sup> [107]. <sup>xix</sup> [108]. <sup>xx</sup> Based on [101]. <sup>xxi</sup> [77].

**Table 9.** Initial state surface parameters. Values are rounded and represent defaults and literature values.

Parameter ( <i>ind</i> )	Unit	<i>imp1</i>	<i>imp2</i>	<i>imp3</i>	<i>p</i>	<i>sol1</i>	<i>sol2</i>	<i>eg</i>	<i>ig</i>
Albedo	—	0.12	0.2	0.23	0.2	0.2	0.25	0.2	0.2
Peak runoff coefficient <sup>xi</sup>	—	1	0.9	0.4	0.2	—	1	{0.4, 0.7}	0.2
Avg. runoff coefficient <sup>xi</sup>	—	0.9	0.7	0.2	0.1	—	{0.9, 0.8}	{0.2, 0.4}	0.1
factor drainage charge <sup>xii</sup>	—	1	0.8	0.3	0	—	1	0.5	0
Evapotrans- piration <sup>xiii</sup>	$\frac{\text{mm}}{\text{a}}$	147	147	277	490	0	138	391	580
Biodiversity <sup>xiv</sup>	$\frac{n}{\text{m}^2}$	0.6	0.6	5.3	13	0.6	0.6	10.6	13
$\text{CO}_2^{\text{mit}}_{2,\text{eq}}$	$\frac{\text{kg}}{\text{m}^2 \cdot \text{a}}$	0	0	0	$10 \frac{\text{kg}}{\text{tree}}$ <sup>xvi</sup>	0	0	0	0
$\text{CO}_2^{\text{fix}}_{2,\text{eq}}$ <sup>xvii</sup>	$\frac{\text{kg}}{\text{m}^2}$	0	0	0.65	2.65	0	0	0.8	2.4
Green waste <sup>xiv</sup>	$\frac{\text{kg}}{\text{m}^2 \cdot \text{a}}$	0	0	0.05	2	0	0	0.1	0.44
$\text{NO}_2^{\text{mit}}$ <sup>xx</sup>	$\frac{\text{g}}{\text{m}^2 \cdot \text{a}}$	0	0	1.17	2.946	0	0	2.33	2.635
$\text{SO}_2^{\text{mit}}$ <sup>xx</sup>	$\frac{\text{g}}{\text{m}^2 \cdot \text{a}}$	0	0	0.33	0.83	0	0	0.65	0.74
$\text{O}_3^{\text{mit}}$ <sup>xx</sup>	$\frac{\text{g}}{\text{m}^2 \cdot \text{a}}$	0	0	2.25	5.82	0	0	4.49	5.15
$\text{PM}_{10}$ <sup>xx</sup>	$\frac{\text{g}}{\text{m}^2 \cdot \text{a}}$	0.1	0.1	0.56	1.6	0.1	0.1	1.12	1.32
Impervious	-	1	1	1	0	—	1	1	1
Ecoscore <sup>xxi</sup>	-	1	1	2	6	1	1	4	5

### 3.5. Case Study District

The case study district is an enclosed mixed-use area in a major city in Germany. It is characterised by a high population density ( $\frac{4111}{\text{km}^2}$ ) and deficiencies regarding physical urban fabric, urban green accessibility, and urban heat accumulation [109]. The masked area of the investigation area is about 42 ha (Figure 3). For this district, a dedicated subsidy program was put into place (from 2018 to 2030). This program supports ecologic rehabilitation, district and building upgrading, and redevelopment of privately owned properties [109]. Hence, the focus of this paper is on the analysis of privately owned properties. Accordingly, results of plots within the masked area that are owned by the public or local authorities, e.g., streets and schools, are not presented (Figure 4). The first subsidy scheme funds unsealing activities where (partial) unsealing expenses (CAPEX) are eligible for a 100% subsidy capped at 15,000€ per plot [110]. The second subsidy scheme funds greening activities by up to  $\frac{1}{3}$  of lump-sum completion expenditures and is capped at 4,000€ per plot/estate/building [111]. However, the ownership structure in the available data is not broken down, so the cap for greening is applied at the building level for roof and facade measures. For both subsidy schemes, special conditions apply that were modelled according to [110,111] (e.g., regarding greening and trees, the case study city requires  $\lfloor \frac{\text{courtyard area}}{100 \text{m}^2} \rfloor$  trees per plot).



**Figure 3.** Case study area mask (left, background map OSM [112]) and resulting geographically referenced surface data (right, without streets, primary data from the City of Karlsruhe [79]).





**Figure 4.** Surface cover type inventory for surfaces of private ownership (primary data from the City of Karlsruhe [79]).

The entire urban surface inventory was determined for the case study, and a comprehensive set of nine intervention measures was assessed. Additionally, the subsidy program was applied to the masked area and evaluated.

#### 4. Results

The following results are mainly presented in aggregated form for the entire case study. In parts, morphological-building-block-level and plot-level aggregated results are presented as well. According to the focus of the study, results for surfaces of private property are considered only.

##### 4.1. Inventory and Structure of Surfaces in the Case Study District

Overall, the masked area comprises 448 plots, 700 buildings, 11,140 facade surfaces, and 5,474 building roof surfaces (Figure 3). The surface cover type is available for plot and building roof surfaces. The geo-analysis created 13,996 surface elements based on this data with surface cover type information (Figure A1). Facades all have the same surface cover type, since the status of vegetation and facade types was not recorded in the available data sets. However, they were classified into three categories according to their position or function (exterior wall, party wall, or other inaccessible wall). In total, the database stores 25,136 unique surface elements. Furthermore, the inventory covers the surface protection status and other key performance indicators and properties for all surface types (Tables 2 and 3).

Table 10 summarises the descriptive statistics and shares of vegetation for the subsets of courtyards and front yards, the ground-level roof of substructures, and roof and facade surfaces of private ownership. Table 11 provides a condensed overview of the initial state. A graphic overview of this subset of the case study and the surface cover type are provided in Figure 4. The descriptive statistics show the considerable fragmentation of the surface elements with relatively small sizes. This indicates the challenge of activating stakeholders and merging many fragments to form practicable patches. Additionally, the total share of impervious surfaces (all footprint surfaces of private ownership) is 89%, underlining the

necessity for action. Another metric is the direct runoff of the footprint surfaces defined by the peak and average runoff of precipitation. In the considered case study area, the peak runoff is 84%, and the average is 74%. Values of zero or near zero are desirable; thus, both those values are high. Widespread building deconstruction is not part of the overarching urban development strategy in the case study district. Thus, a closer analysis of courtyards reveals a share of impervious surfaces (e.g., asphalt and concrete sealing) of 62% (43% average and 51% peak runoff) that could be (partly) removed and revegetated, and where soil functions could be restored.

**Table 10.** Surface inventory of surfaces of private ownership in the case study (Section 3.5). Values are rounded and represent aggregates on plot (pl.) level. Sub.: substructure.

Type of Surface (s)	Count of Plots	Total Area [h]	Median [m <sup>2</sup> ]	Mean [m <sup>2</sup> ]	Total Vegetated [ha]	Count of Vegetated pl.	Median [m <sup>2</sup> ]	Mean [m <sup>2</sup> ]	% of Total Area
Ground <sup>xxii</sup>	372	19.5 <sup>xxiii</sup>	304	524	2.9	—	—	—	15%
Courtyards	330	5.4	87	165	2.2	166	46.4	130.9	40%
Sub. roof	43	1.6	42	364	0.7	14	254	493	43%
Roof	350	14.2	177	237	0.98	—	—	—	7%
Flat	264	5.4	65	203	0.82	23	144	358	15%
Tilted	320	8.8	204	277	0.16	14	65	113	0.02%
Wall	350	51.3	1,062	1,466	NA <sup>xxiv</sup>	—	—	—	—
Facade	350	28.3	528	810	NA <sup>xxiv</sup>	—	—	—	—
Party wall	350	21.2	452	605	NA <sup>xxiv</sup>	—	—	—	—
Other	135	1.8	73	131	NA <sup>xxiv</sup>	—	—	—	—
<b>Total</b>		72.51 (21.2) <sup>xxv</sup>			(3.9)				5% <sup>xxiv</sup> (18%)

<sup>xxii</sup> Total ground-level which includes sub- and superstructures. <sup>xxiii</sup> Represents the footprint area of all sub-, superstructure and soil surfaces. <sup>xxiv</sup> No detailed surface cover type available. Random onsite inspections revealed some vegetation but no widespread vegetation on facades could be concluded. <sup>xxv</sup> Without vertical surfaces.

#### 4.1.1. Ground Surfaces

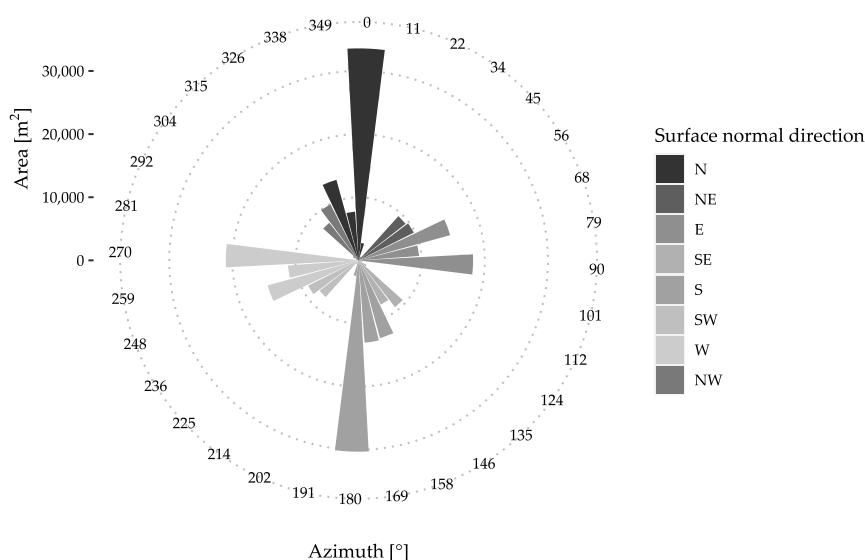
In the case study district, 372 plots have private ownership and cover about 19.5 ha of total area (Table 10). The average plot area in the private ownership subset is 524 m<sup>2</sup>. However, the available sub- and superstructure free areas are relatively small and average 165 m<sup>2</sup>. Forty-two plots are entirely sealed by a super- or substructure, and the remaining plots have courtyards of different surface cover types. Only 166 plots (nearly 45%) comprise vegetated courtyard surfaces. About 11% of the total ground surface area of the plots is vegetated without accounting for substructure green roofs, as the actual soil is sealed. Thus, overall soil sealing of over 89% can be concluded for the case study district. For the total runoff water assessment, roof surfaces had to be considered as well (Section 4.1.2). In accordance with this, peak and average values are 84% and 69.6%.

The difference in the total ground surface area and the surface area of superstructures equals the courtyard area. Forty percent of this difference has some kind of vegetation in the form of green spaces, grass pavers, or other greenery on impervious surfaces. Pure green spaces amount to about 2 ha (10.3%), and only these spaces can be considered unsealed. Conversely, 3.2 ha is the theoretical potential for unsealing. In comparison, ground-level roof surfaces of substructures (e.g., for underground parking) offer only 1.6 ha of total area in the case study district, along with a similarly high vegetation share to the courtyard surfaces. However, this area can only be unsealed if the substructure is decommissioned.

#### 4.1.2. Wall Surfaces

In total, 8,833 walls with 51.3 ha surface area belong to the private ownership subset (Table 10). However, only 55% of this surface area is available as facades which are exterior accessible walls. The remainder are party walls or other walls that are not accessible. Only the available surface area can be considered in the assessment. Accordingly, 28.3 ha of facade surface area offers theoretical potential for developing sustainable intervention measures. The distribution of this surface area and the normal (orientation) of the facade elements are visualised in Figure 5. Furthermore, 810 m<sup>2</sup> of facade area is available on

average and per plot. However, preservation and conservation constraints apply to 40% of the accessible facade surface area in the case study district. As non-vegetated facades are assumed in the original state, the available areas are a potential habitat for about 170 k individuals (see indicator biodiversity in Table 9).



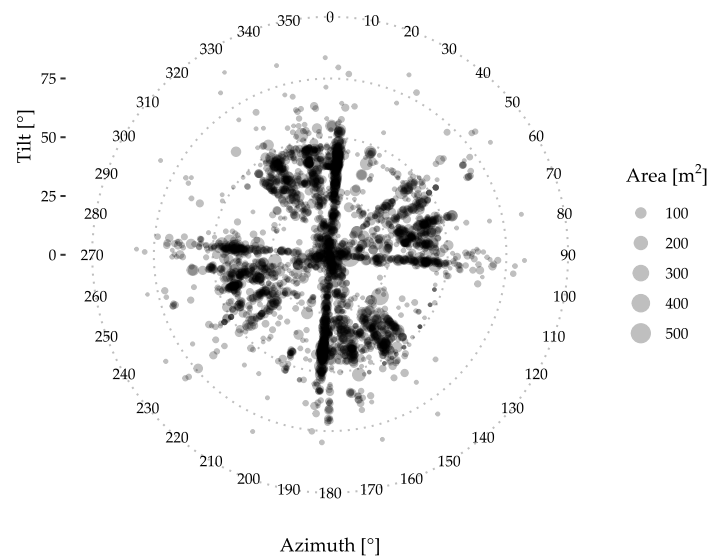
**Figure 5.** Accessible facade surface area and normal directions of the surfaces. North is at 0°.

#### 4.1.3. Roof Surfaces

In total, 14.2 ha of the roof surface area is in the private ownership subset, and nearly 1 ha of it is already vegetated (Table 10). Tilted roofs account for most of the surface area, and on average, each plot has 277 m<sup>2</sup> of tilted roofing. The surface area of private flat roofs is about 5.4 ha, with an average area of 203 m<sup>2</sup> per plot.

Due to the small share of existing vegetated roof surfaces, only small positive effects were identified. For the indicator peak runoff, the value is 96.4%, and the average runoff is 79.8%. In comparison, 1 ha of 5 ha of roof surfaces with public ownership is vegetated. This is almost triple the share (7% vs. 21%). Thus, the overall potential for a more sustainable and beneficial utilisation is mostly untapped on private roofs.

The properties of azimuth and tilt dictate the alternatives of utilisation. Figure 6 visualises the roof surface area, azimuth, and tilt distributions of the tilted roofs. Most roofs follow the facade orientation north and south, but also many roofs are directed east and west and slightly shifted. The interquartile range of tilt is between 27° and 44°.



**Figure 6.** Tilted roofs: surface area, tilt, and azimuth of surface (north is at 0°).

#### 4.2. Potentials

The following subsections present the technical potentials which resulted from considering measure-specific constraints and technical requirements. Furthermore, all results were calculated on the sub-plot level to account for implementation scales and then aggregated to estimate the total effects.

This element-wise assessment followed the element selection procedure  $\sigma_{\varphi}(E)$  in Section 3.3, where technical requirements for each measure  $t$  can be found (ibid.). In our investigation, building and monument conservation constraints considerably impacted realisable potentials and require individual case reviews. Thus, affected surface elements were excluded from the technical potentials. However, these surface elements can be 'activated' if necessary. Hence, the presented potentials do not form the technical potentials alone, as they also include the cultural (socially accepted) potential.

##### 4.2.1. Ground Potentials

Impervious surfaces which are not sealed by a super- or substructures were treated with the measure *sdg*. Ground-level surfaces sealed by a substructure were treated with the measure *upgr*.

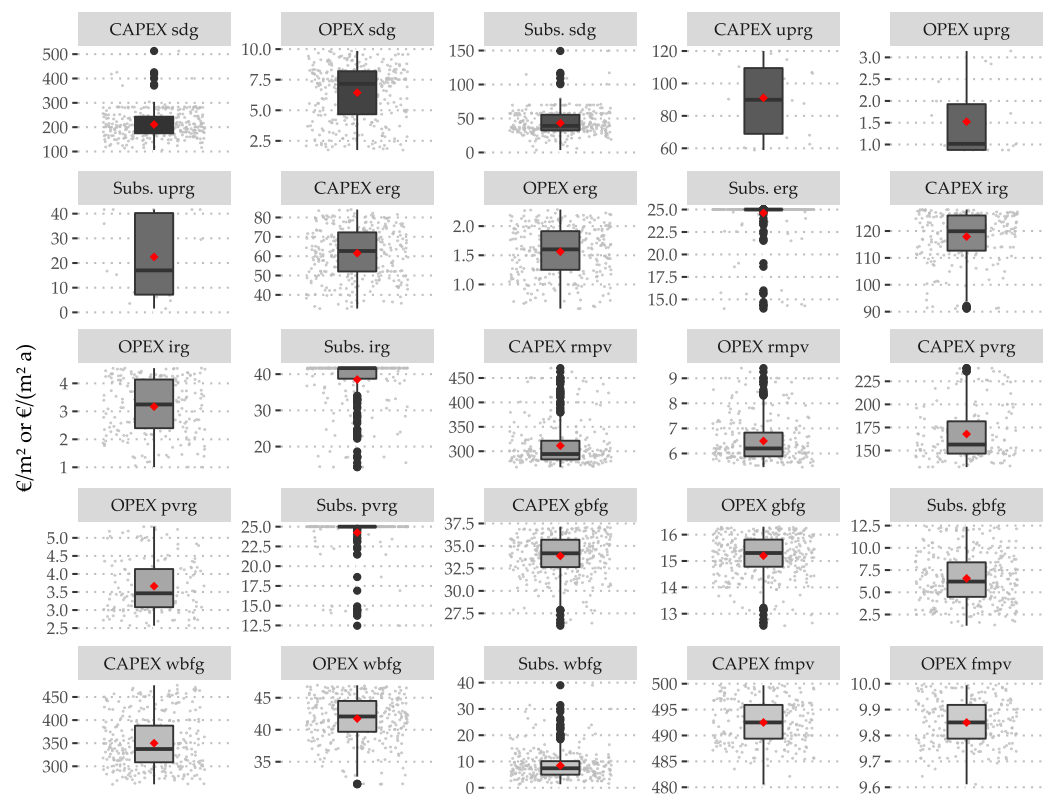
The measure *sdg* comprises the fabrication of different surface types that substitute impervious surfaces with (more) permeable surfaces or mitigate the effect of paving without compromising functionalities—namely, accessible and traversable surfaces for waste containers or parking lots. For example, if parking lot requirements exceed the available area, the individual plot is fabricated to max-out the available area to suit the car parking requirements. In total, 0.78 ha of permeable concrete pavers, 0.85 ha of grass pavers, and 1.9 ha of new urban gardens and green spaces with a configuration of 1:1:1 of short grass, herbaceous plants, and deciduous trees are possible. Figure 7 visualises the potential final stage of removing impervious ground/soil surfaces (*sdg*). For the measure *upgr*, additional intensive substructure roof greening of 0.8 ha can be achieved.

The effects of the measures *sdg* and *upgr* are summarised in Table 11. Regarding the economic indicators, the costs for maintaining (OPEX) the new green/permeable area are much higher than the reduced runoff water charge (Figure 8). Thus, reduced charges have only a minor incentive effect. However, the annual costs (OPEX) are easily offset if the annual and area-specific value of evapotranspiration ( $53.3 \frac{\text{€}}{\text{m}^2 \cdot \text{a}}$ ) or other eco-services are economically assessed and considered.

The subsidy program in the case study area focuses on unsealing impervious surfaces. Thus, the possible subsidies provided by the municipality are the highest for the measure *sdg* (Figure 8).



**Figure 7.** Overview of potential final stage of urban garden or greened courtyard development in the case study district (primary data from the City of Karlsruhe [79]).



**Figure 8.** Box-plots and mean values (red diamond) of area specific investments (CAPEX in  $\frac{\text{€}}{\text{m}^2}$ ), annual maintenance costs (OPEX in  $\frac{\text{€}}{\text{m}^2\cdot\text{a}}$ ), and local subsidies (Subs.) for each of the considered measures.

#### 4.2.2. Facade Potentials

Three alternatives apply to facade surfaces (*gbfg*, *wbfg*, and *fmpv*). The two greening measures (*gbfg* and *wbfg*) can complement each other if ground-based greening is applied to facade elements with ground intersection and wall-based greening to those without ground intersection (*gbfg* and *wbfg*). Hence, the area potentials of *wbfg* and  $gbfg \cup wbfg$  are identical. The *gbfg* and *wbfg* alternatives do not affect runoff water, as they are vertical and hardly receive direct precipitation. Additionally, stormwater retaining effects would rely on the mode of irrigation, which was not considered in this investigation (e.g., passive irrigation via roof gutter). Due to the large available surface area, large potentials could be activated. In total, *wgfb* has the largest effective area of the considered measures and is closely followed by *gbfg*. Each of these alternatives would have more than double the effective area of the measures on roofs or the ground. This is particularly relevant for evapotranspiration purposes.

Energy harvesting via facade mounted PV (*fmpv*) was assessed as an alternative to greening facade surface elements. The mean LCOE of *fmpv* is  $0.26 \frac{\text{€}}{\text{kWh}}$ .

The assessment of *gbfg* assumed that climbing plants entirely cover the selected surface area. In order to achieve this, the period of growth to complete covering is between 2.4 and 22.5 years, with a mean of 9.6. The other measures covered the complete surface area from the beginning. The absolute and specific investments (CAPEX) for *gbfg* and *fmpv* are the highest (Table 11 and Figure 8). The same applies to maintenance costs (OPEX). Due to the large effective area, *gbfg* and *wbfg* offer strong potential for evapotranspiration and air pollutant mitigation. A major difference regarding evapotranspiration originates from the water source. Ground-based facade greening (*gbfg*) is often not dependent on an irrigation system, which is required for wall-based facade greening.

#### 4.2.3. Roof Potentials

Four measures apply to roof surfaces (*erg*, *irg*, *rmpv*, and *pvr*). The measure requirements differ considerably, and thus, depending on the properties of the surface element, different sets of eligible elements were considered. In general, extensive roof greening has the largest set of possible eligible roof elements, and the combination of PV and greening has the smallest set. In total, extensive roof greening has nearly the same potential area as the ground measures *sdg* and *uprg*, while being less expensive (Table 11 and Figure 8). Moreover, extensive roof greening can be combined with PV (the measure of *pvr*). Both measures, *irg* and *pvr*, need flat roofs. In comparison, *pvr* is more expensive but has the benefit of much higher CO<sub>2</sub> mitigation potential. The combination of savings, earnings, and low costs of this alternative seems to be more attractive than all other greening options. Regarding energy harvesting, *pvr* reaches a mean LCOE of 0.165  $\frac{\text{€}}{\text{kWh}}$ , and roof-mounted PV only can reach a mean LCOE of 0.11  $\frac{\text{€}}{\text{kWh}}$ . From all measures on horizontal surfaces, *pvr* does not affect water runoff positively but could worsen it.

#### 4.2.4. Overview of the Technical, Economic, and Environmental Assessment

Table 11 and Figure 8 summarise the results of all considered measures for the case study area. These standalone potentials can be aggregated for the different surface types (*S*) to form an overarching theoretical potential. For example,  $sdg \wedge uprg \wedge erg \wedge gbfg$  could be implemented for approximately 11 m€ with the municipality's involvement in the form of subsidies of about 2.3 m€. Accordingly, the calculated changes in Table 11 can be totalised and yield high benefits in all categories. Regarding the runoff category, the respective change must be area-weighted to retrieve the final potential of reduction. However, the share of impervious surfaces cannot be decreased below *sdg*'s potential. Adding renewable energy harvesting in the form of *pvr* improves the yields further.

The results must be interpreted with overlapping surface element sets in mind concerning the different alternatives for a single surface type. Thus, aggregating alternatives for a given surface type will theoretically cause multiple uses of the same surface element. To generate urban development strategies, different scenarios (alternative combinations) of surface uses/measures have to be selected and compared.

**Table 11.** Potentials in the case study area and assessment of effects. The values represent aggregates for each measure and the effect/change ( $\Delta$ ) from the initial state for the potential area. The column Initial represents the initial state in absolute values. All values are rounded. pp: percentage point.

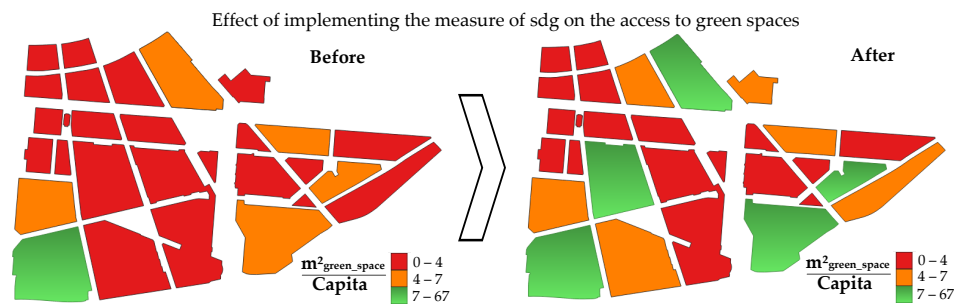
Category	<i>sdg</i>	<i>uprg</i>	<i>erg</i>	<i>irg</i>	<i>rmpv</i>	<i>pvr</i>	<i>gbfg</i>	<i>wbfg</i>	<i>fmpv</i>	Initial <sup>xxvi</sup>
Effective are <sup>xxvii</sup> [ha]	3.35	0.8	4	2.2	1.2 <sup>xxviii</sup>	2 <sup>xxix</sup>	8.5	8.6	1.4	—
Selectable area <sup>xxx</sup>	5.4	1.6	6.68	6.2	5.1	3.4	16.6	16.7	6.2	49.51 <sup>xxxi</sup>
Albedo [-]	0.03	0.01	−0.03	−0.03	−0.01	−0.03	−0.02	0	0	0.211
Runoff peak [pp]	−40	−39	−24	−46	0	−29	0	0	0	84
Runoff avg [pp]	−37	−37	−30	−47	1	−35	0	0	0	69.6
Soil sealing [pp]	−35	0	0	0	0	0	0	0	0	89
CAPEX [m€]	5.6	0.55	2.2	2.4	3.5	3.2	2.7	27	6.8	—
OPEX [ $\frac{m€}{a}$ ]	0.137	0.008	0.05	0.05	0.08	0.07	1.2	3.3	0.14	—
Savings [ $\frac{k€}{a}$ ]	6.6	2	9	11	242	148	0	0	194	—
Earnings [ $\frac{k€}{a}$ ]	0	0	0	0	107	63	0	0	85	—
Local subsidies [m€]	1.12	0.064	0.73	0.52	0	0.37	0.42	0.51	0	—
Green waste [ $\frac{t}{a}$ ]	37	10.7	4	9.8	0	2	25.5	12.9	0	44.5
Evapotrans. [ $\times 10^6 \frac{l}{a}$ ]	7.4	3.2	10.1	8.2	0	5.2	42.5	25.7	0	38.3
Value of evapotrans. [ $\frac{m€}{a}$ ]	1.8	0.77	2.5	2	0	1.3	10	6.2	0	9.3
CO <sub>2,eq</sub> <sup>fix</sup> [t]	40.5	19	32	53.4	0	16.5	102	103	0	6.8
CO <sub>2,eq</sub> <sup>mit</sup> [ $\frac{t}{a}$ ]	3.86	0	0	0	986	585	0	0	790	—
Biodiversity [k n]	220	90	400	250	0	200	1100	860	0	661
NO <sub>2</sub> <sup>mit</sup> [ $\frac{kg}{a}$ ]	52.01	22.2	93	59	0	48	304	200	0	88.3
SO <sub>2</sub> <sup>mit</sup> [ $\frac{kg}{a}$ ]	14.65	6.23	26	18	0.23	13.5	86	56	0.18	24
O <sub>3</sub> <sup>mit</sup> [ $\frac{kg}{a}$ ]	102.3	43.6	180	114	0	92	610	385	0	173.8
PM <sub>10</sub> [ $\frac{kg}{a}$ ]	38.26	10.9	41	27	0	21	175	87	0	90.8
Ecospcore [pt]	85,517	39,690	120,263	88,936	0	61,724	253,069	255,234	0	620,513

<sup>xxvi</sup> All values are absolute and summarise ground, facade and roof surfaces. It should be noted that the facade greening status is unknown. <sup>xxvii</sup> Area of potential. <sup>xxviii</sup> Area need for PV panels. <sup>xxix</sup> Area need for greening with PV panels. Thus, greening area  $\neq$  PV panel area. <sup>xxx</sup> Element area after selection  $\sigma_{\varphi}(E)$ . <sup>xxxi</sup> Union of selectable areas.

#### 4.2.5. Green Area Provision

Based on assessment values from different cities [113], we assessed the direct access of the case study population to green spaces within their perimeter building blocks (Figure 9).  $7 \frac{m^2 \text{green space}}{\text{capita}}$  was selected as the benchmark value for direct access. Only one building block (green, Figure 9 left) fulfilled the benchmark value in the initial state. A clear improvement is apparent (Figure 9, right) if all *sdg* potentials are implemented. However, at the same time, many perimeter blocks could not improve sufficiently. Thus, this example demonstrates that other measures must be implemented to allow equal supply and access to green spaces, e.g., rooftop gardens or public areas.

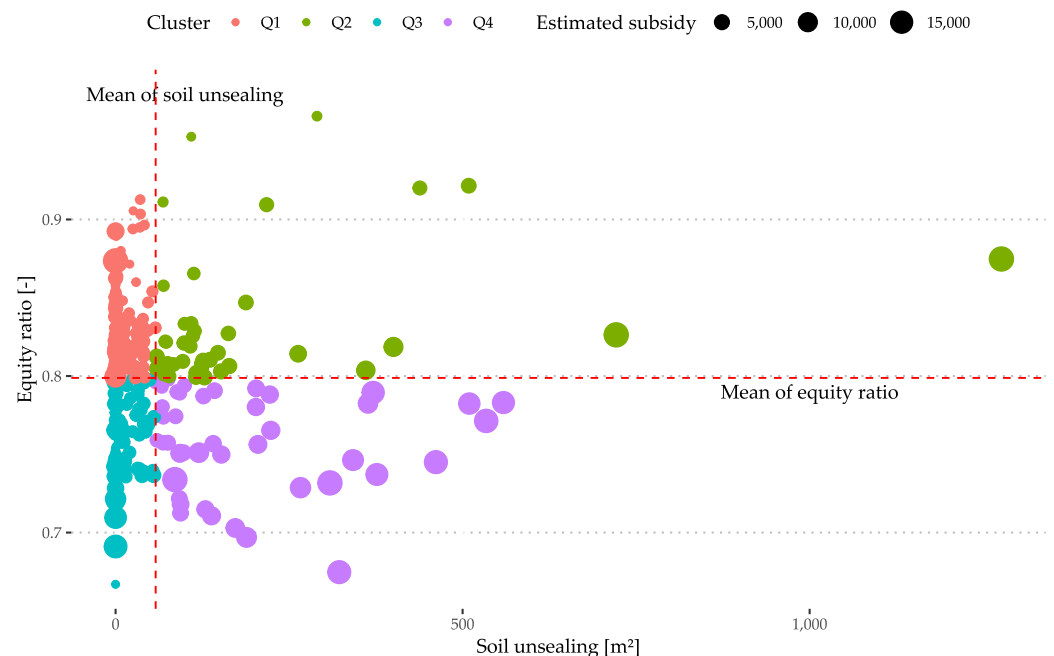




**Figure 9.** Improvement of direct access to green spaces at the building block level through the implementation of the measure *sdg*. The depicted threshold is  $7 \frac{\text{m}^2_{\text{green space}}}{\text{capita}}$  (primary data from the City of Karlsruhe [79]).

#### 4.2.6. Subsidies

As noted in Section 3.5, the case study area is subject to a redevelopment program with subsidy schemes in place. In the following analysis of these schemes, there is focus on soil unsealing (removing impervious surfaces). Soil unsealing only occurs in the measure *sdg*. Furthermore, the amount/degree of unsealing depends on the need for traversable surfaces for waste containers or parking lots. Therefore, the theoretical maximum area cannot be unsealed entirely on most plots. However, the funding schemes focus on two parts: first, on removing soil sealing, and second, on creating green spaces (*sdg*). Applying the funding conditions according to [110,111,114] revealed the possible outcomes summarised in Figure 10 and Table 12.



**Figure 10.** Analysis of the subsidy program in the case study area with a focus on impervious surface unsealing. The mean values of the x-axis and y-axis subdivide the scatter plot into four quadrants. The respective potentials were assigned accordingly to four clusters.

Figure 10 illustrates four quadrants subdivided by the mean of equity ratio and the mean of soil unsealing. The equity ratio provides information about the owners' contributions to the investment: the higher the ratio, the higher the financial contribution of

the owner. The bubble size indicates the estimated subsidy amount, and the soil unsealing represents the potential unsealing per calculated intervention measure. An owner in cluster Q1 (red) would receive relatively low subsidies for subpar soil unsealing. As soil unsealing is a major goal of the funding scheme, this appears reasonable. However, an owner in cluster Q3 (turquoise) would receive high subsidies for subpar soil unsealing, which seems to be overfunding these implementations, as other partially sealing greenery (e.g., greened grids for parking lots) is funded. Owners in Q2 (green) and Q4 (violet) clusters contribute the most to soil unsealing.

The scale of the subsidy allocation is presented in Table 12. The highest subsidy is allocated to the highest potential of soil sealing, indicating a well-formulated funding scheme. However, Q1 and Q3 get more than double the resources for a quarter of the potential, so there is a bias toward small areas and projects. In conclusion, revisiting the funding scheme or reconsidering the targets should account for creating incentives, especially for plots with high unsealing potential. Lastly, with this kind of analysis, prioritising particular plots or building blocks can assist in disseminating information and targeted approaching of owners.

**Table 12.** Local subsidy program analysis for soil unsealing by the measure *sdg*.

Quadrants	Below Average Soil Unsealing	Above Average Soil Unsealing
Above average equity ratio	Q1: 259 k€ subsidies for 1,487 m <sup>2</sup> <sub>unsealing</sub> $\left(\frac{174.4\text{€}}{\text{m}^2_{\text{unsealing}}}\right)$	Q2: 204 k€ subsidies for 8,013 m <sup>2</sup> <sub>unsealing</sub> $\left(\frac{25.5\text{€}}{\text{m}^2_{\text{unsealing}}}\right)$
Below average equity ratio	Q3: 283 k€ subsidies for 1,167 m <sup>2</sup> <sub>unsealing</sub> $\left(\frac{242.2\text{€}}{\text{m}^2_{\text{unsealing}}}\right)$	Q4: 383 k€ subsidies for 8,382 m <sup>2</sup> <sub>unsealing</sub> $\left(\frac{45.6\text{€}}{\text{m}^2_{\text{unsealing}}}\right)$

## 5. Discussion

This study demonstrated the utilisation of a detailed sub-plot GIS-based assessment tool for identifying and assessing sustainable redevelopment and reduction potentials of impervious surfaces in urban districts. The formulated model generates an inventory of surfaces based on widely available urban data and is easily transferable to other case studies. Additionally, the model allows determining the technical (social) potentials for each considered measure individually. Furthermore, it accounts for sub-plot requirements and constraints. Moreover, we derived area size-dependent CAPEX and OPEX curves for individual measures to enable financial resource planning and management. Based on the literature review in Section 1.1, this kind of assessment seems to be underdeveloped. For example, other proposed approaches quantify single surface type potentials, such as green roof potentials (e.g., [67,115]) or trees [116], or focus on creating inventories to quantify the initial state (e.g., [69,73,74,117]). Especially rare are spatially explicit approaches for small-scale intervention measures and that consider facade greening. For the latter, most of the found studies are either empirical, or conceptual, or about facade-mounted PV [118]. The comparison between energy-oriented spatial potential assessments and urban greening shows the lack of economic assessment.

For Germany, our approach can utilise existing data, analyse the surface inventory, and assess greening and other sustainable intervention measures on the sub-plot level. Hence, this paper provides valuable findings that enable the communities of urban planners and researchers to replicate assessments of similar granularity. The focus of this publication was on privately owned properties. However, the use of the tool is not limited to these properties.

### 5.1. Key Determinants for the Assessment and Evaluation of Results

Key determinant for assessing the initial state and green infrastructure alternatives is up-to-date and granular data. In a previous and exploratory investigation, we could demonstrate the limits of using unofficial data from Open Street Maps [78]. The data lacked much information, especially regarding urban greenery.

In addition, most comparable studies are limited to grid/raster-based assessments. The utilisation of cadastral plot data enables a plot-specific analysis, which especially suits the design of policy instruments taking property and ownership characteristics into account. Moreover, this eases the reference to formal development plans. In particular, the lack of considering administrative operations increases the reluctance to integrate such prior approaches into formal instruments. Therefore, this publication contributes to the existing body of knowledge by presenting an approach specifically geared to fit into authorities' procedures and providing additional tools for guiding actions.

A relevant aspect of this work was to establish sound CAPEX and OPEX functions for the economic assessment of the intervention measures. These enable more detailed analysis and provide valuable input to assess expenses, earnings, savings, and subsidies. Additionally, the ecoscore represents a specifically developed metric to assess biotope quality. This metric is based on the German environmental impact assessment that scores biotopes according to their ecoservices. The utilised scoring was modified by Boehnke et al. [77] and accounts for biotope value regarding multiple factors, such as contribution to biodiversity, regionality of plant species, and habitat frequency of occurrence in urban centres.

According to the derived and adopted five-level hierarchy (Figure 1), the investigation showed that strategies focusing the two highest levels, (1) avoidance of additional land consumption/ impervious surfaces and (2) restoration of used and no longer used surfaces to their natural state, are limited in existing urban city districts. Aside from the measure *sdg*, none of them can satisfy these levels. However, greening measures can alleviate the impacts of impervious surfaces (levels 3 and 4). In a narrow sense, all suggested measures are manifestations of the built environment [119,120]. Despite this, urban green infrastructure's potentials and benefits are large. Especially the consideration of vertical and horizontal surface potentials in one approach provides insight into exploiting synergies and mitigating trade-offs. Furthermore, a spatially explicit approach enables engineering urban green infrastructures in the planning phase and allows for establishing corridors of green patches [52] or reducing social inequalities. Correspondingly, Lundholm and Richardson [121] noted the possibility of altering measures by ecological engineering to control measure effects. This is not used in the proposed tool, where generic measures are implemented. However, the results show highly positive impacts of the mitigation and counterbalance measures on the adverse effects of highly impervious surfaces.

Concerning the results, the input values used represent default and literature values. Thus, it has to be noted that microclimate improvement and pollutant removal services are highly variable, and location-, water-, and species-dependent, as brought forward by various investigations [43,44,101].

Due to the large number of indicators, geo-referencing of the results, and assortment of alternatives, decision making requires suitable tools to handle complexity. In particular, spatial decision support systems are needed. Many approaches for multi-criteria decision support exist but require decision-maker-specific designs, e.g., GIS-based multi-criteria decision analysis [122,123], an analytic network process [124], or ELECTRE [125,126].

## 5.2. Implications for the Case Study

The assessment results can be used as input information for formal planning instruments, such as zonal planning and master plans, representing the strategical management level. Moreover, the presented tool can assist operational and tactical decision making in subsidy program development or priority assessments.

Our investigation created an updateable data model for the case study district. With this approach, time-series changes in land use can also be tracked and evaluated. Moreover, the provided assessment of nine different intervention measures delivers insight and improves understanding of the effects of the measures and the economics of investment and subsidy budgets for activating potentials.

The subsidies in place can significantly contribute to investments (CAPEX). However, the appeal of the subsidy schemes is extenuated by additional conditions that could not be modelled in our investigation, such as commitments regarding capped rent increase or additional organisational effort. Hence, encouraging owners to implement greening measures requires additional persuasion efforts. Besides reducing commitments, a redesign of the subsidies could be assessed by the proposed approach and evaluated to infer possible outcomes. Furthermore, OPEX could not be offset by the reduced and low drainage fees, resulting in small savings and delivering only minor incentives.

All measures effectively mitigate air pollutants and provide benefits in significant amounts (compared to the initial state). However, Jones et al. [127], Chen et al. [128], Hirschfeld et al. [129], Stinner et al. [130] showed that many additional dimensions, such as health and less tangible cultural benefits exist, which can significantly influence the economic evaluation of or the willingness to pay for delivered services which have not been considered in the assessment at hand.

Even though the potential interventions in the case study can improve the initial state considerably, the potentials for unsealing are limited and should be exploited. In order to achieve the best results, supplementing unsealing ground surfaces with green roofs and facades must be considered. Particularly for the potential to increase biodiversity, the patch sizes are really small compared to the desired sizes of multiple hectares [52]. However, according to Wooster et al. [131] and Pfoser et al. [37], relatively small green building surfaces can considerably support urban fauna. Limitations arise for measures that include PV. For these, emission mitigation is indirect, as they substitute other environmentally harmful technologies elsewhere and not necessarily in the district of consideration. Furthermore, air pollutant mitigation of PV will be lower due to the ongoing decarbonisation and energy system transformation. Hence, the gap between current renewable-energy-related mitigation and natural metabolic and deposition mechanisms will shrink while implementing PV. Stormwater retention is an essential benefit that facade greening and PV options cannot provide directly. In areas with high sealing and runoff coefficients, as the case study district, future weather scenarios predict more severe precipitation, increasing the pressure for action. However, energy harvesting on utilised surfaces should always be encouraged, and wherever possible, combined with greening.

Forecasts also predict more heat. Regarding this, evapotranspiration and shade from green infrastructures promise to provide cooling and prevent urban centres from overheating. In the case study district, ground-based facade greening provides both in high quantities. The investigation did not consider additional benefits, such as the protective effects [37,39,45] on construction products from shading and reducing weather exposure. However, these effects could offset OPEX and encourage the adoption of facade or roof greening. Furthermore, water consumption via irrigation is not considered in the model, nor the water availability in hot months or the functioning of urban green in that period. Future models should include such simulations eventually, along with rainwater harvesting, to secure irrigation and evapotranspiration of urban greenery throughout the year.

Moreover, the model could be extended to public spaces and to assess other sustainable inventions, e.g., water bodies; mobility; or social benefits.

## 6. Conclusions

Urban planners need to consider different alternatives for avoiding, restoring, efficiently utilising, mitigating, and compensating land use. The presented informal five-level hierarchy for a land-sensitive urban development strategy provides a guiding principle. However, potentials in urban centres are limited, and strong trade-offs must be made by urban planners and policy/decision makers. Hence, determining formal logic applying the hierarchy needs a political and administrative consensus. In order to provide decision support, authorities are challenged and need appropriate tools to quantitatively and qualitatively evaluate strategies on the sub-plot/small scale level.

The presented data model and assessment approach show the economic, technical, and environmental impacts of implementing green infrastructures. Besides the individual effects of each measure, a given subsidy scheme can be assessed. In the presented case study, the latter revealed optimisation potentials, especially ones promoting the first two levels of the five-level hierarchy more strongly and reducing overfunding of unsealing very small areas. Furthermore, it has been shown how large the potentials are and that services provided by the measures are very high. However, the quantification of services is based on literature values, and model estimations that could be inaccurate. Hence, accounting for uncertainties and comparing against local experimental/meteorological data in such assessments should be addressed in future research.

Promising extensions of the developed approach include coupling the data model with microclimate simulation engines, such as PALM4U, to facilitate compiling/generation of static drivers or to calculate and assess microclimatic effects. Furthermore, integrating other tools into the approach is possible—e.g., i-Tree to incorporate detailed tree assessments—to increase versatility and provide the capability to address services and disservices in more detail. Correspondingly, the intervention and restoration measures mix could be extended by blue infrastructures (water bodies). Additionally, providing an integrated multi-criterion decision analysis would enhance the practicability.

Treating surfaces as valuable assets beyond real estate and managing them proactively in dense urban areas is a crucial factor in ensuring a sustainable, healthy, and resilient urban development. This task is a societal challenge, and for privately owned property, the willingness to act needs to be reflected by the respective citizens and individuals in all cities.

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## Abbreviations

The following abbreviations are used in this manuscript:

ALKIS®	Authoritative Real Estate Cadastre Information System
CAPEX	Capital expenditure
EOS	Economies of scale
erg	Extensive roof greening
fmpv	Facade-mounted photovoltaics
gbfg	Ground-based facade greening
Geom	Geometry
GIS	Geo information system
INT	Intersection
irg	Intensive roof greening
LCOE	Levelised cost of energy
Lidar	Light detection and ranging
LOD	Level of detail
OPEX	Operational expenditure
pp	Percentage point
PV	Photovoltaic
pvrg	Photovoltaics and roof greening
rmpv	Roof-mounted photovoltaics
SCT	Surface cover types
sdg	Soil unsealing/domestic garden
uprg	Underground parking roof greening
wbfg	Wall-based facade greening

## Appendix A



**Figure A1.** Surface cover type inventory without streets (primary data from the City of Karlsruhe [79]).

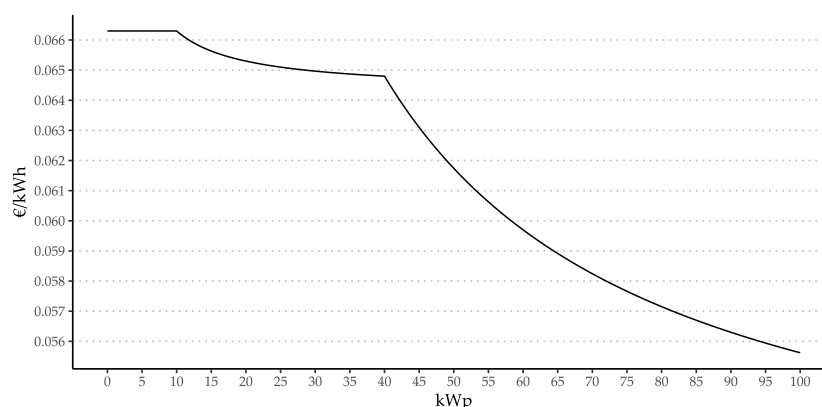


Figure A2. Feed-in tariff  $c_{cost,el}^{feedin}(kWp)$  [98].

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