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NBS Impact Evaluation with GREENPASS Methodology Shown by the Case Study 'Fischbeker Höfe' in Hamburg/Germany

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Citation: Scharf, B.; Kogler, M.; Kraus, F.; Garcia Perez, I.; Gutierrez Garcia, L. NBS Impact Evaluation with GREENPASS Methodology Shown by the Case Study 'Fischbeker Höfe' in Hamburg/Germany. *Sustainability* **2021**, *13*, 9167. https://doi.org/10.3390/su13169167

Academic Editor: Sebastian Kot

Received: 23 June 2021
Accepted: 10 August 2021
Published: 16 August 2021

Abstract: The implementation of nature-based solutions (NBS) in urban regeneration aims to improve citizens' health and well-being. Therefore, tools need to be applied to identify the most suitable and efficient location and type of NBS. Within the CLEVER-cities H2020 project, the Greenpass method has been chosen to evaluate different design solutions regarding thermal comfort and physiological equivalent temperature (PET), energy, water and air fluxes. The Greenpass system comprises of standardized tools, reports and a unique set of Key Performance Score (KPS) and Key Performance Indicators (KPI). This paper deals with the impact assessment of NBS by the use of the innovative Greenpass system for the CLEVER-cities project 'Fischbeker Höfe' in Hamburg, Germany to ensure human health and well-being improvements for the citizens. To that end and considering the climate change context, thermal comfort is a KPI with high relevance in terms of the NBS co-benefits. Based on the PET within a project area Greenpass calculates the Thermal Comfort Score (TCS). The share of the different PET classes within the project area is multiplied with a weighting factor and summarized to the TCS. The results of the climate resilience analysis of the urban development area 'Fischbeker Höfe' in Hamburg are presented and discussed in comparison to a conventional architecture that disregards NBS, showing improvement with regards to four out of five KPS. Based on the evaluation results, advice is given to the co-creative design team on how to further improve the design towards climate resilience. The Greenpass system has proven to be a powerful and tailored tool to support climate resilient urban design and architecture. It provides a standardized and comprehensible but still scientific basis for decisions in a highly efficient and understandable way.

Keywords: climate resilience; urban planning; nature-based solutions; decision making tools; greenpass

1. Introduction

Even if the COVID-19 situation competes with the climate change issue from a society and publicity point of view, climate change proceeds. At least to that end, the COVID-19 pandemic had positive effects by causing a reduction of approximately 10% of greenhouse gas emissions [1]. On the other hand, the global crises fortiori underlines the relevance of sufficient and qualitative urban open spaces and the adaption of urban areas. Undisputed, NBS reveal to be a potential key-changer to face climate change impacts and to improve the citizens quality of life [2–4]. The CLEVER-cities H2020 project focusses on implementing NBS in urban regeneration projects to improve citizens' health and well-being. However, to define the most suitable NBS, multiple variables have to be considered. To understand the energy-water and air fluxes in urban environment simulation software solutions, ENVI-met and similar programs/simulation tools, have been developed [5,6]. These software solutions allow for impact modelling of different NBS solutions and provide highly valuable and useful support and information during the co-design solution process for efficient and successful implementation of NBS. Furtherqmore, in terms of monitoring the impact of these measures, software-based modelling and standardized evaluation tools proved to be a relevant and important supportive approach for NBS impact assessment and the mainstreaming of NBS in urban planning as basis for informed decision making [7].

In the context of the CLEVER-cities project, the NBS are expected to contribute to the following urban regeneration challenges: human health and well-being, sustainable economic prosperity, social cohesion and environmental justice as well as citizen security. Human health and well-being is addressed here following the approach and inputs proposed in this paper since it is devoted to reducing physical, psychological and physiological stress, damage and negative health impact (e.g., exposure to noise, air pollution, obesity, depression, morbidity, lacking sense of place, etc.) [8,9]. On a more holistic view the comprehensive CLEVER urban regeneration strategy could be useful also to strengthen community ties and decision-making processes since it contributes to inform the NBS impact and empowers communities.

At its core, this paper aims to demonstrate the holistic CLEVER-cities approach and the Greenpass evaluation method. Based on the small urban development area of 'Fischbeker Höfe' in Hamburg the question shall be answered whether the Greenpass Key Performance Scores, Key Performance Indicators, Maps and Diurnal Performance Diagrams are suitable to identify differences in performance of NBS implementations and allow an informed decision-making process.

The implementation of NBS determines a broad variety of environmental aspects and qualities that have a direct impact on human health and well-being [10,11]. One of these environmental aspects concerns thermal comfort [12], which is of great relevance for sojourn quality and regeneration of people [13]. Especially in the context of global climate change and the over proportional effects on cities and accordingly all urbanites, thermal comfort needs to be considered as a decisive factor. Heretofore the use of state-of-the art bio-human indices, like the physiological equivalent temperature (PET) or universal thermal climate index (UTCI) which are qualified to assess and express the thermal comfort of human beings, represent an appropriate methodological approach [14]. These approaches are usually linked to computational expert simulation models for microclimate, like e.g., one of the world's most used software in the realm, ENVI-met [5,6].

To mainstream NBS in urban planning policies, simplicity and efficiency is crucial to implement informed and evidence-based decision making by relevant stakeholders [15]. Therefore, the innovative Greenpass technology has been developed in the recent 10 years in course of several research projects [16–20]. Greenpass provides a single software interface to planners and designers and standardized project processing along with a unique set of key performance scores and indicators to guarantee profound and scientific ground for decision making.

The Greenpass system has been selected within the CLEVER-cities H2020 project to evaluate the actual climate resilience and assess the improvements of the 'Fischbeker Höfe' expected from NBS implementations.

CLEVER-Cities Case Study 'Green Roof and Façade'

The city of Hamburg, which is located in the north of Germany, is a large metropolitan area with a high population rate and growth. Hamburg is one out of three frontrunner cities besides Milano and London within the CLEVER-cities project with the focus to foster the implementation of NBS in the city to deal with climate change and strengthen citizen engagements. The CLEVER-cities project area is a highly diverse area including very rural sites as well as highly urbanized and new development areas. Hamburg contributes to the

CLEVER-cities Project with three case studies in the southwest of Hamburg (see Figure 1). Arlati et al. [21] provides a more detailed description of the case study area.

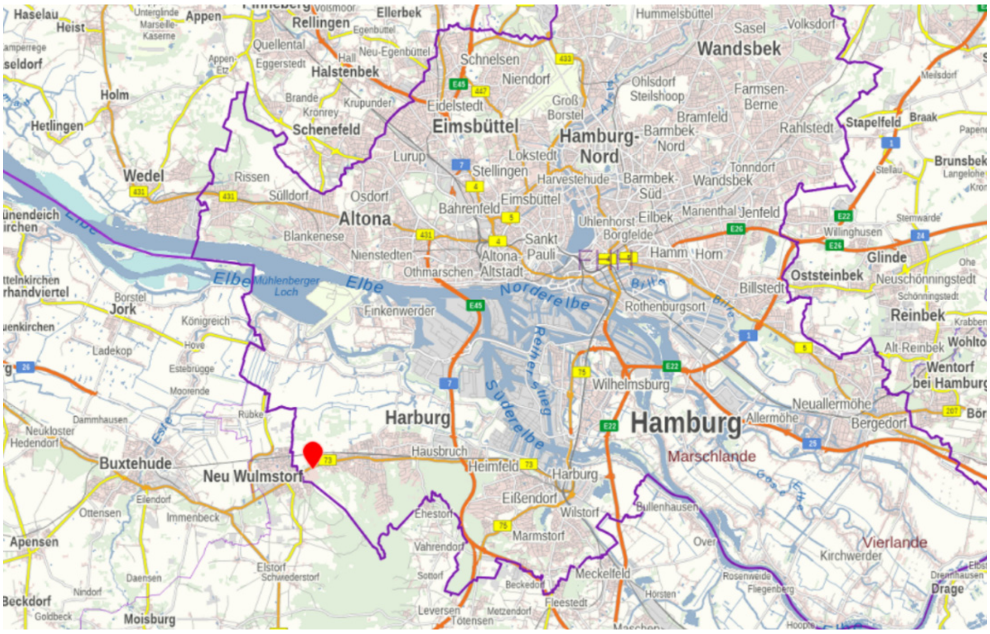

Figure 1. Location of 'Fischbeker Höfe' in the southwest of Hamburg/Germany, The Free and Hanseatic City of Hamburg (2020).

One of Hamburg's projects concerns an area of approximately 1.1 ha as shown in Figure 2. New residential buildings with environmental considerations shall be constructed called 'Fischbeker Höfe' on former military grounds. Recycled building materials shall be used in combination with innovative NBS which are 976 m^2 green roofs and 502 m^2 façade greening (see Figure 3).

Figure 2. Project area 'Fischbeker Höfe' in Hamburg/Germany. Project area framed in red. The Free and Hanseatic City of Hamburg (2020).

(**a**) (**b**)

Figure 3. NBS implementation of Green Wall and Green Roof within CLEVER-cities case study 'Fischbeker Höfe' in Hamburg/Germany: (**a**) southview, (**b**) northview © DeepGreen Development.

2. Greenpass NBS Impact Evaluation Methodology

Greenpass is the world's first standard and easy-to-use Software as a Service (SaaS) for climate-resilient urban planning and architecture. It can be applied at different scales including the city, district or object level for new urban developments as well as in retrofitting. According to the respective phase of a project's development, it provides tailored tools in accordance with the service phases 1 to 5 as defined in the Honorarrichtlinie für Architekten und Ingenieure [22]. The tools are optimized for the conceptional design, urban design competitions, schematic design to detailed design development (see Figure 4) and deliver the accuracy and level of detail as appropriate to the respective phase [17–20,23,24]. The internationally applicable Greenpass technology has been successfully applied in more than 100 projects so far in 10 European countries with different project sizes from 0.1 to 24 ha and aims to set a global standard for climate-resilient urban planning and architecture [25] (see Table 1).

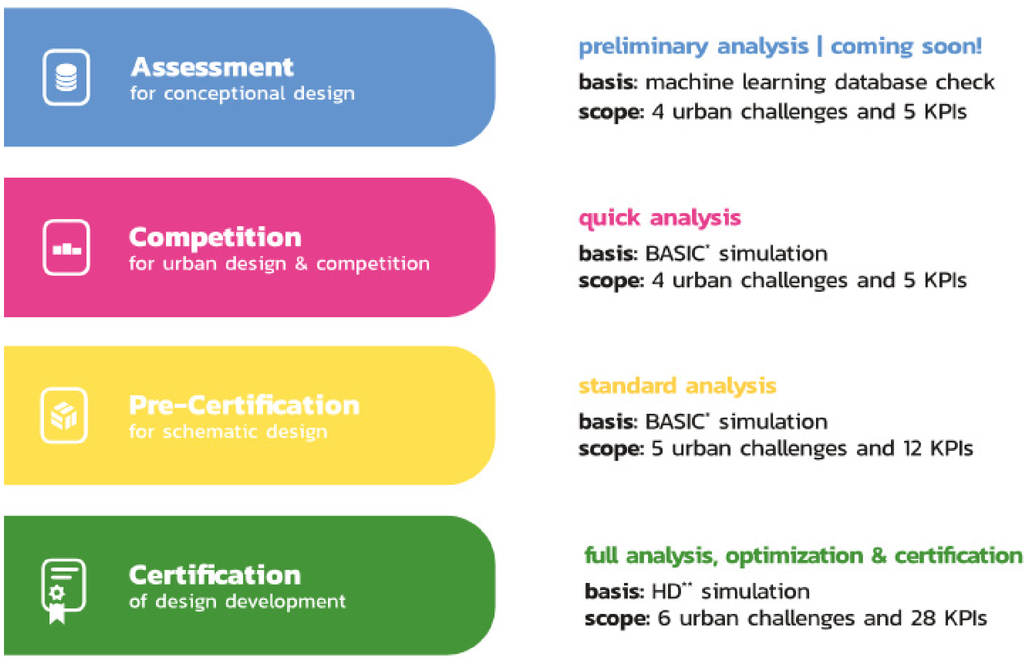

Figure 4. Greenpass Toolbox providing tailored tools for different project development stages.

Table 1. Selection of previous Greenpass projects with each project size in ha (status 03.08.2021).

GREENPASS Project List Summary				
Total Projects	108	Projects can be processed by several sub-projects		
Total Sub-Projects	130	Projects below are an abstract of public communicated projects		
Countries	10			
Countries	**No. of Projects**	**No. of Sub-Projects**	**Size (ha)**	**More Information**
Austria	70	90		
IKEA Westbahnhof Vienna			0.4	https://greenpass.io/2021/06/25/ikea-westbahnhof-wien/ (accessed on 3 July 2021)
Biotope City Vienna			6.8	https://greenpass.io/2021/03/09/biotope-city/ (accessed on 3 July 2021)
MAHI 10–18 Vienna			0.8	https://workdrive.greenpass.io/external/QCWWu4HQwJ-lTZKpT (accessed on 3 July 2021)
aspern Seestadt Vienna			24.0	https://neuelandschaft.de/artikel/it-gesteuerte-natur-in-der-dichten-stadt-12892.html (accessed on 3 July 2021)
Oberes Hausfeld Vienna			20.0	-
An der Schanze Vienna			10.5	https://www.iba-wien.at/en/projekte/projekt-detail/project/urban-wilderness-event-corridor-greenpass (accessed on 3 July 2021)
Belgium	2	2		
Playhouse Elief Antwerp			0.1	https://www.mdpi.com/2075-5309/9/9/205/htm (accessed on 3 July 2021)
Hibernia Antwerp			0.1	https://www.antwerpen.be/info/5f1ac11b2888ff1d7f5d31c4/spelen-en-groen-combineren-dankzij-eenhorizontale-en-verticale-puzzel (accessed on 3 July 2021)
Czech Republic	4	4		
Brno Rakovecka			1.9	https://9d16c711-fa4a-4b74-9624-2fc4da78e12d.filesusr.com/ugd/43f56c_7e405a02865945288dec9e269733146c.pdf (accessed on 3 July 2021)
Opava City			1.5	https://27d02548-2c2d-4fc8-bd95-f1d6041f7d4f.filesusr.com/ugd/c546d5_7c211db6cd864c3c9da473465cd12c27.pdf (accessed on 3 July 2021)
České Budějovice			0.5	https://greenpass.io/wp-content/uploads/2021/03/2020-03-16_CZ-2020-CB-PreCert-CZ-final.pdf (accessed on 3 July 2021)
Germany	10	10		
KUHLIO Frankfurt			0.5	https://bautecfokus.at/a/vorreiter-sre-erhaelt-erstes-greenpass-zertifikat-deutschlands (accessed on 3 July 2021)
TZR Bochum			0.8	https://m.facebook.com/enablinglivablecities/posts/1868707086612511 (accessed on 3 July 2021)
Willy-Brandt-Platz Krefeld			1.1	https://krefeld.meine-stadt-transparent.de/file/16040/ (accessed on 3 July 2021)

Table 1. *Cont.*

GREENPASS Project List Summary				
Italy	8	9		
Segrate Milano Due			16.0	http://www.ibpsa.org/proceedings/BS2019/BS2019_211002.pdf (accessed on 3 July 2021)
CityLife Milano			4.0	https://greenpass.io/wp-content/uploads/2020/12/GREENPASS%C2%AE-Reference-Book_v2.2_low.pdf (accessed on 3 July 2021)
Piazza Loreto Milano			4.0	-
Netherlands	2	2		
Hamerkwartier Amsterdam			11.0	-
Beatrixkwartier Den Haag			21.2	https://issuu.com/urbanboost/docs/oteam_eerste_hulp_bij_gebiedsontwikkeling_finaleve/s/12137330 (accessed on 3 July 2021)
Slovakia	4	4		
Zvolen			1.0	-
Corvus Malacky			1.0	-
Switzerland	4	4		
Poststrasse Uster			0.6	-
Prime-Tower Zürich			2.7	-
England	3	4		
Thamsmead Southmere London			6.3	https://clevercities.eu/london/ (accessed on 3 July 2021)
Thamsmead Parkview London			22.0	https://www.london.gov.uk/what-we-do/environment/parks-green-spaces-and-biodiversity/clever-cities-thamesmead (accessed on 3 July 2021)
Woburn Court Croydon, London			1.0	-
USA	1	1		
Campbell Court—City of Roanoke			0.9	-
For more information please visit:			**www.greenpass.io/references www.greenpass.io/blog/**	

As Figure 4 illustrates, the scope of key performance indicators delivered by Greenpass increases along with the progress in project development as does the applied methods and level of detail. While the assessment is based on a unique machine learning engine that examines the structure of urban fabrics and their proportion of NBS, the other tools include expert simulations.

The different tools conclude in a standard reporting system that has been designed to present the results in a comprehensible way, also suitable for non-experts and especially stakeholders as representatives of the municipalities or developers. The Greenpass report provides most relevant project information, as location, size etc., and illustrates the climate resilience performance as key performance scores, performance profiles and figures as heat maps.

The phase of the new 'Fischbeker Höfe' and adjacent area can be assigned to schematic design within the scope of the CLEVER-cities H2020 project. Accordingly, the Greenpass Pre-certification tool has been selected, being the most appropriate one.

2.1. Greenpass Key Components

Beside the tailored toolbox, the innovative Greenpass system comprises three interacting main components:

- Software
- Expert Systems
- Evaluation System

2.2. Software—Greenpass Editor

The Greenpass software has been created for planners and designers to serve as an interface between the planning world and scientific expert simulation tools. It is easy to use, allows the import of standard planning files and includes a comprehensive database of urban materials. The software creates digital simulation models for expert simulation tools which are processed and analyzed according to the Greenpass environmental assessment system. The Greenpass editor software (GP.e) is a GIS-based modelling software system and the crucial interface between the world of expert simulation systems and practice. It allows a straightforward import of common planning data, including CAD (.dxf), GIS (.shp) or OSM (.osm) files. The objects imported are assigned to an urban material from the comprehensive database of different building and surface materials as well as NBS (see Figure 5). New materials can be added to the database, provided the relevant properties are underlaid with scientific proof (e.g., thermal conductivity or albedo). The material properties and geometry, plant species etc. of the project are automatically transformed into a digital simulation model expert system [26].

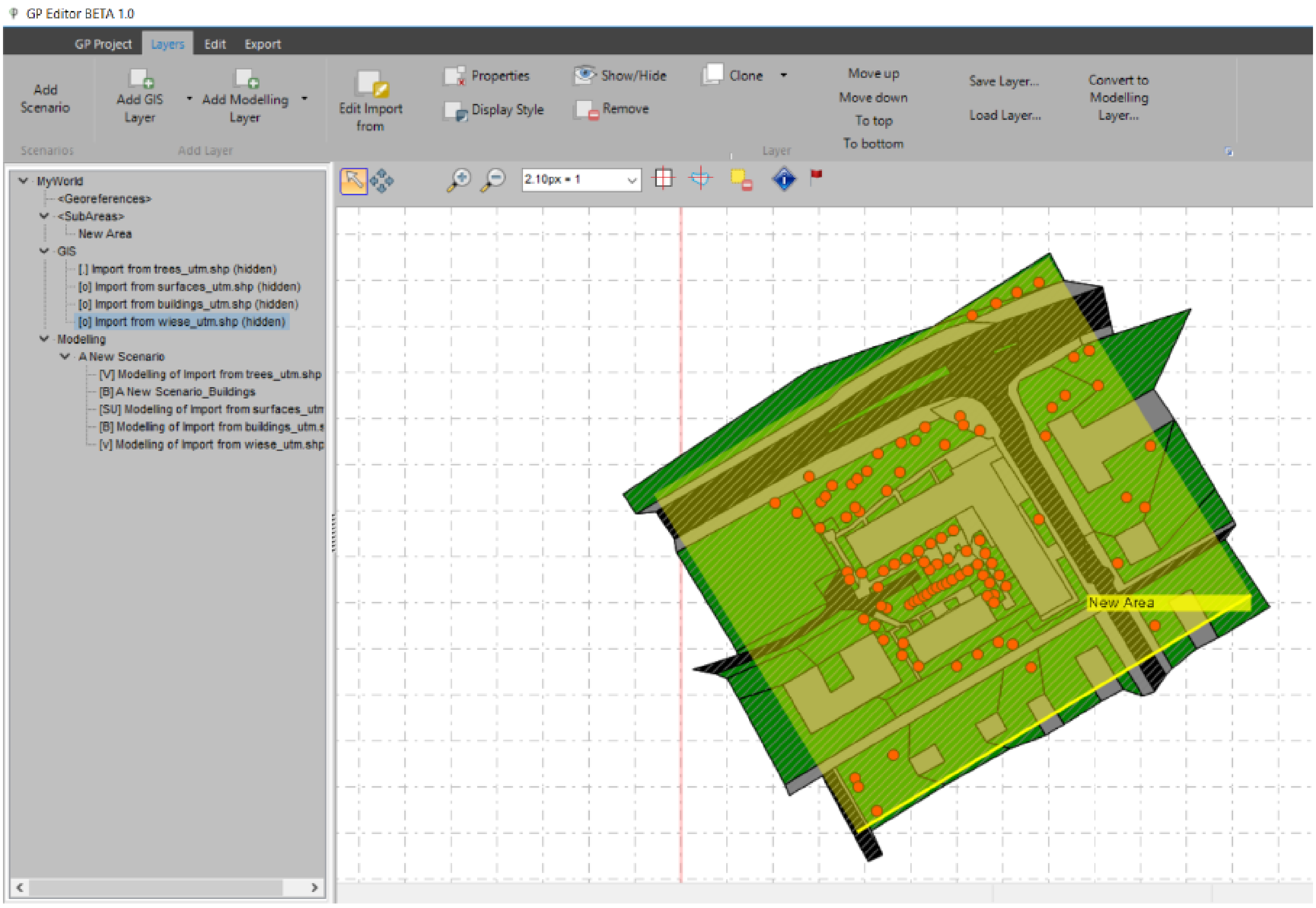

Figure 5. Screenshot of georeferenced and modelled 'Fischbeker Höfe' within Greenpass editor software.

2.3. Microclimate and Wind Expert Simulation Systems

The Greenpass software serves as single access for planners to receive different state of the art environmental assessment services. Currently, Greenpass is capable of automatically generating the microclimate model for ENVI-met and wind Computational Fluid Dynamics model Rheologic. The scope of environmental assessment simulation systems attached to Greenpass will be extended to an acoustic model and hydraulic run-off in a next step.

2.4. Greenpass Evaluation System

The standardized evaluation and decision-making system considers up to 28 Key Performance Scores and Indicators that can be ascribed to six different urban challenges: climate, water, air, biodiversity, energy and cost (see Figure 6).

Figure 6. Greenpass covers up to 6 urban challenges: climate, water, air, biodiversity, energy and cost.

The worldwide applicable evaluation system and method consists of two different indicator types.

Key Performance Scores (KPS): KPS are 1st order indicators within the Greenpass system. The five KPS are extremely meaningful because they indicate the thermal comfort and well-being as well as climate resilience (Urban Heat Islands impact and Run-Off) and CO_2 sequestration. These indicators are used in all Greenpass tools accordingly:

- Thermal Load Score (TLS)
- Thermal Comfort Score (TCS)
- Thermal Storage Score (TSS)
- Run-off Score (ROS)
- Carbon Sequestration Score (CSS)

Key Performance Indicators (KPI): KPI are highly relevant as 2nd order indicators within the Greenpass system and comprise the following seven indicators:

- Thermal Performance (PET)
- Radiation (RAD)
- Albedo (ALB)
- Shading Area Factor (SAF)
- Leaf Area (LAR)
- Evapotranspiration (EVA)
- Wind Resistance (WRS)

These indicators and scores draw a precise profile of any project regarding qualities and deficiencies. Together with standard figures and maps it allows users to analyze and optimize the design of urban developments and architecture or compare different designs. The use of NBS in urban planning and design processes considers and illustrates their impact and efficiency.

The Greenpass Pre-Certification analysis, as applied for the 'Fischbeker Höfe', allows standardized, climate-effective planning, and the optimization of projects and fact-based decision-making on climate change adaptation measures and especially the increase of the thermal comfort and quality of life for residents. The Pre-Certification results also provide an effective tool for public relations in order to show authorities, customers and/or residents the various positive effects of climate-sensitive measures (such as green and blue infrastructure) in a more accessible and understandable way. Greenpass Pre-Certification also offers the option of optimization as well as the use of reference scenarios in order to set the best possible course at an early stage and to increase the significance of the results by using additional scenarios.

In the following section, the Thermal Comfort Score, which is related to human thermal comfort, health and well-being, is described in extensive in detail.

2.5. Thermal Comfort Score

The Thermal Comfort Score is an easy to understand and comparable number that explains the human thermal comfort of a project area in open space in a single number, based on the ratio of areas with thermo-physiological stress for a standard male person [27]. The indicator is calculated on the basis of the physiological equivalent temperature (PET) and a visual heat map and divides the areas within the project area into scientifically based sensation classes (from very cold to very hot) for the respective climate zone. Each class of sensation has a valuation weighting, which results in the respective points rating/class (see Figure 7). The sum of all sensation class points delivers the thermal comfort score for a single (one hour) or diurnal (10 h) time observation.

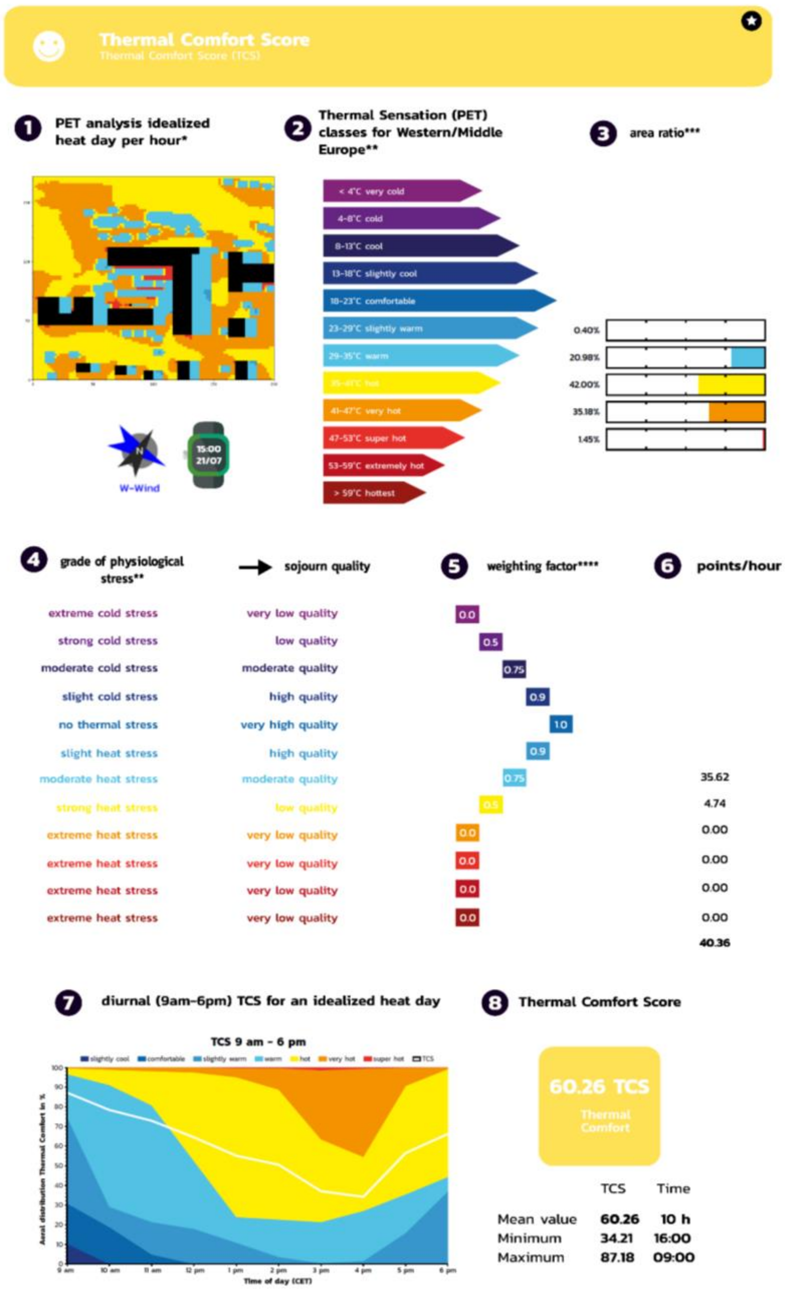

Figure 7. Greenpass Thermal Comfort Score (TCS) Methodology.

The Thermal Comfort Score methodology consists out of eight basic components and is shown in brief in Figure 7 and is explained in detail in Table 2.

Table 2. Thermal Comfort Score (TCS) Methodology Components and Calculation Process.

No.	Component	Explanation
1	PET Analysis	An analysis of the physiological equivalent temperature (PET) coming from expert simulation results (e.g., ENVI_met), in form of a heat map, serves as base for the TCS calculation. The heat maps are colored with a standardized color set and legend classes and are linked to the perception classes.
2	Thermal sensation classes	The TCS is based on thermal sensation classes linked to the bio-human thermal index PET, selected for the respective climate zones and cultural behavior expressing the thermal perception and sensitivity of human beings in terms of thermo-physiological stress. As shown in Figure 7 the sensation classes for Western/Middle Europe were applied within the project frame [28].
3	Area ratio	In a next step, the relative ratio of the particular human sensation classes, occurring in the heat map result of the project area, is split and shows the appearance of areas with thermo-physiological stress within the project area at the observation time.
4	Sojourn quality	The sojourn quality is related to the quality of open space and strongly linked to human sensation classes and areas with thermo-physiological stress. The qualities vary from 'very high quality', 'high quality', 'moderate quality', 'low quality' to 'very low quality'. A 'comfortable' thermal sensitivity induces no thermal stress and thus following featuring a very high sojourn quality, while 'slightly warm' creates a slight heat stress leading to a high sojourn quality in open space. 'Warm' areas generate a moderate heat stress and a moderate sojourn quality, 'hot' areas induce a strong heat stress with a low sojourn quality. From 'Very Hot' upward it creates extreme heat stress with a very low sojourn quality. The same principle is applied for the thermal sensation classes below 'comfortable' regarding cold stress (see Figure 7).
5	Weighting factor	The weighting factors are based on the grade of thermo-physiological stress and the linked sojourn quality classes. According to the Predicted Mean Vote grading system and the principle of Index Indicators, the weighting factors have been defined, counting 'comfortable' with no thermal stress and a very high sojourn quality as the upper index base (1) and 'very hot' (and above) and 'very cold' with extreme heat and cold stress and related very low sojourn quality as lower index base (0). For the thermal sensation classes in between, a gradation linked to the grade of physiological stress and sojourn quality has been defined (0.5 ǀ 0.75 ǀ 0.9) in accordance to the Predicted Percentage of Dissatisfied model methodology [29] (see Figures 7 and 8).
6	Points	The TCS expresses total points, calculated by the occurring area ratio of thermal sensation classes in the project area with the respective weighting factor for the classes and summing up in points at the particular observation time.
7	Diurnal TCS	In the next step, the described components and steps (1–6) are applied for a diurnal time span from 9 a.m. to 6 p.m. (10 h) and visually expressed in an intuitive graph and in line with the same color set from step 1 and 2, showing the thermal comfort distribution of the project area for human beings during the course of the day.
8	Thermal Comfort Score	The TCS is finally expressed in a mean value of the diurnal TCS values as well as the minimum and maximum value with their respective time points, showing the ratio of areas with thermo-physiological stress across the day.

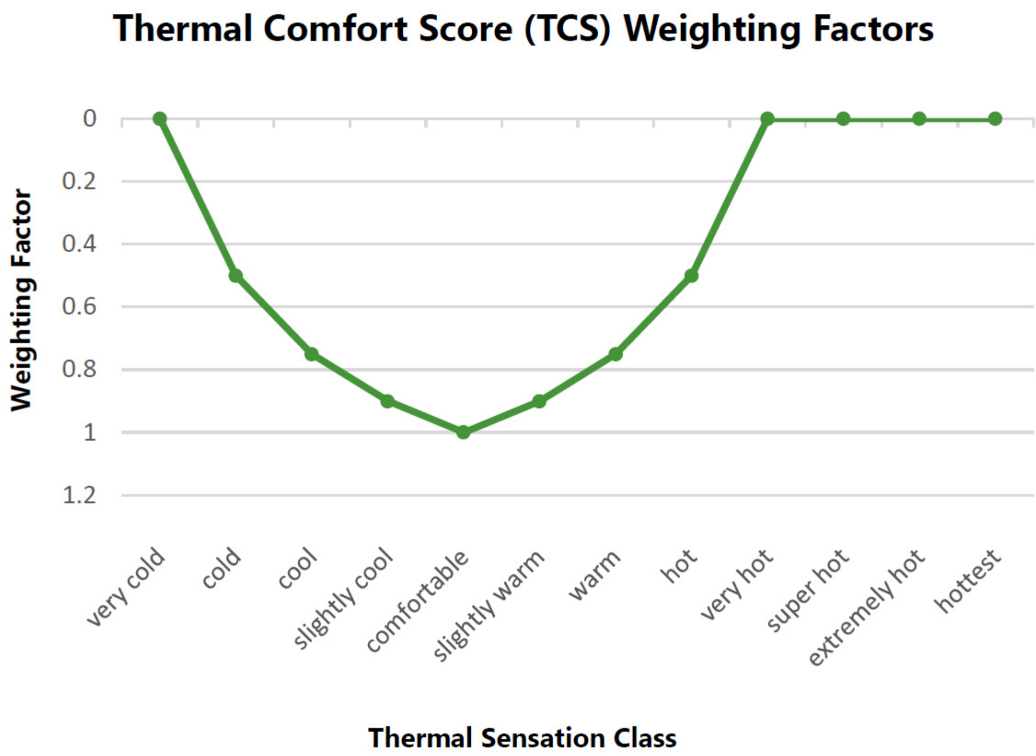

Figure 8. Thermal Comfort Score (TCS) Weighting Factors.

2.6. Evaluation of 'Fischbeker Höfe'

In the following, the evaluation of the new residential buildings 'Fischbeker Höfe' is described and explained in detail.

2.6.1. Selected Expert Simulation Systems

The evaluation within the Greenpass Pre-Certification is based on numerical key indicators, as described before. The results for the indicators in course of a Pre-certification consist of one or several 3D simulations—depending on the number of designs that shall be evaluated with simplified material assumptions and multi parametric analysis combined with areal analyses from the Greenpass editor, such as the Run-Off. In accordance with the CLEVER-cities research focus on vulnerability against heat, pluvial flooding and strong wind, the simulations are performed using one or more of the following expert simulation systems: microclimate (powered by ENVI-met), wind Computational Fluid Dynamics (CFD) (powered by Rheologic). For the case study of 'Fischbeker Höfe' the microclimate expert system was selected and assessed according to the baseline situation with respect to the five KPS and seven KPIs. The improvements delivered by co-designed NBS implementations were assessed following exact the same methodology, allowing a comparison along the KPS and KPI.

Within the application of the Greenpass Pre-Certification for 'Fischbeker Höfe', accordingly, two scenarios have been digitalized and built within the GP.e. Firstly, a planning scenario without NBS, which is used as a reference, and secondly, a new design with NBS has been digitalized using the GP.e as well. The planning scenarios are based on the planning data coming from the municipality, design team and co-creative process. After digitalization, a simulation model for ENVI-met expert system was generated automatically by the GP.e including the surrounding area with a total size of 3.3 hectares. The horizontally cell resolution of the simulation models is standardized 2 $\times$ 2 m. The following Figure 9 shows the ENVI-met simulation models for the two planning scenarios with additional green roofs and façade greenery and without any NBS implementation:

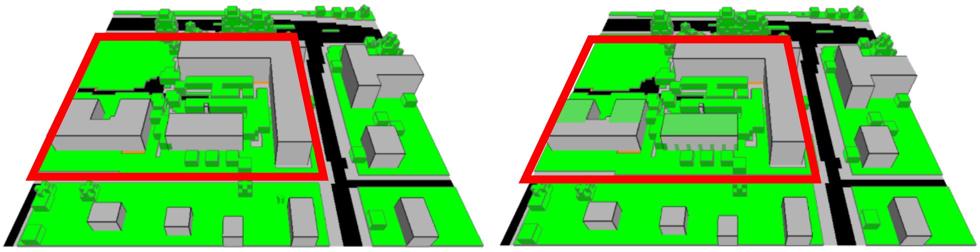

Figure 9. Simulation model for scenarios planning without NBS (**left**) and planning with NBS in form of green roofs and façade greenery (**right**) out of the GP.e for ENVI-met expert simulation. Project area framed in red.

2.6.2. Input Drivers

The simulation model runs with parameters for an idealized heat day, which are extracted in a standardized process out of meteorological data. In the case of 'Fischbeker Höfe', air temperature, humidity and precipitation from a local weather station at Neugraben-Fischbek from Meteoblue of the last 10 years (2009–2019) and wind direction and wind speed from the Airport Hamburg-Finkenwerder from Windfinder of the last 20 years (2001–2020) have been analyzed. The 20th hottest day (80% percentile) without precipitation were identified from the data pool, which in temperate latitudes means about +/−30 °C and is a good representation of a typical heat day. The determined day serves as input driver for air temperature, air humidity, wind direction and wind speed, which are used in the simulation. The following Figure 10 summarizes the climate data and sources used to drive the simulation model.

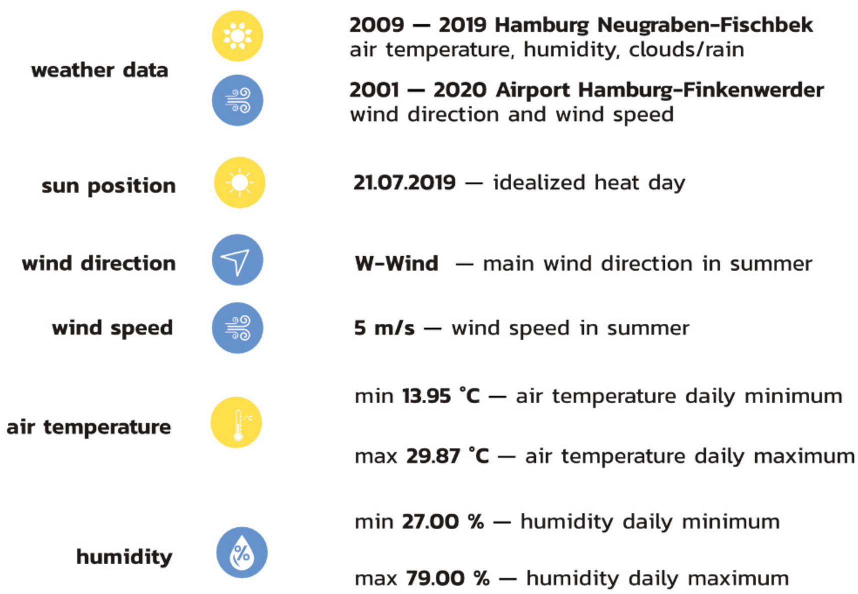

Figure 10. Simulation input data for an idealized heat day—based on Greenpass standardized input driver method.

For the idealized heat day, the solar altitude of the 21 July 2019 from 8 a.m. to 8 a.m. the next day was taken as simulation basis with a main summer wind direction coming from west and an average wind speed of 5 m/s. The air temperature was defined with 13.95 °C as daily minimum and 29.87 °C as daily maximum. Relative humidity was framed with 27% in the daily minimum and 79% in daily maximum (see Figure 10).

3. Results Green4Cities GmbH

The results consist of extracted data from the expert simulation results, combined with areal analyses from GP.e and presented in form of numerical indicators and visual elements and graphs, consisting out of heat maps and performance bars for the KPS. Last ones allow thereby a direct comparison of the Planning scenario without NBS and Planning scenario with NBS.

3.1. Climate-Resilience Analysis—Planning without NBS/with NBS

The analyses show that the envisaged Planning scenario with NBS achieved a moderate climate resilience performance. In the Planning scenario with NBS (green roofs and façade greenery) most values improved—which is remarkable considering the rather small area of NBS. The Planning scenario with NBS improves the situation in four of five KPS—Thermal Load Score, Thermal Comfort Score, Thermal Storage Score and Run-off Score. Figure 11 shows the difference between the two scenarios in form of direct difference heat maps for the air temperature (above) and the Physiological Equivalent Temperature (PET) (below) for 3 p.m., 10 p.m. and 4 a.m. on an idealized heat day (21 July) for 'Fischbeker Höfe'. Regarding the air temperature, Figure 11 shows that the new design with NBS generates a wide area in the southeast with a cooling performance of up to −0.09 °C at 3 p.m. on the heat day. This is caused by façade and roof greening on a large-scale at the small building in the center. The lower air temperature expands with the wind direction. At evening time (10 p.m.) and in the morning (4 a.m.) the cooling performance pattern is similar during the day, but with less intensity. At the hottest time of the day (3 p.m.) the PET can be locally reduced by up to −0.2 °C for certain areas around the interventions. At evening (10 p.m.) there are scattered areas with a higher thermal comfort increase of up to −0.2 °C and areas with a lower thermal comfort of up to +0.2 °C. At nighttime respectively in the morning at 4am the areas with higher thermal comfort in the southeast remains the same but only with a smaller increase of up to −0.1 °C.

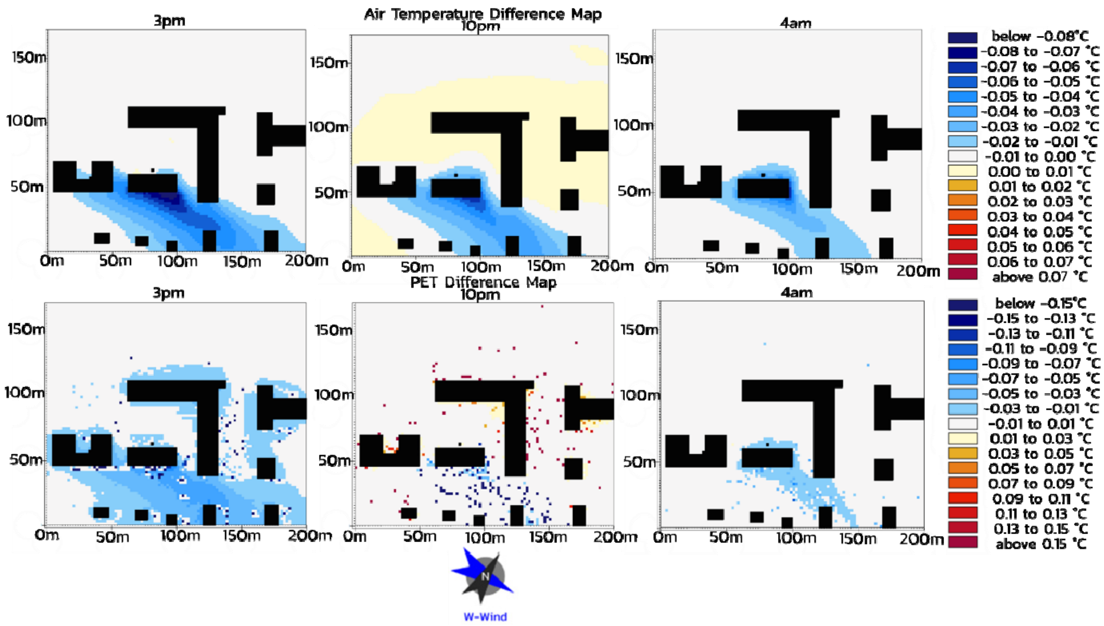

Figure 11. Heat difference maps between Planning scenario with NBS and without NBS 'Fischbeker Höfe' for air temperature (**upper line**) and Physiological Equivalent Temperature (**bottom line**) and for 3 p.m. (**left**), 10 p.m. (**center**), 4 a.m. (**right**) on an idealized heat day (21 July–22 July). Cross-sections of buildings appear black.

3.2. Thermal Comfort Score (TCS)

As the air temperature and the PET in the heat difference maps, the TCS increases slightly for the project area from 60.18 in Planning scenario without NBS to 60.26 in the Planning scenario with NBS over the diurnal cycle. This effect occurs mainly due to shading of additional vegetation and shows a slight improvement of thermal comfort situation on an idealized heat day for the Planning scenario with NBS, compared to the Planning scenario without (see Figure 12).

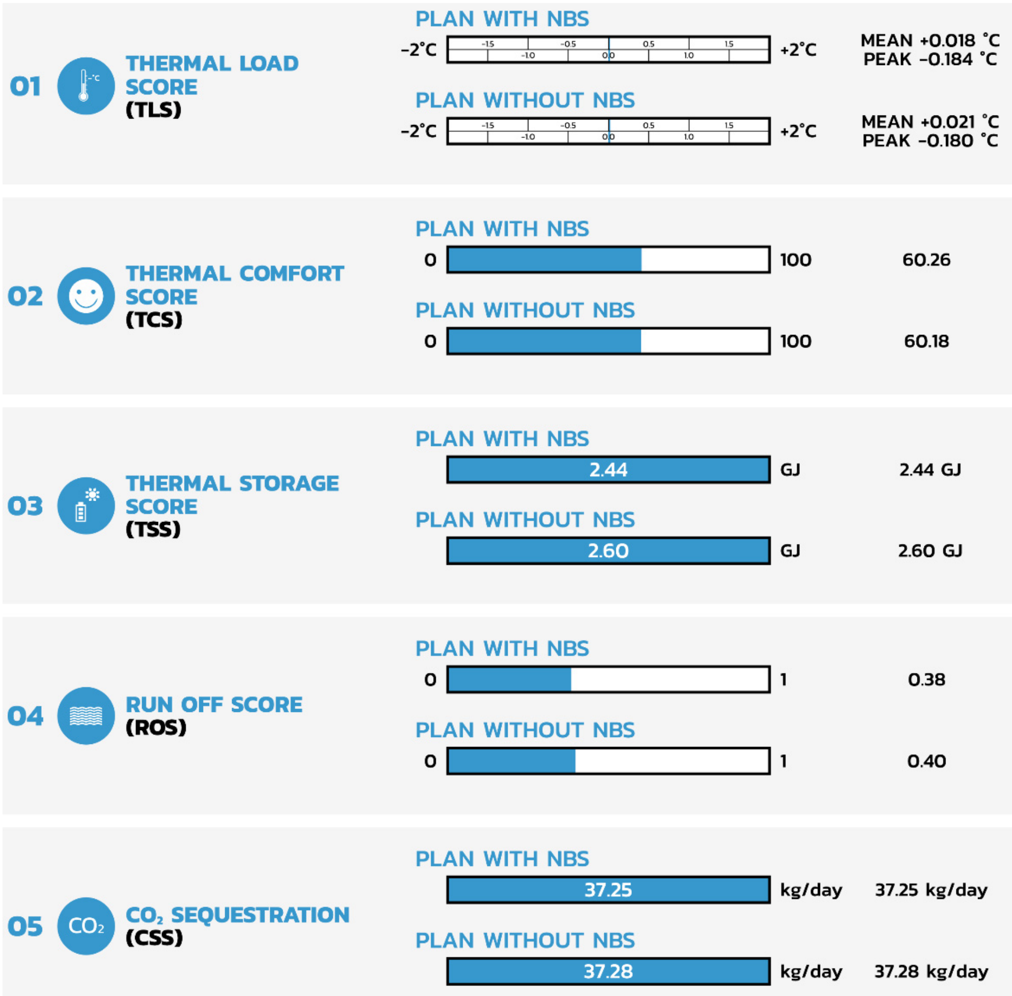

Figure 12. Key Performance Indicators for 'Fischbeker Höfe' planning scenario with (**above**) and without NBS (**below**).

Figure 13 shows the Thermal Comfort for the idealized heat day at 3 p.m. based on the PET map out of the expert simulation. The share of Thermal Sensation Classes is also illustrated in the same colors as used for the PET map. 21.38% of the area is within the thermal sensation class 'warm' or 'slightly warm' providing a decent thermal comfort for pedestrians. The largest thermal sensation class within the area is 'hot' with 42% of the area, resulting in a low thermal comfort, as the second largest class 'very hot' covers 35.18% of the area. Only 1.45% of the area is occurring in the 'super hot' class (see Figure 13).

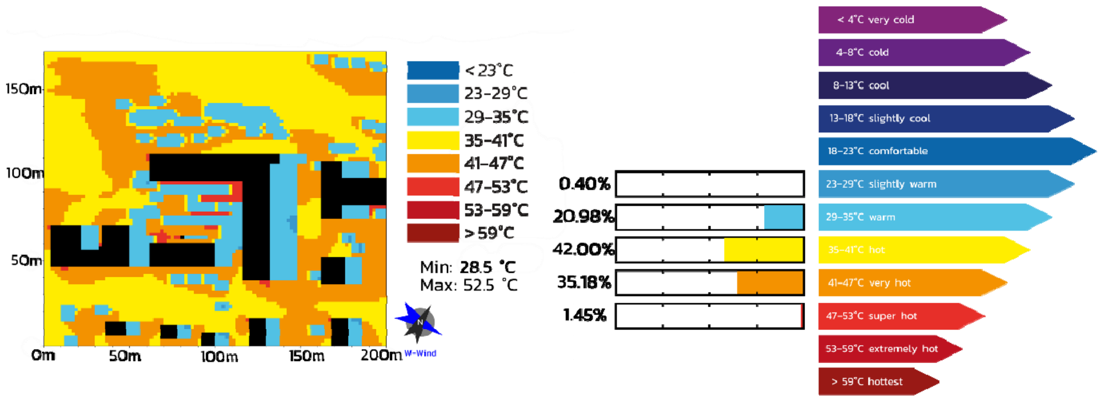

Figure 13. Physiological Equivalent Temperature (PET) with Thermal Sensation Classes for 'Fischbeker Höfe' Planning scenario with NBS at 3 p.m. on an idealized heat day (21 July).

Figure 14 finally illustrates the diurnal thermal comfort score. The graph contains the colored ratio of thermal sensation classes between 9 a.m. and 6 p.m.—when sunlight is most relevant for the PET—as well as the TCS value for every observation hour. The lowest thermal comfort of 34.13 TCS points occurs at 4 p.m. in the afternoon. In the morning at 9 a.m., where nearly all areas are in the thermal sensation classes 'warm', 'slightly warm', 'comfortable' and 'slightly cool', the project has a very good TCS of 87.18 points (see Figure 14).

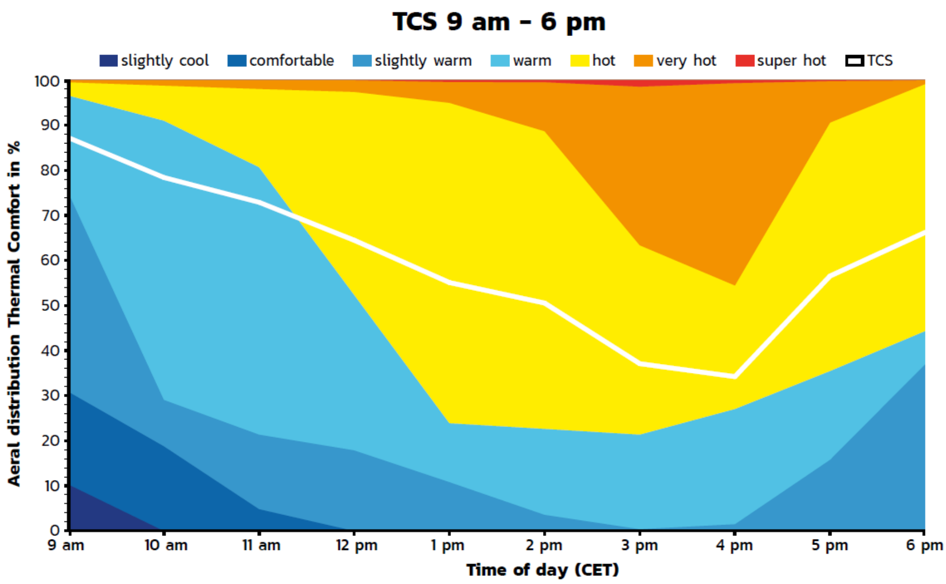

Figure 14. Diurnal Thermal Comfort Score for 'Fischbeker Höfe' Planning scenario with NBS for 9am-6pm on an idealized heat day (21 July).

3.3. Thermal Load Score (TLS)

The Planning scenario without NBS revealed a Thermal Load Score of +0.021 °C in average and a peak of −0.180 °C on a heat day. Compared to the Planning scenario with NBS with an average of +0.018 °C and a peak of −0.184 °C, the average value of thermal load decreases, which means that the planning scenario with NBS emits less heat to the surroundings. With façade and roof greening, the cooling performance increases slightly (see Figure 12).

3.4. Thermal Storage Score (TSS)

With a thermal storage capacity of 2.44 GJ in the Planning scenario with NBS, a minor reduction of stored energy can be achieved by the additional use of facade and roof greening, compared to the scenario without NBS with 2.6 GJ (see Figure 12).

3.5. Run-Off Score (ROS)

The Run-off Score, that is calculated based on areal analyses within the GP.e, of the planning scenario with NBS accounted for 0.38 and is slightly decreased compared to 0.40 in planning scenario without NBS, due to the used façade and roof greening (see Figure 12). The value of 0.38 means, that 38% of the water will run-off straight into the sewage system, while 62% can be stored and evapotranspirated by vegetation showing the open potential for optimization.

3.6. Carbon Sequestration Score (CSS)

The Carbon Sequestration Score shows a performance of 37.28 kg per heat day for the planning scenario without NBS (see Figure 12). The additional roof and facade greening has almost no impact on the Carbon Sequestration Score.

3.7. Climate-Optimized design

In the ongoing design process the focus lays on optimization of human thermal comfort and wind flow. Based on the Greenpass expert simulation and analysis, a set of optimization potentials was derived and defined as input for the co-creative design process (see Figure 15).

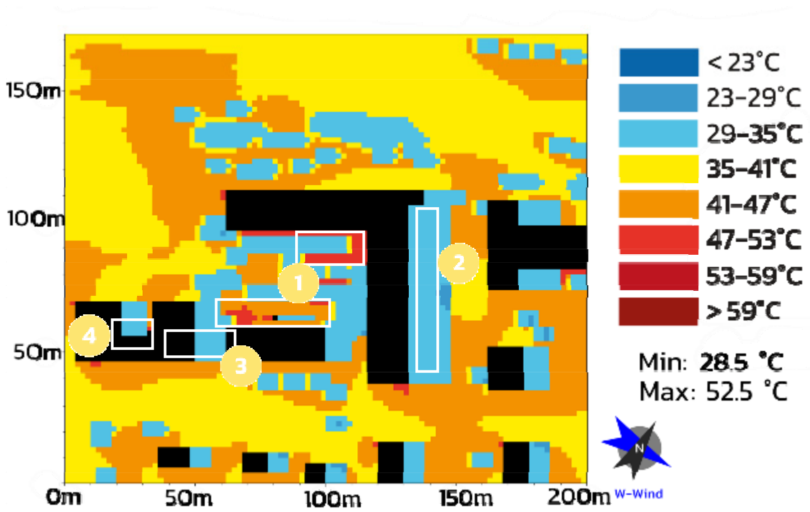

Figure 15. Climate optimization areas for 'Fischbeker Höfe' in Hamburg framed in white.

Figure 15 locates the recommended areas for optimization potentials, primarily the additional plantings of trees and shrubs to avoid hotspots (1), as well as unsealing parking spaces to lower the ROS and to lower surface temperature (2). Further on intensive instead of extensive roof greening on both buildings (3) and additional façade greening (4) would be beneficial to lower Thermal Storage Score.

In Figure 16 the wind optimization measures for 'Fischbeker Höfe' are shown, including the advice to plant additional trees and shrubs to avoid wind peaks in significant areas (1).

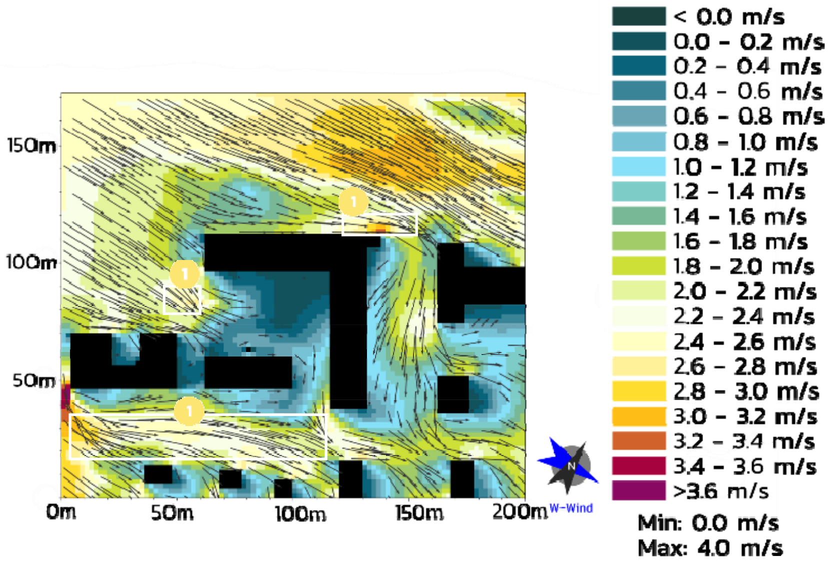

Figure 16. Wind optimization measures for 'Fischbeker Höfe' in Hamburg framed in white.

4. Discussion and Conclusions

The application of NBS has proven to be a valuable measure to improve climate resilience and quality of life for citizens as well as environmental justice and social coherence. However, the impact of NBS is complex and not easy predictable. Therefore, any planning or design process should be supported by tools that utilize an informed decision-making process to all involved stakeholders.

We ultimately must react on the occurring urban challenges and the clear need to adapt our urban areas towards climate change impacts and to provide qualitative open space areas with high thermal comfort and sojourn quality for citizens, especially for summer conditions. Within the last years various solution approaches for a successful urban climate adaptation have been tested and applied within the practical field of urban planning and architecture. One of which are so-called urban climate analysis maps [30] as in Figure 17 for a citywide analysis of heat vulnerability as an illustration of the existing climate conditions. Another includes expert simulation models for different regional scales (meso- and microclimate) producing fancy heat maps [7,31] and information on average heat days or tropical nights for a given time period.

These approaches are all important and valid, but unfortunately not practically suitable for deriving concrete and ideal planning decisions. The resolution is way to coarse and provides no information on the microclimatic framework on the building scale. To be more precise, Climate Analysis Maps are based on land use data without temporally or 3D information. The impact of single NBS implementations cannot be assessed by such maps. However, relevant stakeholders need to know, where to implement NBS and achieve the best effects, especially to successfully mainstream NBS in urban policies. Another approach chosen by many cities to adapt the urban fabric to climate change is the so call Biotope and Open Space Factor as e.g., the London Greening Factor. This method addresses a factor to any type of NBS. When it comes to a new planning or retrofit, the area of the envisaged NBS is multiplied with the factor. The sum of all NBS areas multiplied with the respective factors is related to the project footprint area [32]. The method of Biotope and Open Space Factor is often linked to climate adaptation. But microclimatic simulations have proven that the impact of NBS is strongly related to the surrounding. A tree in the North of a tall building, for instance, has a minor impact compared to the same tree in the south of the same building. Summarized the applicability of conclusive decision-making tools for NBS implementation processes in combination with citizen engagement is proven by the use of the innovative Greenpass technology for the CLEVER-cities project 'Fischbeker Höfe' in Hamburg/Germany. This paper shows that innovative and easy-to-use software tools, such as Greenpass, provide a very good and holistic approach as supporting tool for design and monitoring processes within urban planning and NBS implementation. Allowing to efficiently assess and optimize the impact of NBS in a holistic way by using digital, software-driven approaches with the focus on human health and well-being to ensure a high quality of life. The standardized evaluation method is applicable worldwide and ensures comparability of different design scenarios or reference scenarios, as e.g., with and without NBS comparison, as done for the project 'Fischbeker Höfe' and is thus suitable for stakeholders and decision makers. The different maps, in the case of 'Fischbeker Höfe' especially the Heat Difference Maps reveal the differences of the two designs, even though the project area was small and the implementation of NBS was limited to green roofs and façade greenery on two buildings. Despite the intelligibility and significance of the Heat Difference Maps, showing and localizing the direct impacts between two scenarios, the importance of a standardized evaluation for a project observation area by using meaningful and comprehensive key performance indicators for fact-based decision making by stakeholders, is underlined. In this paper the Thermal Comfort Score (TCS) is presented in detail, while other Key Performance Scores will be explained in consequent papers. The TCS transforms the Physiological Equivalent Temperature (PET) into a Performance Score. In contrast to the frequently used mean PET value for a specific time of the day, the TCS illustrates the sojourn comfort more precisely. Apart from general limitations of mean values (not accounting for range and relevance of considered values), the difference of the mean PET of the project in 'Fischbeker Höfe' with and without NBS is only 0.01 °C (with NBS: 34.25 °C; without NBS: 34.26 °C), while the TCS varied by 0.08 (with NBS: 60.24; without NBS: 60.18). This assessed difference in TCS is especially remarkable, when considering, that the investigated NBS implementation on less than 4% of the total project area is very limited. The TCS is, therefore, a very sensitive and valuable indicator. The Greenpass technology also illustrates the diurnal variation of comfort classes and TCS (see Figure 13). This information may be used to optimize the sojourn quality for certain times of the day as e.g., the school pause or lunch time. One of the interesting applications of this approach in CLEVER is its contribution to assess the NBS impact in different cities and interventions to develop a cross comparability to evaluation and benchmarking cross-case analysis between similar projects. This paper presents the chosen new approach and methodology that helps to understand the complex energetic processes in an urban climate system. The implementation of NBS and moreover its impact on thermal comfort and climate resilience is illustrated comprehensibly for stakeholders, politicians, decision-makers and planning experts alike. In this regard, the results obtained with Greenpass evaluations in the CLEVER Frontrunner cities, Milan, Hamburg and London, will be useful as lessons learnt with regards to informing politics with NBS implementation, implementing mainstream NBS in daily life and enabling liveable cities all over the world.

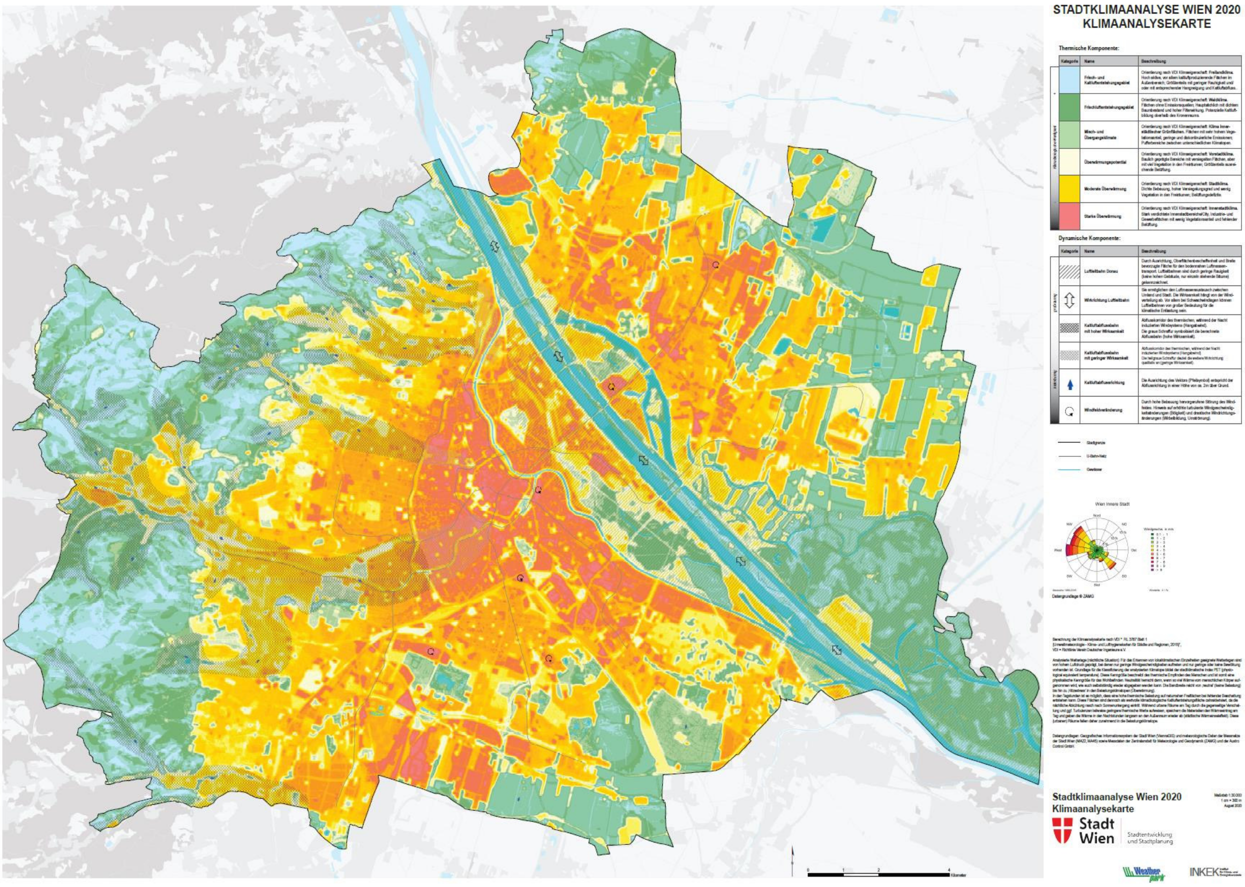

Figure 17. Climate Analysis Map, City of Vienna (2020), download link: https://www.wien.gv.at/stadtentwicklung/grundlagen/stadtforschung/pdf/stadtklimaanalyse-karte.pdf (accessed on 12 July 2021).

Author Contributions: Conceptualization, B.S., F.K., I.G.P. and L.G.G.; methodology, B.S. and F.K.; software, M.K.; formal analysis, M.K.; writing—original draft preparation, B.S., M.K., F.K., I.G.P. and L.G.G.; writing—review and editing, B.S., M.K. and I.G.P.; visualization, M.K.; supervision, B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This project has been applied in the frame of EU H2020 Project CLEVER-cities funded from the European Union's Horizon 2020 innovation action program under grant agreement No 776604.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

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