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53/2022

Final report

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Concepts for avoiding heat islands and for a comfortable indoor climate

by:

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Guidehouse Germany GmbH, Cologne

Sibylle Braungardt, Veit Bürger, Daniel Kocher

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Wörlitzer Platz 1
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Phone: +49 340-2103-0
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Internet: www.umweltbundesamt.de

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50829 Cologne

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Abstract

Against the backdrop of increasing urbanisation and climate change, the objectives of the present study is to identify climate-consistent solutions for the increasing summer heat stress in urban quarters and to quantify their effects. Both the microclimate and the indoor climate of buildings in the quarter are considered. The focus is on existing quarters as well as inner-city redensification and new-build quarters. To this end, various solution options were investigated for five selected real quarters (in Hamburg, Cologne, Frankfurt, Tunis, and Madrid) using extensive simulation calculations. To determine the influence of the microclimate measures on the indoor climate, microclimate simulations were carried out for the first time over a complete reference year. The results were used as input data for dynamic thermal building simulations. The natural (greening) and technical solutions on the district and building level proven to be effective are transferable to other inner-city quarters in Germany, Southern Europe, and the MENA region. The project also included discussions with relevant stakeholders to identify existing obstacles and shortcomings in the implementation of possible solutions. Based on this, effective and target-oriented proposals for actions to improve the existing incentive system could be developed. With the findings from the simulation calculations and the derived practice-relevant proposals for action, the project makes an important contribution to counteracting the worsening problem of urban heat islands and the associated impairment of the quality of life. Furthermore, these findings provide for easing the threat to climate protection goals through additional energy demand for air conditioning in a targeted and well-founded manner.

Kurzbeschreibung

Vor dem Hintergrund der zunehmenden Urbanisierung und des Klimawandels ist es Ziel der vorliegenden Studie, klimagerechte Lösungen für den zunehmenden sommerlichen Hitzestress in innerstädtischen Quartieren zu identifizieren und deren Wirkungen zu quantifizieren. Dabei wird sowohl das Mikroklima als auch das Innenraumklima der Gebäude im Quartier berücksichtigt. Im Fokus stehen dabei sowohl Bestandsquartiere als auch innerstädtische Nachverdichtungen und Neubauquartiere. Für fünf reale Quartiere (in Hamburg, Köln, Frankfurt, Tunis und Madrid) wurden verschiedene Lösungsoptionen anhand von umfangreichen Simulationsberechnungen untersucht. Um den Einfluss der Mikroklimamaßnahmen auf das Innenraumklima zu bestimmen, wurden erstmalig Mikrolimasimulationen über ein komplettes Referenzjahr durchgeführt und die Ergebnisse als Eingangsdaten für dynamisch thermische Gebäudesimulationen verwendet. Die dabei als wirksam nachgewiesen natürlichen (Begrünung) und technischen Lösungen auf Quartiers- und Gebäudeebene sind übertragbar auf andere innerstädtische Quartiere in Deutschland, Südeuropa und der MENA-Region. Im Rahmen der Studie wurden außerdem Interviews und Diskussionen mit relevanten Akteuren durchgeführt, um vorhandene Hindernisse und Defizite bei der Umsetzung der möglichen Lösungen zu identifizieren. Darauf aufbauend konnten wirksame und zielgerichtete Handlungsvorschläge zur Verbesserung des bestehenden Anreizsystems ausgearbeitet werden. Mit den Erkenntnissen aus den Simulationsberechnungen und den daraus abgeleiteten praxisrelevanten Handlungsvorschlägen liefert das Projekt einen wichtigen Beitrag, um dem sich verschärfenden Problem der städtischen Hitzeinseln und der damit verbundenen Beeinträchtigung der Lebensqualität entgegenzuwirken. Auch der Gefährdung der Klimaschutzziele durch zusätzlichen Energiebedarf für Klimatisierung kann auf dieser Basis zielgerichtet und fundiert begegnet werden.

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Glossary

albedo	Fraction of solar radiation reflected from a surface in relation to the insolation
shadowing	Shadowing caused by objects (e.g. trees or buildings)
Efficiency house 55 or 40 standard	Energy standard of buildings. The number describes the ratio of the energy reference area-specific primary energy demand in relation to that of the reference building in the German Building Energy Act (GEG) in percent
evapotranspiration	Sum of the evaporation of water released by living beings, especially vegetation, as well as by soil and water surfaces
fc value	Reduction factor of the solar energy input through shading devices
g-value	Reduction factor of the solar energy input with glazing
global radiation	Total solar radiation striking a horizontal surface
infiltration	Uncontrolled ventilation due to leaks in the building envelope
low exergy systems	Heating systems with low system temperatures or cooling systems with high system temperatures
quarters	In the context of the following investigations, a quarter is understood to be a coherent urban mixed-use area (main use: residential) with a high building density. Typical dimensions are 500 m * 500 m
U-value	Heat transfer coefficient of components
shading	Reduction of direct solar radiation entering buildings through sun protection devices or shading elements
VRF air conditioning	Multi-split air conditioning system with variable refrigerant mass flow

List of abbreviations

A/V	Ratio of building envelope area to building volume
BauGB	Building code
Construction NVO	Building Utilization Ordinance
BEG	German Federal Funding Program for Efficient Buildings
BAF	Biotope area factor
CEEB	Energy efficiency standard
DGNB	German Society for Sustainable Building
EFH	Detached house
GEG	German Building Energy Act (*Gebäudeenergiegesetz*)
GF	Floor area
GFF	Green space factor
GRZ	Floor area count
GFZ	Floor space according to BauNVO
HFC	Hydrofluorocarbon (climate-damaging refrigerants)
HFO	Hydrofluoroolefins (polluting refrigerants)
HQE	Haute Qualité Environmentale - French certification for sustainable construction
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MENA	Middle East and North Africa
NECP	National Energy and Climate Plan
PET	Physiological Equivalent Temperature
PHI	Passive House Institute
PHPP	Passive house planning package (Excel-based calculation tool)
PPD	Predicted Percentage of Dissatisfied (according to ISO 7730). The PPD increases with increasing discomfort. According to the definition, 5% of occupants are always dissatisfied
RED	Renewable Energy Directive
SEER	Seasonal Energy Efficiency Ratio (efficiency parameter of an air conditioner)
SFP	Specific Fan Power (efficiency parameters of a ventilation system)
SRI	Solar Reflectance Index
t_{max}	Maximum interior temperature
TRNSYS	Transient System Simulation Tool (building simulation software)
UHIE	Urban heat island effect
VERDE	Sustainability certificate
ZUB	Centre for environmentally conscious construction

Summary

Motivation of the project

Due to climate change, population growth and ongoing urbanization, overheating in summer is becoming an increasing problem for cities. Overheating affects both the areas where people stay in urban spaces (urban heat island effect) and the indoor climate in living and working spaces.

The aim of this research project is to improve the understanding of the causes, the interrelationships and possible solutions to avoid or limit overheating.

The effectiveness and climate resilience of different measures to reduce the heat island effect and summer overheating in buildings is quantified. They are both highly dependent on local conditions.

For indoor spaces, the question also arises as to whether - and if so, under which conditions - active cooling (and thus also the use of climate-damaging HFC refrigerants) can be dispensed with in the long term. If active cooling is indispensable to ensure minimum comfort in summer, it is also necessary to clarify which solutions are compatible with climate objectives.

Finally, based on this understanding, effective proposals for the adaptation of the legal framework and further instruments are to be developed. The project will thus close existing knowledge gaps and make an important contribution to climate resilience and climate protection of cities in Germany and beyond.

Project structure

To solve the questions and tasks described above, the following project structure was chosen:

1. Research on basics and state of knowledge
The current state of knowledge on the urban heat island effect and possible measures to reduce urban heat islands as well as climate-appropriate measures to avoid overheating indoors were determined on the basis of a literature research.

2. Creation and analysis of optimised quarter concepts
On the basis of five real quarters (three in Germany, one in Madrid and one in Tunis), the presumably most effective measures against overheating in summer were quantified by means of simulation calculations. A novel method was applied, in which year-round microclimate simulations were carried out for the first time and coupled with dynamic thermal building simulations.

3. Proposals for the adaptation of the legal framework and further instruments
Based on these findings and those from the stakeholder engagement (see below), 10 proposals for the adaptation of the legal framework and further instruments were developed.

During the project, actors and stakeholders were involved in a workshop and an online survey to ensure the greatest possible practical relevance.

The main findings from the chapters are summarized below.

1. Research on basics and state of knowledge

Basic facts about urban heat islands

The nature of cities can lead to the formation of urban heat islands in summer, where temperatures are sometimes considerably higher than in the surrounding countryside. Large areas of sealed surfaces, dark pavements and buildings have surfaces that heat up quickly and for long periods in the summer. The urban heat island effect leads to an impairment of the

quality of life and well-being of the urban population. Significant health consequences, including death, can occur, especially in vulnerable populations such as the elderly or young ill people.

The effect of urban heat islands depends on the time of year and time of day. While these can be observed throughout the year, the effect is particularly pronounced and critical during the summer months. Significant temperature differences between city and surrounding countryside occur predominantly during the nighttime.

Climate-resilient and climate-neutral building concepts.

A multi-step approach was used to identify and analyse effective climate-resilient and climate-neutral building concepts.

Firstly, a research was carried out, on the basis of which a compilation and subsequent evaluation of realized buildings with climate-resilient or climate-appropriate concept approaches was carried out.

From this, the most important concepts were extracted and summarized in an overview (see following table).

Table 1: Overview of measures to ensure climate-smart comfort in climate-neutral buildings

No.	Concept	Short description
1	Building design/building volume and orientation	The building design is decisive for the physical properties of the building. The ratio of external surface to volume (A/V) has a strong influence on heat loss and heat gain. In addition, the orientation of sunlit surfaces, especially the building's openings (windows), is essential for solar gain into the building. The positioning and size of windows can therefore be used for the targeted contribution or avoidance of solar heat.
2	Choice of materials and design	The choice of material has an influence on the storage capacity of the building. Solid walls increase the inertia of the building, whereas lightweight construction reacts faster to temperature changes. Depending on climate requirements, this option can be used to maintain the comfort range in the interior (19-26°C). The choice of colour also has an effect on the warming component of the building. The solar reflectance index (SRI) indicates the properties of the component in terms of reflection of solar radiation (black = 0; white = 100).
3	Energy standards building envelope/component quality	Additional insulation or a high energy quality of building components such as windows and doors influence the heat transfer from inside to outside (vice versa in the heating season). Well-insulated building components and an airtight building envelope maintain the desired indoor temperature for longer due to low heat transmission. To avoid summer heat, the type of glazing is also essential: selective solar control glass with a low g-value keeps solar gain low but does not replace solar shading.
4	Summer thermal protection through solar shading	Various measures for shading building components, especially windows, are possible. While simple fixed shading elements can be effective for south-facing windows, effective flexible solutions such as external sliding elements or sun protection louvers are recommended in most cases. In Germany, the summer thermal insulation of rooms in new buildings must be proven [1].
5	Building ventilation active/ passive	Ventilation concepts range from passive solutions such as cross-ventilation concepts, post ventilation and air shafts to ventilation systems with heat recovery and dehumidification as well as ground or groundwater pre-tempering. Passive and active measures can also be combined to achieve a sufficient cooling function.

[1]The proof shall be provided on the basis of DIN 4108-2:2013-02.

No.	Concept	Short description
6	Building cooling measures	In addition to air conditioning systems with climate-compatible (natural) refrigerants, other efficient technologies can also be used for cooling buildings. E.g. sorption refrigeration systems can generate cooling by means of heat, i.e. without electricity, and therefore effectively use e.g. solar thermal generated heat (=> solar cooling). In temperate climate regions, the ground or groundwater can also be used as a heat sink. An effective measure to improve the efficiency of cooling systems are surface cooling/heating/cooling ceilings. These so-called low exergy systems improve the efficiency of cooling, reduce losses and enable renewable heat/cooling, e.g. the use of groundwater.
7	Greening/water use	Greening the roof and facade contributes to an improved microclimate. Rainwater can be utilised and gray water recycled for this purpose.
8	Efficient appliances	Electrical appliances and lighting should have high efficiency to reduce internal heat inputs and reduce electricity consumption.
9	Renewable cooling/heating	For climate-friendly cooling and heating, renewable energy systems can be used on/ in the building to actively produce the desired indoor temperature. Solar thermal systems, photovoltaics (e.g. for electric solar cooling), biomass, geothermal energy and groundwater can be used.

Based on the above analysis, a climate zone-specific systematization of the researched example concepts was created.

The systematization showed that almost all the identified concepts are applicable to all building types in all climate regions. Exceptions concern, for example, existing buildings, where the building design can no longer be optimised, or ventilation cooling, which is considerably less effective in tropical regions.

Climate-resilient quarter concepts

The research project compiles an overview of the most important measures to avoid heat islands and considers the technical and economic framework conditions as well as the applicability of the measures under different climatic conditions. Table 2 summarizes the measures considered and their areas of application.

Table 2: Overview of the measures considered to avoid urban heat islands.

No.	Description	Effect in terms of avoiding urban heat islands			Suitability for different climatic conditions				Suitability for new constructio n/ existing quarters	
		shadowing	evaporation	albedo	Air circulation	Central Europe	Southern Europe	Desert climate	Existing quarter	New construction
1	Brightening of coverings and surfaces in open spaces	-	-	x	-	X	x	x	x	x
2	Securing and expanding the tree population	X	x	-	-	X	x	-	x	x
3	Safeguarding existing and creating additional forest areas	(x)	x	-	-	X	x	-	(x)	x

No.	Description	Effect in terms of avoiding urban heat islands			Suitability for different climatic conditions				Suitability for new constructio n/ existing quarters	
4	Unsealing of surfaces in open space/ avoidance of sealing	-	x	-	-	X	x	x	x	x
5	Securing and expanding green and open spaces	(x)	x	-	(x)	x	x	(x)	x	x
6	Preservation of urban air circulation and interconnectedness of open spaces	-	-	-	x	x	x	x	(x)	x
7	Roof and greening	-	x	-	-	x	x	(x)	x	x
8	Increasing the proportion of water in the quarter	-	x	-	-	x	x	-	x	x
9	Shadowing of open spaces and paths	X	-	-	-	x	x	x	x	x

Legend: x = suitable; (x) conditionally suitable; - unsuitable

On this basis, a selection of sample quarters was compiled in which strategies to prevent heat islands have been successfully implemented.

2. Creation and analysis of optimised quarter concepts

Simulation-based proof of effectiveness of optimised quarter and building concepts

Based on existing findings, packages of measures for heat-resilient quarters and buildings were compiled. The basic packages or their contents are listed below. Further details and specifications, e.g. regarding climate regions or building qualities, are described in the corresponding chapter.

Measures for heat-resilient quarters:

- Securing tree cover and existing wooded areas and planting new trees that provide both shade and evaporative cooling.
- Shadowing open spaces and pathways.
- Preservation of urban air circulation and interconnectedness of open spaces (=> measure when creating quarters)
- Urban planning: Appropriate ratio of building volume to open spaces (=> measure for quarter development)
- Use of light-coloured materials for roofs, facades, streets, and sidewalks.

Measures for buildings to ensure comfort in summer or to reduce cooling energy demand

- Provision of effective sun protection.
- Cooling or nighttime ventilation
- Insulation and thermal glazing (qualities depending on the climate zone)

- Ensuring a high level of air tightness
- Compact building design, moderate proportion of window area (=> measure for new buildings)
- High thermal storage masses (=> measure for new buildings)

Quarter selection for the simulation calculations

The quarters were selected to cover as wide a range as possible of real and future residential quarters. The focus was on urban quarters with high residential densities, such as those found in the city centres of many large cities. In the case of German quarters, an attempt was made to cover both summer-cool regions and regions that are hot during summer. In addition, both new construction and existing quarters as well as post-densification areas were to be considered.

On this basis, quarters were selected in the following cities.

- Existing quarter Tunis
- New-build quarter of Madrid
- New-build quarter of Cologne
- Existing quarter in Hamburg
- Redensification quarter Frankfurt

<u>Microclimate simulations</u>

The application of high-resolution microclimate models enables the numerical prediction of the effects of structural changes in urban planning areas on the urban climate at the scale of building and green planning.

In this context, two different applications of high-resolution urban climate models were used in the present study: first, there is the possibility to adapt regional (large-scale) climate data to the specific conditions of the building site in its urban context ("Urbanization of climate data"). This slightly modifies the climatological data series so that the influence of the immediate surroundings on the microclimate can be considered. On the other hand, the high-resolution simulation data is used to represent and evaluate the spatio-temporal distribution of outdoor thermal comfort. This analysis focuses primarily on humans as users of urban open spaces. The thermal comfort index PET (Physiologically Equivalent Temperature) was used in the analysis of the data. The PET describes the thermal sensation of a person under the influence of radiation fluxes (especially solar radiation), wind, air temperature and humidity.

Both application possibilities differ with respect to their spatial and temporal resolution: For urbanized climate data, the further use in building simulations is the focus of interest. Therefore, longer-term time series, ideally a complete annual cycle, must be generated here and made available as boundary conditions. In the high-resolution simulation of outdoor thermal comfort, on the other hand, selected situations, usually typical weather conditions or extreme situations, are analyzed. These extend over a few days and can therefore only be used to a very limited extent for further energy calculations.

Results

Microclimate modelling provides a large number of different parameters in space and time. In order to come to an evaluation of measures, it is therefore necessary to consider and compare selected parameters.

To describe the thermal comfort, the air temperature on the one hand and PET on the other hand were selected as indicators in this project.

Looking at the effects of the quarter measures on air temperature, the differences are initially small. This is due to the fact that the changed areas are relatively small and the air as a physical medium also reacts sluggishly to changes. Nevertheless, already achievable changes of 1 to 2 K can mean a significant improvement of the situation, especially in the evening and night hours. In addition, significant local temperature reductions of 5 K and more can be achieved by spraying water (evaporative cooling).

The changes in PET are usually much greater when the opportunity for additional shadowing presents itself. This perceived temperature can differ by -20 K or more in the shaded areas from the sunlit areas. Thus, shadowing of outdoor facilities is the most efficient solution for reducing heat stress during daytime hours, especially in summer.

<u>Building simulations</u>

The dynamic thermal building simulations were carried out using TRNSYS software. The buildings or the apartments in the buildings were modelled using multi-zone models.

As previously described, the building simulations were fed with the microclimate simulation results.

Results

The optimisation measures considered to reduce the heat island effect at the quarter level have a measurable, but comparably small, positive impact on summer indoor comfort. The most noticeable effect can be observed in the Madrid quarter, where cooling energy demand in many attic apartments is reduced by almost 10 kWh/m^{2}a. Regarding the energy aspects of the buildings, the slight reduction in cooling energy demand resulting from the measures is often almost compensated for by the slight increase in heating energy demand. Except for the buildings in Hamburg, cooling is required in all cases to ensure good summer comfort to meet the selected comfort criteria, despite extensive avoidance measures (ventilation cooling, solar shading and improvement of the building envelopes). The rooftop and mid-floor apartments in particular prove to be critical in terms of overheating issues. The cooling energy demand of the buildings is largely independent of the year of construction (i.e., the envelope quality) and, apart from the ventilation behaviour, is rather influenced by the envelope and sun protection quality. Compared to other consumers, such as household electricity, domestic hot water demand or heating energy demand, the final energy demand for cooling in German quarters is comparatively low. This is not least due to the highly efficient cooling systems taken into account (e.g. passive floor cooling powered only by geothermal energy, cf. Clouth quarter in Cologne). In this context, it is even more important to avoid the use of fluorinated refrigerants, which cause unavoidable direct greenhouse gas emissions or, in the case of hydrofluoroolefins (HFO) or their decay products, further environmental damage. Regarding the targeted climate neutrality, the available roof area is the limiting factor. While the quarter in Tunis can generate as much electricity through PV systems on the roofs as is needed in the optimised quarter due to the high irradiation and the predominantly low number of storeys, this is not possible even in Madrid, which is also very sunny. Due to the eight-storey buildings, only 1 kWp of installed PV power was possible per flat. In the German quarters studied, the available roof area is also not sufficient for an annual neutral electricity balance, despite the lower number of storeys and the extensive improvement measures on the buildings. This is mainly due to the remaining household electricity demand. A minimisation of the household electricity demand is therefore an essential element for achieving climate neutrality in (residential) quarters. A calculated annual climate neutrality is possible if differentiated CO_2 factors (i.e., higher emission factors for PV and electric heat generation [2]) are taken into account. In large city districts with a high residential density (cf. Campo Bornheim district in Frankfurt), however, a further improvement of the CO_2 electricity mix factor in the electricity grid is necessary.

Stakeholder analysis and workshops

In Germany, as in many other countries, the avoidance of urban heat islands is an increasingly important component of urban planning processes. In numerous larger cities, concrete measures have been developed as part of climate adaptation concepts, based on an analysis of the initial situation (e.g. Berlin, Munich, Stuttgart, Düsseldorf, Freiburg).

Despite the increasing importance of the topic, there are numerous obstacles that hamper the development and implementation of measures to prevent heat islands at the municipal level.

Within the framework of the research project, obstacles to the implementation of measures to prevent heat islands at the municipal level were investigated based on interviews with representatives and solutions were proposed.

Strengthening climate adaptation as a mandatory task through a strong legal framework is named as a central field of action, since the lack of binding and concrete measures to avoid heat islands is an important obstacle in practice.

Other strategies for action include improving the data base at the municipal level in the form of climate analyses, by quantifying the effect of heat island avoidance measures, and by providing quantitative information on the consequential effects of heat islands on the population.

Networking of relevant actors to plan and implement heat island prevention measures within the municipality as well as networking and exchange with actors from other municipalities and institutions were named as further success factors.

3. Proposals for adapting the legal framework and further instruments

Finally, in the last section, proposals were developed to improve various aspects around the topics of urban climate, summer heat protection and sustainable building cooling. The 10 fields of action were selected based on a previously drawn up long list. Thematically, identified opportunities for improvement in municipal, state-specific, national and international (EU level) legislation and regulations as well as funding programs are addressed.

In detail, the following fields of action were addressed:

1. Overcoming the obstacles for natural refrigerants
2. Economic efficiency requirement and summer thermal insulation in the Building Energy Act (GEG)
3. Tightening the regulatory requirements for limiting the cooling energy demand of buildings - improvement proposal for the implementation of the GEG
4. Practical assistance for inspection authorities - proposals for improving the enforcement of the requirements for summer thermal insulation in accordance with: DIN 4108-2: 2013-02
5. BEG (Federal Support Program for Efficient Buildings): Proposal for the consideration of natural refrigerants (bonus regulation)
6. Elaboration on the requirement of an urban climate neutrality verification in environmental impact assessments for new quarters
7. Definition of renewable cooling within the framework of the EU Renewable Energies Directive

[2]860 g/kWh (displacement electricity mix (GEG 2020)); for further background on the calculation approach, see Chapter 2.2.5.4.3.2

8. Proposals for action to concrete the impact of the microclimate on urban planning
9. Building regulations: Elaboration of a proposal for a green space factor GFF (like GRZ, GFZ)
10. Best practice proposals for the implementation of climate adaptation measures at municipal level.

1 Basics and level of knowledge

1.1 Urban heat islands and their causes

The nature of cities can lead to the formation of so-called urban heat islands in summer, which means that temperatures are sometimes significantly higher than those in the surrounding area. Large areas of sealed grounds, dark streets and buildings are surfaces that heat up quickly and for a long time in summer. This urban heat island effect leads to a reduction in the quality of life and well-being of the urban population. Health consequences can occur especially for vulnerable population groups such as children, old or sick people.

The effect of urban heat islands depends on the time of year and time of day. While urban heat islands can be observed throughout the year, the effect is particularly pronounced and critical in the summer months. During the day, the intensity of the urban heat island is greatest at night. This is due to the fact that urban areas initially heat up less strongly than the surrounding countryside over the course of the day, since the building structure usually results in increased shadowing. On the other hand, after sunset, rural areas cool down more quickly than urban areas, as the heat stored in sealed surfaces and buildings is released to the environment in the latter.

The increase in temperature in urban areas compared to the undeveloped surrounding area is due to various effects:

- Reduced albedo compared to rural areas: In urban areas, depending on the nature and colour of the surfaces (e.g. roofs, facades, streets, parking lots, etc.), solar energy is absorbed and converted into heat more than in rural areas.
- Reduced evapotranspiration compared to rural areas: Due to the significantly lower proportion of permeable surfaces and vegetation, there is significantly less water and thus evaporative cooling available in cities.
- Anthropogenic heat generation: Compared to rural areas, more heat is generated in cities through combustion processes (e.g. engine waste heat, industrial production) or waste heat from electrical devices (e.g. air conditioning systems).
- Heat storage in buildings: Compared to a rural environment, the urban areas have a more pronounced three-dimensional surface due to the built structure, which increases the total surface area where heat can be absorbed.
- Change in wind conditions: In urban areas, building development leads to a reduction in wind speed. This depends on the building structure and the roughness of the surfaces.

Against the background of global warming, population growth and increasing urbanization, the urban heat island effect is becoming increasingly important, since the climate in cities is not only getting warmer, but more and more people will also be affected by this warming.

The adaptation of urban populations to heat is by no means an industrial age phenomenon. For example, light-coloured surface materials have been used in the construction of buildings in the Arabian and Mediterranean regions for thousands of years.

In Germany, as in many other countries, avoiding urban heat islands is becoming an increasingly important part of urban planning processes. In numerous larger cities, concrete measures were developed as part of climate adaptation concepts based on an analysis of the initial situation (e.g.

Berlin, Munich, Stuttgart, Düsseldorf, Freiburg). The strategies for avoiding urban heat islands include the following areas of action:

- Evaporative cooling: e.g. unsealing or preservation of unsealed areas, increase in vegetation through preservation or expansion of green areas and city trees, roof and facade greening, increase in the proportion of water.
- Brightening surfaces: increasing the albedo by brightening surfaces, e.g. use of light-coloured asphalt, subsequent application of light-coloured paint, use of light-coloured building materials.
- Maintaining or improving air circulation: e.g. taking local wind conditions into account when planning quarters, maintaining contiguous open spaces.
- Shadowing: Reduction of direct solar radiation through shadowing elements, e.g. city trees or mobile sun sails.

Despite the increasing importance of the topic, there are numerous obstacles that make it difficult to develop and implement heat island prevention measures at the community level.

1.2 Climate-resilient and climate-neutral buildings: state of the art

1.2.1 Methodology

A multi-stage process was chosen to identify and analyse effective climate-resilient and climate-neutral building concepts.

1. Research and compilation of suitable realized buildings and concepts

   A list of climate-resilient and climate-friendly buildings was compiled based on a literature and internet research as well as the project experience of the project team and its networks. Only concepts that have at least one generally applicable effective measure that is expedient in terms of climate resilience and climate neutrality were considered and documented for each climate region and building type. Profiles were drawn up for the respective buildings, in which the essential data are listed:

   a) Building type (residential or non-residential)

   b) Status (new construction or renovation)

   c) Energy standard

   d) Technology used

   e) Description

   f) Sources

2. Summary assessment of the example buildings

   In the next step, the example buildings described in the profiles were evaluated regarding the following relevant parameters:

   a) Climate resilience

   b) Climate protection effect

   c) Indoor climate quality

   d) Economic efficiency

   e) Transferability

   The further consideration of the concepts within the framework of the project was based on this evaluation.

3. Extraction and summary of the essential concepts for ensuring climate-resilient comfort in buildings

   From the projects described in stages 1 and 2, the key concepts with regard to ensuring climate-resilient comfort were compiled again and described in more detail in the 3rd stage.

4. Systematization and assessment of applicability according to climate zones

   Finally, the measures found were evaluated qualitatively regarding their suitability for

   a) Various uses (residential buildings, non-residential buildings),

   b) Climate zones (temperate: Central Europe, subtropical: Southern Europe/ North Africa/ desert climate, tropical) and

   c) Existing and new construction.

Together with the results from chapter 1.3 (climate-resilient districts) and chapter 1.4 (practical examples of avoiding heat islands), the results of this chapter form the basis for the development of the recommended packages of measures in chapter 2.

1.2.2 Profiles of example buildings

In the following, climate-resilient and climate-friendly buildings identified as part of the research are presented in the form of profiles.

When compiling the example buildings, the (balance sheet) climate neutrality was decisive. Ideally, the buildings should achieve energy self-sufficiency without additional costs (as the sum of investment and operating costs over the life cycle) compared to the local standard. At the same time, it should apply to the interior climate concepts that even with future rising outside temperatures in summer, a maximum of 26 °C (or outside temperature -6K) should prevail i.e., a sustained high level of comfort should be achieved. However, due to the limited number of examples available, the above objectives were not a necessary condition. It was considered sufficient that (partial) concepts were implemented that basically have the potential to meet the above-mentioned goals.

The example buildings, including the implemented measures, can be assigned to the various climate zones according to the following criteria:

- Tropical climate (incl. desert climate) - emphasis on cooling
- Subtropical: Southern European, Mediterranean climate (MENA region) - heating and cooling
- Central European temperate climate - emphasis on heating

1.2.2.1 Tropical climate (incl. desert climate)

1. AREE Aqaba Residence (Jordan)

- **Building type**: Detached house
- **Status**: New build (2009)
- **Standard**: Low energy with passive components; Primary energy demand 52 kWh/m²a
- **Technology**: Solar system, solar cooling (adsorption cooling system), shading devices, passive cooling (ventilation system), green roof with gray water filter system

- **Description**: EU-funded pilot project to test passive and active measures for hot climates

Source: Khasawneh 2011

2. Passive House Research Institute Dubai (UAE)

- **Building type**: Office
- **Status**: New build (2016)
- **Standard**: Passive house – cooling energy demand: 50 kWh/m^{2}a;
  cooling load: 9.7 W/m^2;
  Primary energy demand 143 kWh/m^{2}a
- **Technology**: Photovoltaic, power storage, ventilation with cold recovery, geothermal energy, heat pump, supply air cooling and dehumidification, circulating air and floor cooling, shading elements
- **Description**: EU-funded pilot project to test passive and active measures for hot climates

Source: Passive House Institute (PHI); Passive House Institute (PHI)

3. Austrian Embassy Jakarta (Indonesia)

- **Building type**: Office
- **Status**: New build (2016)
- **Standard**: Passive house; Primary energy demand 117.1 kWh/m^{2}a
- **Technology**: Ventilation with heat- and moisture recovery, surface cooling, thermal solar system for domestic hot water, small heat pump, fixed shading elements
- **Description**: PHI-certified passive house, solid construction, brick, consideration of local climate conditions, combination of traditional techniques, local materials, and modern technology to ensure room quality, climate comfort and sustainability

Source: Passive House Institute (PHI)

1.2.2.2 Subtropical climate

1. Autonomous urban habitat, Rabat (Morocco)

- **Building type**: Detached house
- **Status**: Stock
- **Standard**: Renovation to an energy-autonomous house
- **Technology**: Solar thermal (thermosiphon), photovoltaic, battery storage, rain and gray water use, green roof, insulation with cork, natural ventilation
- **Description**: Old riad (traditional Moroccan house) in the old town has been renovated and designed as an energy, water, and waste autonomous house, heating exclusively by solar gains.

Source: Soussan 2015

2. African Development Bank, Casablanca (Morocco)

- **Building type**: Office
- **Status**: New build (2016)
- **Standard**: Low energy (HQE Class C), primary energy demand 132 kWh/m^2a
- **Technology**: Heat pump, solar thermal, VRF air conditioning[3]
- **Description**: Regional pilot project, Energy-optimised design using thermal simulation, ISO 14001 and ISO 9001 certified

Source: Agadi 2019

3. 32 Fal El Hanaa, Casablanca (Morocco)

- **Building type**: Apartment building (640 units)
- **Status**: New build (2015)
- **Standard**: Low energy - Energy Efficiency in the Construction (CEEB), primary energy demand 53 kWh/m^2a
- **Technology**: Natural ventilation (openings in the stairwell), sun protection, thermal building optimization, solar thermal energy, humidity-controlled ventilation
- **Description**: Europe Aid demo project, energy-optimised design using thermal simulation

Source: Sadik 2015

[3]Climate-damaging refrigerants are used in VRF air conditioning systems, which reduces the climate compatibility of this example building

4. Local heating/cooling network, Olot (Spain)

- **Building Type**: Residence/ School, Office, Museum
- **Status**: Network installation (2016)
- **Standard**: -
- **Technology**: Renewable energies for a heating/cooling network
- **Description**: Local heating and cooling network for an urban district in Spain, based on biomass, photovoltaics and geothermal energy

Source: Laudy 2016

5. Fuencarral Residential Building, Madrid (Spain)

- **Building type**: Apartment building (2 units) + shop on the ground floor
- **Status**: Existing building
- **Standard**: Renovation to the low-energy standard "3 hojas VERDE" Cert. A; Primary energy demand 26 kWh/m^{2}a
- **Technology**: Photovoltaic, daylight control, insulation, replacement windows, heat pump, underfloor heating, solar thermal, reversible. Heat pump for cooling, chilled ceiling, ventilation with heat recovery
- **Description**: Very extensive renovation to a zero-energy building

Source: Greciano 2014

6. Apartment building, Lleida (Spain)

- **Building type**: Detached house
- **Status**: New build (2009)
- **Standard**: Passive house; Primary energy demand 52 kWh/m^{2}a
- **Technology**: Solar thermal, photovoltaic, biomass boiler, natural ventilation, shading elements
- **Description**: Solar optimised passive house with courtyard; Timber construction with sheep's wool insulation; Allegedly positive CO_2 balance considering the CO_2 binding of the building materials used

Source: Passive House Institute (PHI)

7. Notre Dame du Mont (Lebanon)

- **Building type**: Residence
- **Status**: Existing Building
- **Standard**: none, 83% solar coverage
- **Technology**: solar thermal (solar pergola), buffer storage
- **Description**: Subsequent installation of a roof shading and solar system (patent)

Source: Aoun 2015

1.2.2.3 Temperate climate (Germany)

1. Dieckmannstrasse climate protection settlement, Münster

- **Building type**: Apartment building (34 units)
- **Status**: New build (2012)
- **Standard**: Passive house,
  solar coverage 90%,
  heating load ≤ 10 W/m^2;
  Primary energy demand ≤ 120 kWh/m^{2}a
- **Technology**: Ventilation with heat recovery, solar thermal (350 m^2 collector area), thermal storage (50 m^3 water), heat pump
- **Description**: Funded by the NRW state programme "100 climate protection settlements", meets passive house criteria, solar house

Source: NRW Energy Agency

2. Project 42 climate protection settlement, Bonn

- **Building type**: Residence (32 units)
- **Status**: New build (2015)
- **Standard**: Passive House and Efficiency House 40 Plus
- **Technology**: Ventilation with heat recovery, photovoltaics, geothermal heat pump, battery storage, smart home, controlled shading elements, wooden construction, 40 cm cellulose insulation
- **Description**: Ecological student dormitory, funded by the NRW state programme "100 climate protection settlements", meets passive house criteria, energy-plus house

Source: 42! 2017

3. Active Stadthaus, Frankfurt am Main

- **Building type**: Apartment building (74 units)
- **Status**: New build (2015)
- **Standard**: Effizienzhaus Plus
- **Technology**: Photovoltaic (roof and facade), heat pump using waste heat from the sewage system, buffer and battery storage, carsharing with electric cars
- **Description**: Plus energy pilot project with 45% solar coverage, annual balance climate-neutral, no active cooling

Source: HHS Hegger Hegger Schleiff Architects 2015

4. Active Stadthaus in Frankfurt am Main

- **Building type**: Apartment building (74 units)
- **Status**: Existing building
- **Standard**: Refurbishment to become an Effizienzhaus Plus (electricity-only house); Envelope standard: KfW 70 standard primary energy demand 15 kWh/m²a
- **Technology**: Renovation of the building shell, photovoltaics (on the roof and on the facade), ventilation system
- **Description**: Plus energy reached by rooftop PV

Source: ABG Frankfurt Holding 2021

5. LVR Central Administration, Cologne

- **Building type**: Office
- **Status**: Existing building
- **Standard**: -
- **Technology**: Groundwater cooling system (passive cooling via heat exchanger)
- **Description**: This type of cooling is ideal because it is close to the Rhine. The heated water is returned to the Rhine

Source: Umweltbundesamt 2015

6. Max Planck High School, Karlsruhe

- **Building type**: School/day care centre
- **Status**: Existing building
- **Standard**: Effizienzhaus Plus
- **Technology**: Insulation of the building envelope, replacement of windows with automatic window opening for fan-assisted night ventilation, CO_2-controlled activation
- **Description**: Refurbishment of a school, development of a window ventilation system as a low-investment measure

Source: Umweltbundesamt 2014

7. ZAE Research and Administration Würzburg

- **Building type**: Office
- **Status**: New build (2013)
- **Standard**: -
- **Technology**: Passive infrared cooling system (PINC), cooling ceilings, rainwater cold storage, building automation system, vacuum insulation panels, energy-optimised textile cover, phase change material (PCM)
- **Description**: Pilot project for research purposes; Test and monitoring of various techniques. A fire-fighting water tank filled with rainwater serves as a cooling water reservoir. The re-cooling takes place through natural cooling (roof collectors to use the night cooling)

Source: Umweltbundesamt 2012

1.2.3 Summary assessment of the example buildings

The evaluation of the 18 example buildings from different climate zones provides a good overview of the state of the art, especially regarding building cooling. Both design optimization measures and active and passive cooling and ventilation techniques have been implemented in many buildings. The evaluation shows that in climate zones with increased cooling requirements, a variety of building cooling measures are used. In contrast, active cooling measures are rather rare in the examples of temperate climate (Germany). The future development in relation to summer heat and how to avoid it is often not sufficiently considered.

Examples from Germany show that the summer comfort range (i.e. operative room temperatures up to 27 °C) cannot (or no longer) be maintained in many apartments[4]. Even with new, exemplary zero-energy buildings, summer comfort problems often arise. For example, as part of a monitoring and a user survey in the active house built in Frankfurt in 2015 (see above), 35% of the residents surveyed stated that the apartment heats up quickly in summer (Nusser and Dietel 2016) .

The following table shows an evaluation overview of the example buildings.

[4] See e.g. Schroeder 2019

Table 3: Summary assessment of the example buildings

Building	Climate	Climate resilience	Climate protection effect	Indoor climate quality[5]	Costs and profitability	Transferability of the concept
AREE Aqaba Residence (Jordan)	Tropical or desert	Passive and active cooling measures	Not climate-neutral - but good approaches regarding passive measures	Good - passive and active measures for cooling	Investments 50% higher than in conventional buildings	Good transferability of the various measures
Research Institute Passive House Dubai (UAE)	Tropical or desert	Passive and active cooling measures	Good - Passive House	Good - passive and active measures for cooling	Not specified	Since it was designed for research purposes, technical concept transferable only to a limited extent
Austria Embassy Jakarta (Indonesia)	Tropical	Passive and active cooling measures	Good – Passive House	Good - passive and active measures for cooling	Not specified	As a model building, only transferable to a limited extent
Autonomous urban habitat Rabat (Morocco)	Subtropical	Passive cooling measures	Climate neutral	Sufficient - passive measures for cooling (mud walls, ventilation)	Renovation costs: €70,000	Good transferability of the various measures
African Development Bank Casablanca (Morocco)	Subtropical	Passive and active cooling measures	Not climate-neutral - but a good approach for measures in new buildings,	Good - passive and active measures for cooling	New building €18 million incl. data centre; Investment costs: approx. €1,000/m²	Good transferability of the various measures, apart from the use of HFCs
32 Hanaa El Fal Casablanca (Morocco)	Subtropical	Passive cooling measures	Not climate-neutral - but good approaches to passive measures	Sufficient - passive measures for cooling (ventilation, orientation)	Investment costs: €12.5 million; €380/m²	Good transferability of the various measures
District heating/cooling	Subtropical	Active cooling	Climate neutral	Good – active cooling	Investment costs: €935,000	Good transferability of the overall concept

[5]Qualitative assessment by the authors, based on the specified cooling system

Building	Climate	Climate resilience	Climate protection effect	Indoor climate quality[5]	Costs and profitability	Transferability of the concept
Network Olot (Spain)						
Fuencarral residential building, Madrid (Spain)	Subtropical	Passive and active cooling measures	Not climate-neutral - but a good approach for measures in existing buildings	Good - passive and active measures for cooling	Investment costs: €200,000; 950 €/m²	Good transferability of the various measures
Residential building, Lleida (Spain)	Subtropical	Passive and active cooling measures	Climate neutral	Sufficient - passive measures for cooling, solar control glazing	Investment costs: €195,000; €1,100/m²	Good transferability of the various measures or overall concept
Notre Dame du Mont (Lebanon)	Subtropical	Shading devices, solar energy	Solar generation	No information on cooling	Not specified	Good portability
Climate protection settlement Dieckmannstraße, Münster	Moderate	Good insulation standard, no measures for cooling	90% solar contribution margin	No information on cooling	Not specified	Good portability
Climate Protection Settlement Project 42, Bonn	Moderate	Good insulation standard, timber construction	Climate neutral	Good thermal insulation, controlled shading	Not specified	Good portability
Active Stadthaus, Frankfurt am Main	Moderate	No cooling measures	Climate neutral	No information on thermal insulation - according to monitoring, too warm for 35% of those surveyed	Not specified	Good transferability for inner-city living
Active Stadthaus am Main existing building stock	Moderate	Improvement through renovation	Climate neutral	Improvement through renovation	Not specified	Good transferability as there are many buildings of the same type in Germany

Building	Climate	Climate resilience	Climate protection effect	Indoor climate quality[5]	Costs and profitability	Transferability of the concept
LVR central administration, Cologne	Moderate	Improvement through low-investment measures	Not climate-neutral - but a good approach for measures in existing buildings	Good - efficient provision of cold	Not specified	Limited transferability of the measure due to the problem of groundwater/river heating up
Max Planck High School, Karlsruhe	Moderate	Improvement through low-investment measures	Not climate-neutral - but good approaches for measures in existing buildings	Good - CO_2 concentration and summer heat reduced	Not specified	Good transferability of the measures to other schools/day care centres
ZAE Research and Administration Würzburg	Moderate	Improvement through low-investment measures	Not climate-neutral - but a good approach for measures in new buildings	Good - efficient provision of cold	Not specified	Good transferability of the measures to other office buildings

1.2.4 Extraction and summary of climate-neutral concepts to ensure climate-resilient comfort in buildings

As a result of the research on the practical examples, the various measures that are used to avoid high room temperatures at building level are summarized in Table 4:

Table 4: Overview of measures to ensure climate-resilient comfort in climate-neutral buildings

No.	Designation	Short description
1	Building design/ building volume and orientation	The building design is decisive for the physical properties of the building. The ratio of external surface area to volume (A/V) has a strong influence on heat losses and heat gains. In addition, the orientation of sunlit areas, in particular the building openings (windows), is essential for the solar input into the building. The positioning and size of the windows can therefore be used for targeted gain or to avoid solar heat.
2	Material choice and construction	The choice of material has an impact on the storage capacity of the building. Solid walls increase the building's inertia, while lightweight construction responds more quickly to temperature changes. Depending on the climate requirements, this option can be used to maintain the indoor comfort range (19-26 °C). The choice of colour also influences the warming up of components. The *solar reflectance index* (SRI) indicates the properties of the component regarding the reflection of solar radiation.
3	Energy standards building envelope/component quality	Additional insulation or a high thermal quality of the components, such as windows and doors, influences the heat transfer from the outside to the inside (vice versa in the heating season). Well-insulated components and an airtight building shell maintain the desired interior temperature for longer thanks to low heat transmission. The type of glazing is also important to avoid heat in the summer: selective sun protection glass with a low g-value reduces the solar input, but it is not effective sun protection and prevents solar gains during the heating period.
4	Summer heat protection through shading devices	Various measures for shading components, especially windows, are possible. While simple fixed shading elements can be effective for south-facing windows, flexible solutions such as external sliding elements or sun protection slats are recommended in most cases. In Germany, the summer thermal protection of rooms in new buildings must be proven[6].
5	Building ventilation active/passive	Appropriate ventilation concepts can make a significant contribution to avoid overheating in summer. Ventilation concepts range from passive solutions such as cross-ventilation concepts, night ventilation, and air shafts to ventilation systems with heat recovery and dehumidification as well as ground or groundwater pre-tempering. Passive and active measures can also be combined to achieve sufficient cooling.
6	Building cooling measures	In addition to air conditioning systems with climate-friendly (natural) refrigerants, other efficient techniques for cooling buildings can also be used. For example, sorption chillers can generate cold using heat, i.e., without significant electricity requirements and therefore e.g., using solar thermally generated heat effectively (=> solar cooling). In moderate climate regions, the ground or groundwater can also be used as a heat sink. An effective measure to improve the efficiency of cooling systems are surface cooling / heating / cooling ceilings. These so -called *Low Exergy* Systems improve the efficiency of refrigeration, reduce losses and allow the use of renewable heat and refrigeration, e.g., allow the use of groundwater.
7	Greening/ water use	The greening of the roof and facade contributes to an improved microclimate. Rainwater can be used for this, and gray water can be recycled.

[6] The verification is based on DIN 4108 Supplement 2

No.	Designation	Short description
8	Efficient Applications	Electrical devices and lighting should have high efficiency, which reduces power consumption on the one hand and internal heat input on the other.
9	Renewable cold/heat generation	Renewable energy systems can be used on/in the building for the climate-friendly generation of cold or heat to actively yield the desired indoor temperature. Solar thermal systems, photovoltaics (e.g., for electrical solar cooling), biomass, geothermal energy and groundwater can be used to supply decentralized or central systems (e.g., district cooling).

Especially in climate zones in which heating and cooling are required in roughly equal proportions (subtropical climate), often a lot can be achieved through passive and low-investment measures. This is due to the relatively small deviation of the average outside temperature from the inside temperature (average temperatures: Indonesia 25.8 °C (tropical), Tunisia 19.2 °C (subtropical), Germany 8.5 °C (temperate)).

An analysis of the IEA case studies (Donn and Garde 2014) found that in cold and temperate climates it is most efficient to limit heat flux through good insulation of the building envelope. It is therefore essential to choose the lowest possible U-value for walls, roof, floor, and windows as well as an airtight building envelope. In subtropical climates, the roof and, if necessary, the walls should have good thermal insulation, while the floor should not be insulated to allow heat dissipation through the floor in summer. Here, the implementation of an optimal combination of passive design parameters leads to significant energy savings by reducing the annual heating and cooling loads. Passive cooling measures such as shading devices and natural ventilation lead to savings of more than 50% in the cooling load in almost all regions.

According to the IEA case studies, the most used passive measure in dwellings is natural ventilation. Geothermal heat exchangers are mainly used in Mediterranean climates where natural ventilation is less effective during the hot summer periods due to high nighttime temperatures. Additional measures are usually applied to non-residential buildings. In addition to natural ventilation, geothermal heat exchangers, green roofs or facades, "thermo chimneys" and evaporative cooling are used. The results show that in about 70% of the cases active cooling was not used.

1.2.5 Systematization of the results

As a basis for the development of district concepts with climate-friendly buildings, the results of the research on the measures at building level are systematized according to the following criteria:

- Suitability for different types of use
- Suitability for different climatic conditions
- Suitability for new construction/ existing buildings

Table 5: Systematization of the concepts for ensuring climate-resilient comfort in buildings
Legend: x = suitable; (x) conditionally suitable; - not suitable

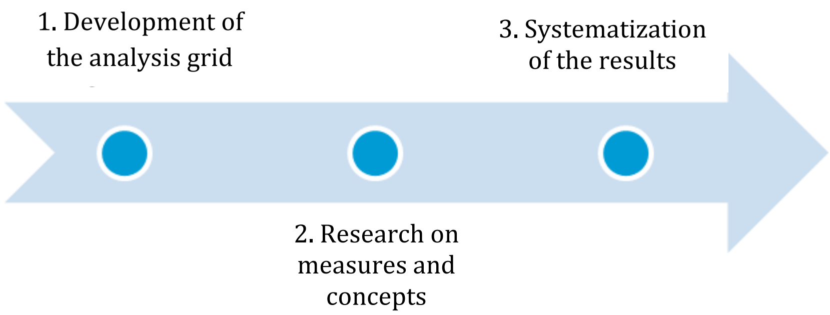
No.	Concept	Suitability for different types of use		Suitability for climatic conditions			Suitability for new construction/existing buildings	
		Residential building	Non-residential building	Temperate (Central Europe)	Subtropical (Southern Europe / North Africa)	Tropical	Existing building	New building
1	Building design/ building volume and orientation	x	x	x	x	x	-	x
2	Material choice and construction	x	x	x	x	x	(x)	x
3	Energy standards building envelope/component quality	x	x	x	x	x	(x)	x
4	Summer heat protection through shading devices	x	x	x	x	x	x	x
5	Building ventilation active/ passive	x	x	x	x	(x)	x	x
6	Building cooling measures	(x)	x	(x)	x	x	(x)	x
7	Greening/ water use	(x)	x	x	(x)	x	(x)	x
8	Efficient applications	x	x	x	x	x	x	x
9	Renewable cold/heat generation	x	x	x	x	x	(x)	x

Overall, it can be stated that the listed measures at building level are almost entirely applicable to all building types. Restrictions arise above all in the building stock, where e.g., the building design cannot be optimised. Measures for active cooling in residential buildings in the temperate climate zone have not been widespread up to now, partly for economic reasons.

1.3 Climate-resilient districts: state of the art

In this section, an analysis of the state of the art on the climate resilience of quarters regarding the development of urban heat islands is carried out. The methodological approach to research is divided into three steps (see Figure 1), which are described in the following sections.

Figure 1: Overview of the procedure for analyzing the measures to avoid heat islands



Source: Own illustration, Öko-Institut

1.3.1 Creation of an analysis grid

In the first step, an analysis grid was developed for the systematic presentation of the measures to be determined to avoid urban heat islands. The following elements were identified:

1. Brief description: Short summary of the mode of action of the measure, depending on the availability of data, quantitative effect, presentation of various parameters for the design.
2. Constraints: Description of possible obstacles and trade-offs related to the measure.
3. Applicability according to climate zones: Brief assessment of the extent to which the measure is also suitable for other climate zones in addition to Central Europe.
4. Legal framework: Description of the regulations that may play a role in connection with the measure.
5. Practical examples: Short description of practical examples in which the respective measure was implemented.
6. Sources: Indication of the literature used.

The points mentioned were summarized in a template that formed the basis for the research (see following section).

1.3.2 Measures to avoid heat islands

In the second step, measures are identified based on a literature search and examined with regard to the points presented in the analysis grid. Table 6 provides an overview of the measures considered. The results of the detailed investigation using the analysis grid (see section 1.3.1) are presented in Appendix A.

Table 6: Overview of the measures considered to avoid urban heat islands

No.	Designation	Short description
1	Brightening of coverings and surfaces in open spaces	Radiation absorption on hot days is reduced by using bright and reflective surface materials with low heat storage capacity. The lighter the buildings and surfaces in a city, the less heating, because short-wave radiation is reflected, and the materials heat up less. In return, the increased reflection from surfaces in the areas where people live also leads to increased radiation exposure. This has a negative effect on the comfort feeling. The previously described positive effect of the temperature reduction can be reduced or even overcompensated in this way.
2	Securing and expanding the tree population	Reduction of the (perceived) temperature and stabilization or positive influence on the urban climate through: Shadowing from leaves and treetops; Evaporation: Release of water vapor through leaf pores (transpiration).
3	Securing existing and creating additional forest areas	Forest areas close to the city contribute to the avoidance of urban heat islands due to the following modes of action: Evaporation by releasing water vapor through leaf pores; Influence of the air circulation by temperature difference between cool forest and heated city.
4	Unsealing of open space surfaces/ avoidance of sealing	The unsealing of surfaces helps to avoid the UHIE: Well-watered, unsealed surfaces release moisture into the air and cool it. If enough rainwater can seep away, the groundwater level rises. On unsealed areas, the runoff of rainwater into the sewage system is lower. If the rainwater cannot run off and keeps the soil well moistered, it evaporates, absorbing energy in the form of heat from the environment and thus having a cooling effect on the microclimate.
5	Securing and expanding green and open spaces	Green infrastructures such as roadside greenery, green inner courtyards and brownfield sites are important parts of the city and contribute to reducing the urban heat island effect. The positive effect of the plants is based, among other things, on the shadowing of horizontal earth and vertical building surfaces as well as evapotranspiration. Irrigated plants have a higher evaporation rate (Brandenburg et al. 2015). The use of rainwater is suitable for both the irrigation of plants and the evaporation of water for urban cooling in general (Sieker et al. 2019).
6	Preservation of urban air circulation and networking of open spaces	By creating and keeping undeveloped axial aisles connected to the surrounding area, urban air circulation can be promoted, and the supply of cold and fresh air guaranteed. In particular, large, contiguous agricultural and forestry areas are cold air production sites.
7	Roof and facade greening	Green roofs and facades reduce the summertime heating of the building surfaces through shadowing. Due to their evaporation capacity, they also have a positive effect on the ambient temperatures and, through both effects, also reduce the interior temperatures (smaller ΔT between inside and outside). Depending on the substrate layer, a distinction is made between extensive and intensive green roofs.
8	Increasing the proportion of water in the district	The cooling effect of water surfaces is based on the fact that the energy required for evaporation is withdrawn from the surrounding air which results into its cooling. Moving water (e.g. in fountains) generally contributes more to evaporative cooling than simple water surfaces due to the larger surface area. The cooling effect can be increased by water atomizers or sprinkler systems.
9	Shadowing of open spaces and paths	The shadowing of open spaces and paths reduces the heating of surfaces and thus leads to a slight improvement in the microclimate. By reducing the direct radiant power, the "perceived" temperature is significantly reduced and thus people's well-being is increased.

1.3.3 Systematization of the results

As a basis for the creation of the district concepts, the results of the research on measures to avoid urban heat islands are systematized according to the following criteria:

- Effect in terms of avoiding urban heat islands: The effect of the respective measure is assigned to the following four categories:
  - Shadowing
  - Evaporation
  - Albedo
  - Air circulation
- Suitability for different climatic conditions: The applicability of the measures in Central Europe (moderate climate), Southern Europe (subtropical climate) and in tropical regions is assessed.
- Suitability of the measures for existing quarters or new quarters.

Table 7 shows the classification of the measures for the categories described above.

Table 7: Overview of the measures considered to avoid urban heat islands

No.	Designation	Effect regarding the avoidance of urban heat islands				Suitability for various climatic conditions			Suitability for new construction/existing quarters	
		Shadowing	Evaporation	Albedo	Air circulation	Central Europe	Southern Europe	Desert climate	Existing quarters	New building
1	Brightening of coverings and surfaces in open spaces	-	-	x	-	x	x	x	x	x
2	Securing and expanding the tree population	X	x	-	-	x	x	-	x	x
3	Securing existing and creating additional forest areas	(x)	x	-	-	x	x	-	(x)	x
4	Unsealing of open space surfaces/ avoidance of sealing	-	X	-	-	x	x	-	x	x
5	Securing and expanding green and open spaces	(x)	x	-	(x)	x	x	(x)	x	x
6	Preservation of urban air circulation and networking of open spaces	-	-	-	x	x	x	x	(x)	x
7	Roof and facade greening	X	x	-	-	x	x	(x)	x	x
8	Increasing the proportion of water in the district	-	x	-	-	x	x	-	x	x
9	Shadowing of open spaces and paths	X	-	-	-	x	x	x	x	x

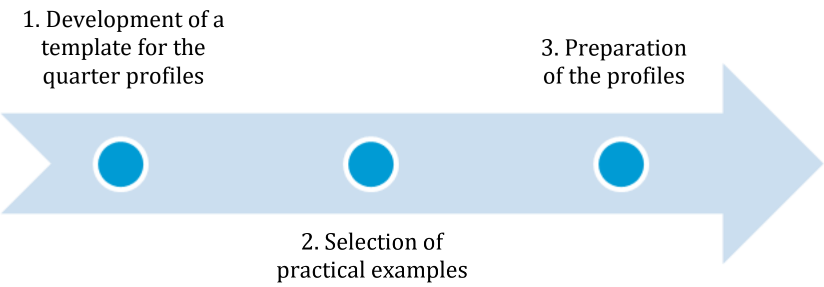
Legend: x = suitable; (x) conditionally suitable; - not suitable

1.4 Practical examples for avoiding heat islands

The measures and concepts for avoiding urban heat islands described in the previous section are already considered to varying degrees in the planning of new quarters and in existing quarters. As a basis for the development and investigation of the optimised district concepts (see chapter 2), practical examples were examined in which one or more of the measures shown in Table 6 were successfully implemented or considered in the planning phase.

The methodological procedure for the selection and documentation of the practical examples is shown in Figure 2.

Figure 2: Overview of the procedure for examining practical examples for avoiding urban heat islands



Source: Own illustration, Guidehouse

1.4.1 Development of quarter profiles

A standardized profile was developed to document the practical examples, which takes the following aspects into account:

- Brief description: The relevant characteristics of the quarter are presented
- Concept: Description of the approaches considered in the quarter to avoid urban heat islands
- Structure of the building stock: Information on the construction method and building structure
- Evaluation: The quarter is evaluated with regard to the measures implemented and potential for additional measures is identified
- Sources: Indication of the sources used

1.4.2 Selection of practical examples

Based on a literature analysis, a total of 14 quarters were selected as practical examples. To cover a broad spectrum, eight quarters in Germany, three quarters in Southern Europe and three quarters in the MENA region (MENA: Middle East and North Africa) are considered.

As a further criterion, the following three age classes were taken into account:

1. Older quarters
2. Newer quarters (from 2008)
3. New construction/planning

Regarding the quarter types considered, the following categories were taken into account:

- Inner city quarter (compact urban structure, mainly characterized by residential use, closed perimeter block development)
- Densely populated residential area (outskirts of the inner city, predominantly residential use, compact perimeter block structures, large row buildings and high-rise buildings)
- Relaxed residential area (mainly residential use, detached single-family houses and small apartment buildings)
- Industry and commerce (factory sites and industrial areas)

The selected quarters are shown in Table 8 (Germany) and Table 9 (Southern Europe and the Middle East).

Table 8: Overview of the quarters considered in Germany.

No.	Quarter name	Location	Brief description of the UHIE-relevant aspects	Construction age	Quarter type
1	Bahnstadt	Heidelberg	Passive house development, green roofs, shadowing, guidelines for investors, environmentally friendly air conditioning	New construction/ planning	Dense residential area
2	Bausemshorst settlement in Altenessen	Essen	Rainwater use and infiltration, use of water surfaces	Newer quarter	Downtown district
3	It's - New Forms of Living	Düsseldorf	Densification, unsealing, use of water surfaces[7]	Older quarter	Downtown district
4	Media Harbor Solar Settlement	Düsseldorf	Closure of block perimeter development, use of solar and geothermal energy, passive cooling	Newer quarter	Downtown district
5	Campo Bornheim	Frankfurt am Main	Inner-city passive house quarter, Green Building Award 2011	Newer quarter	Downtown district

[7] Source: National Urban Development Policy 2015

No.	Quarter name	Location	Brief description of the UHIE-relevant aspects	Construction age	Quarter type
6	Clouth quarter	Cologne	Open space concept "From gray to green", low-energy and passive house standard	New construction/ planning	Dense residential area
7	Commercial area Neuland 23 (in planning)	Hamburg	Green roof, PV for shadowing, specification of maximum building height	New construction/ planning	Industry and commerce
8	Vauban	Freiburg	Car-reduced quarter with low asphalt content	Older quarter	Residential area (suburb)

Table 9: Overview of the quarters under consideration in Southern Europe and the MENA region

No.	Quarter name	Location	Brief description of the UHIE-relevant aspects	building age	quarter type
1	Bosco Verticale	Milan, Italy	Roof and facade greening with around 900 trees and 2,000 shrubs	Newer quarter	Downtown district
2	Besòs	Barcelona, Spain	Heating and cooling network with waste heat utilisation and sea water cooling	Older quarter	Downtown district
3	Zorrotzaurre Peninsula	Bilbao, Spain	Conversion area, unsealing, new green spaces	New construction/ planning	Downtown district
4	Masdar	Abu Dhabi, UAE	Optimised building structure, UHI analyses	New construction/ planning	Downtown district
5	Hashtgerd	Iran	Optimised building structure, UHI analyses	New construction/ planning	Downtown district
6	znata	Morocco	Optimised building structure, use of rainwater, green spaces	New construction/ planning	Downtown district

1.4.3 Creation of the profiles

Based on a literature review, the quarters shown in Table 8 and Table 9 were examined in more detail regarding their concepts for avoiding urban heat islands and their characteristics were compiled in the form of profiles.

1.4.3.1 Profiles of example quarters in Germany

1. Bahnstadt Heidelberg


Quelle: Wikimedia Commons 2014

- **Brief description**: New, 116 hectare quarter of Heidelberg on the site of the former goods station and largest passive house settlement in the world. The quarter is both a residential area and a location for science and commerce and was planned from an ecological point of view, which is intended to inhibit the development of urban heat islands.
- **Concept**: 66% of the building stock with extensive green roofs; 10% of the area of the quarter are open and green spaces; due to the high proportion of green and open spaces and green roofs, a lot of rainwater can seep away instead of running off, which provides additional cooling; light facades and surfaces that heat up less; water surfaces in public space.
- **Structure** of the building stock: Nationwide passive house standard with up to 50% less CO_2 emissions than conventional settlements. Bahnstadt is supplied with electricity and heat by district heating, which comes 100% from renewable sources.
- **Evaluation**: In the Bahnstadt Heidelberg, various techniques to avoid UHIE in the planning, such as the preservation of open spaces, extensive roof greening and the use of light-coloured surface materials and water areas were implemented. The combination of these different techniques creates synergy effects, which should result in an additional avoidance of heat island. However, there are also indications that the concept is not effective to the intended extent and that the temperatures in the quarter are even higher than in other quarters of Heidelberg (Kükrekol 2020).

2. Bausemshorst settlement in Altenessen, Essen

- **Brief description**: Improvement of the living environment through rainwater management in a multi-generational quarter
- **Concept**: The rainwater seeps into hollows and trenches on the settlement area. The rainwater from the roofs is channeled through open gutters into planted water basins in the inner courtyards of the settlement, which results in a noticeable improvement in the microclimate due to the evaporation coolness of the water and the release of water vapor from the plants. 60% of the approximately 3-hectare area is integrated into the natural rainwater management system, which means that around 12,240 cubic meters of water per year are kept away from the sewage system.
- **structure of the building stock**: New construction of 99 residential units and 10 single-family low-energy houses in accordance with the German KfW energy efficiency house 70 standard.
- **Evaluation**: The environmentally friendly rainwater concept creates a pleasant microclimate throughout the settlement area. The rainwater is fed into the natural water cycle through infiltration, and the tenants are largely exempt from sewage fees. To achieve an additional cooling effect, green roofs and facades could be installed.

Sources: Raasch 2015; Wilhelm 2018

3. "It's - New Forms of Living" Düsseldorf

- **Brief description**: New construction of a car-free residential complex with 82 residential units on the site of a former car dealership.
- **Concept**: Revitalization of a completely sealed site; The degree of sealing and development could be reduced by 30% each; at the same time, extensive green and water areas have been created, which increase climate comfort; Use of bright surface and facade materials.
- **Structure of the building stock**: Three-storey residential complexes in low-energy house standard with green roofs and inner courtyards; unsealing and planting of surrounding open spaces and creation of 700 m^2 water areas; underground car park with 82 parking spaces. The underground car park ramp is cover with a pergola construction and planted with greenery.
- **Evaluation**: Due to the high proportion of unsealed surfaces, the residents are comfortable. The mix of bright facades, green roof and open spaces, as well as the generous water areas create synergies that reduce the formation of heat islands.

Sources: National Urban Development Policy 2015; Rasch 2015

4. Media Harbor Solar Settlement in Düsseldorf

- **Brief description**: Newly built residential complex with 101 residential units, facade-integrated photovoltaic system, use of geothermal energy and passive cooling.
- **Concept**: passive cooling of the rooms by geothermal probes; sheltered courtyards with shadowing effects; 260 m^2 green roof.
- **Structure of the building stock**: The urban structure of block perimeter development that is predominant in the quarter is continued, resulting in an attractive, protected residential courtyard; Energy standard: so-called “3 liter house” according to PHPP.
- **Evaluation**: In addition to the green roof, greening of the facade could be applied.

Sources: NRW Energy Agency; Wortmann & Wember 2009

5. Campo Bornheim, Frankfurt am Main

- **Brief description**: Located in Frankfurt-Bornheim; Revitalization of an inner-city industrial wasteland (downtown district); year of construction 2009 (new construction); residential houses in the passive house standard; awarded the German Urban Development Prize 2010 and the Frankfurt Green Building Award 2011
- **Concept**: Conversion of the former Bornheim tram depot into a residential area in passive house standard with apartment buildings, retail and gastronomy; 20% less sealed areas (mainly inner courtyards unsealed); underground car park with 250 parking spaces (avoidance of additional sealing by above-ground parking spaces); a five-storey block edge is rounded off by the building and an alley is created (public route in North-South direction)
- **Structure of the building stock**: Area approx. 10,000 m², of which 1,100 m² is commercial space; 11 townhouses with a total of 140 apartments (four- and five-storey blocks); houses are fed with waste heat from the supermarket; heating energy demand 15 kW per square meter per year
- **Assessment**: Low per capita GHG emissions, increased proportion of green space, new pedestrian walkway. In order to achieve additional cooling, the roof areas could also be greened here.

Sources: AS+P; German Academy for Urban Development and Regional Planning 2010; Mauritz; National Urban Development Policy 2015

6. Clouth Quarter Cologne

- **Brief description**: New quarter in Cologne on a former industrial site. A total of 1,200 low-energy and passive house standard residential units were built on the 14.5 hectare site.
- **Concept**: “From gray to green” open space concept with the creation of a large number of public and semi-public green spaces; new planting of 50 trees on the centrally located airship square; Creation of a 7,000 m² large continuous green area; footpaths within the quarter are car-free and consist of light dolomite split, which is water-permeable
- **Structure of the building stock**: The 3-storey residential complexes are arranged around green and shaded inner courtyards; partial greening of roofs in the form of accessible roof gardens
- **Evaluation**: Due to the size of the contiguous green area, a noticeable improvement in the climate comfort of the residents can be expected. Since predominantly dark facade materials with a low albedo were used, the full potential of avoiding heat island development is not achieved. In order to achieve an additional cooling effect, the roof and facade areas could be greened and water areas created on the site.

Sources: Kölner Wochenspiegel 2018; Rhein Exclusiv 2017

1.4.3.2 Profiles of the southern European and subtropical quarters

1. Sant Adrià de Besòs, Barcelona (Spain)

- **Brief description**: In the quarters of Forum and 22@, a municipal district heating/cooling network was developed, which is operated with renewable energies and has been in operation since 2004.
- **Concept**: In the production centre Forum of Districlima S.A., steam from the nearby waste incineration plant Sant Adrià de Besòs is mainly used for heating and cooling. Four steam/water heat exchangers for heat supply and two absorption chillers indirectly cooled with seawater for cold generation are operated via the process steam. The remaining cooling capacity required is provided by a total of four compression refrigeration systems, some of which are directly and some indirectly cooled with seawater [8]. The system includes a 5,000 m^3 cold water tank as a buffer option. A gas boiler serves as backup for the steam from the waste incineration. The compression refrigeration systems can dissipate 6.7 MWh of heat per year using the coolant water.
- **Structure of the building stock**: A total of 94 buildings are connected to the system. These are mainly public buildings such as universities and hospitals, but also apartments and offices.
- **Evaluation: The district heating/cooling network saves around 17,000 t of CO_2** per year. How big the influence of the relocation of the refrigeration systems from the city centre to the outskirts is on the urban microclimate is not described. In addition to the cooling of the buildings by the district cooling network, roof and facade greening could also be established to achieve an additional synergistic cooling effect.

Sources: Faustmann and Hollauf 2014; Hollauf and Faustmann 2014; Serrano 2016; ENGIE 2013

[8] The systems will probably be operated with conventional HFC refrigerants instead of the climate-friendly natural refrigerants that are recommended.

2. Bosco Verticale, Milan (Italy)


Quelle: Wikipedia.org

- **Brief description**: Bosco Verticale (Eng. vertical forest) are the names of the green twin towers of a high-rise complex in Milan.
- **Concept**: The concept of the project is to use the urban space as effectively as possible, not to further seal it and at the same time to improve the biodiversity in the metropolis of Milan. With the planting of the towers, new living and feeding areas for insects and birds were created; In this way, the residential towers can function as steppingstone biotopes between the public parks, the avenues and inner city wasteland. The towers are intended to contribute to a biotope network system in a city. The trees and plants on the facade are intended to improve the microclimate in the apartments and on the balconies; the plants are said to mitigate noise, dust, and heat. This improves the residents' quality of life and establishes a connection with nature in an urban environment. In total, the facade greening consists of around 900 trees, 5,000 shrubs and 11,000 other plants, which corresponds to a planted forest area of around 7,000 m^2.
- **Structure of the building stock**: The high-rise project consists of the two towers Torre E with a height of 110 m and 27 floors and Torre D with a height of 80 m and 19 floors.
- **Assessment**: There is sufficient evidence in the literature that Bosco Verticale brings about an 'improvement' of the microclimate. However, this improvement is not quantified in absolute figures in the literature examined, which is why a final assessment of a reduction in the UHIE does not appear permissible. To achieve additional cooling, areas of water could be created around the towers. Brightening up the facade is out of the question, as it is completely green. Maintenance and care effort of the plants is not documented (probably not insignificant).

Sources: Giacomello and Valagussa 2015; Spagnoli Gabardi 2014; Wang 2014; Wikipedia 2021

3. Zorrotzaurre Peninsula, Bilbao (Spain)

- **Brief description**: The Zorrotzaurre Peninsula is a new quarter in Bilbao that is planned to be built on an artificial peninsula of the Nervión river.
- **Concept**: The use of light-coloured surfaces and the creation of approximately 130,000 m^2 of green space (20% of the total area) should bring about a reduction in the UHIE. The cooling of the buildings is to be achieved using geothermal energy.
- **Structure of the building stock**: A total of around 5,400 new apartments are to be built.
- **Evaluation**: In the study 'Design solutions for Urban Heat Island mitigation in the City of Bilbao' it was found that the microclimate in Bilbao could be positively influenced by appropriate development of the Zorrotzaurre Peninsula.

Sources: (ZORROTZAURRE MANAGEMENT COMMISSION; ZORROTZAURRE MANAGEMENT COMMISSION; RESIN 2016; Sustainia 2018)

4. l'Écoquartier Andromede a Blagnac, Toulouse (France)

- **Brief description**: The Écoquartier Andromede à Blagnac is an 'eco-quarter' in Toulouse built in the early 2000s with around 4,000 inhabitants and 10,000 jobs.
- **Concept**: The concept of the Écoquartier is comparable to that of Heidelberg's Bahnstadt. An avoidance of the UHIE should be brought about by synergy effects of bright facades, facade greening and green spaces. The green areas cover 70 hectares, which is one third of the total area. Since the quarter is traffic-calmed, the proportion of closed asphalt surfaces is lower compared to conventional quarters, which also makes a positive contribution to the climate situation in the Écoquartier.
- **Structure of the building stock**: The quarter has a mixed use of residential and non-residential buildings.
- **Evaluation**: The concept combines various measures to reduce urban heat islands.

Source: (Vivre Andromede 2015)

5. Masdar, United Arab Emirates


Source: Wikipedia 2021b

- **Brief Description**: Masdar is a planned 'eco-city' in the Emirate of Abu Dhabi. Construction started in February 2008. The project, announced as a "CO_2-neutral city of science", is to be powered entirely by renewable energies. After completion, around 47,500 people will live here.
- **Concept**: Fresh air corridors and park areas are to permeate the building areas and drastically reduce the temperature compared to the city of Abu Dhabi. The walls of the houses in Masdar slope upwards to provide more

shade. Due to this narrow, shady construction, the buildings heat up less and require less energy to be cooled. The proven local idea of cooling with wind towers is to be revitalized in a modernized form: some large buildings will be grouped around huge 'modern wind towers'. These towers emit a fine mist of water that cools the air. Since the cool air is heavier than the warm air, it falls around the towers and is supposed to cool the surrounding quarters. Seawater is treated with solar-powered desalination plants and pumped into the city's numerous fountains. Deep wells, which have also proven their worth in old Arab settlements, also bring coolness from the depths of the earth to Masdar City. Awnings and modern insulating materials also shield the heat. Additional cooling is to be provided by the installation of water areas and 'urban green'. As a result of the measures described, the temperature should be around 10 K below that of neighboring Abu Dhabi.

- **Structure of the building stock**: Narrow position of the buildings and formation of shaded 'urban canyons'; bright surfaces; about 45 m high 'modern wind towers'.
- **Evaluation**: To date, it has not been possible to reliably state the extent to which the Masdar City sustainability concept has an effect, since the savings potential of 65% that has always been announced relates to the average consumption in the emirate, or that of the entire Arabian Peninsula, which is one of the highest worldwide. Some of the measures planned as part of the project are very cost-intensive and therefore cannot be fully transferred to cities in comparable climatic regions (e.g., the numerous city fountains that are operated with fresh water from solar-powered desalination plants). Completion is scheduled for 2030.

Sources: Schulz 2017

6. Shahre Javan Community, Hashtgerd New Town (Iran)

- **Brief description**: The pilot project 'Shahre Javan Community' was planned as part of the 'Young Cities' project and includes 2,000 housing units for 8,000 inhabitants. The project aims to test innovative solutions for climate-neutral and climate-resilient buildings and quarters, adapted to the climatic, ecological, cultural and economic context in Iran. The quarter covers an area of almost 45 ha in the southern part of New Town Hashtgerd (approx. 35 ha of living space and approx. 9 ha of open and green space).

Source: Wikipedia 2020

- **Concept**: Innovative technologies in the building envelope reduce heating up in summer and cooling down in winter, so that the building's energy consumption is reduced. Solar modules and collectors on the roof generate electricity and hot water for the building and provide shadow. Reducing the temperature through shadowing, open and green spaces. In the planning phase, implementation of microclimate simulation to investigate the effects of different building structures and vegetation alternatives on heat development.
- **Structure of the building stock**: compact construction; Energy efficiency in the building envelope

- **Evaluation**: Some of the measures applied in the project have been proven to be highly effective and easily transferrable (e.g. shadowing by PV elements).

Sources: (Cleaner Production Germany 2021; Sodoudi et al. 2013)

7. Eco-Cité Zenata, Casablanca (Morocco)

- **Brief Description**: The Zenata Eco-City was designed based on the three pillars of sustainable development, which aims to combine urban development with local realities to create a green and open city. The Eco-Cité Zenata will be built on an area of 1830 hectares North of Casablanca. In addition to residential buildings for 300,000 residents, a campus area, a medical centre and a shopping centre are also planned. A total of 470 hectares of green space is to be created.
- **Concept**: urban development taking into account the wind direction from the Atlantic to aerate the building structure; nearly 1/3 of the territory is green space, distributed in a way that supports the urban ventilation approach; concept for sustainable water use based on retention areas; Application of the 'city of short distances' principle with local supply options distributed across the quarter; connection to public transport.
- **Structure of the building stock**: The quarter has a mixed use of residential and non-residential buildings, the development structure is optimised for the use of natural cold air.
- **Evaluation**: The urban planning concept is based on reducing urban heat islands. The consideration of sustainable principles in the basic planning of the city should be positively emphasized.

Sources: Agoumi 2016; Roby 2017

2 Creation of optimised quarter concepts

Within the scope of this chapter, the effectiveness of measures to avoid urban heat islands in climate-friendly city quarters is to be quantified using simulation calculations. Based on the results of the previous chapter, firstly optimised packages of measures for heat-resistant quarters are compiled.

The concepts distinguish between two climate regions:

- Temperate climate: Central Europe, specifically Germany
- Subtropical Regions: Southern Europe, North Africa

In the investigations for subtropical regions, measures are considered which are also relevant for the tropical zone, so that the results are useful for large cities in all hot climate zones.

In the second part, the numerical proof of the effect of the measures takes place. On the one hand with regard to avoiding overheating and minimising the cooling energy demand, on the other hand with regard to the requirements for climate protection (goal: climate neutrality).

Using the simulation calculations, three quarter concepts for German (moderate) climatic conditions and two for subtropical and Southern European/North African climatic conditions were examined.

Based on the initial situation, a microclimatically optimised quarter concept is first developed for each location. The effect of the optimization measures is quantified based on microclimate simulations.

To show the effect of the quarter measures on the buildings, the initial state of the buildings is first taken into account in thermal building simulations, both in the original quarter and in the optimised quarter.

Based on this, a step-by-step approach is followed, in which it is first checked which level of comfort can be achieved with "passive" measures, such as e.g., improved thermal envelope qualities and sun protection. Based on further variants of the thermal simulations, suitable technical measures are then successively added until finally both the requirements for thermal comfort and at the same time the goal of climate neutrality are met. The type and number of measures selected depend on the individual circumstances in the respective quarter.

2.1 Packages of measures for UHIE-optimised quarter concepts

Based on the findings from Chapter 1.3, packages of measures for heat-resistant quarters are compiled. Where necessary, a distinction is made between packages of measures for subtropical regions (Southern Europe/North Africa) and moderate climate regions. Measures that only apply for new quarters are marked accordingly. The given order corresponds to the relevance. The aspects of effectiveness and costs (investment and maintenance) were considered qualitatively.

2.1.1 Recommended package of measures

2.1.1.1 Package of measures for heat-resistant quarters

A detailed description of the measures is provided in Annex A.

1. Securing the stock of trees and existing forest areas as well as planting/maintaining new trees that provide both shadow and evaporation cooling[9]
2. Shadowing of open spaces and paths

   a) Awnings for shadowing squares and paths

   b) PV for shadowing walkways in front of residential and commercial buildings and parking lots
3. Preservation of urban air circulation and networking of open spaces (=>for planning of new quarters)
4. Urban planning: Suitable ratio of building volume to open spaces (=> measure for planning of new quarters)
5. Use of light-coloured materials for roofs, facades, possibly also streets and sidewalks (=> measure for new construction or renovation)

Special measures for temperate climate regions (Germany)

a. Increasing the proportion of water in the quarter
b. Unsealing of open space surfaces/ avoidance of sealing
c. Roof and facade greening (extensive, with little maintenance)

2.1.1.2 Measures for climate-neutral and climate-resilient buildings

1. Measures to ensure comfort in summer or to reduce the cooling energy demand

   a) Sun protection measures (external moveable sun protection e.g., automatic venetian blinds, possibly overhangs with south-facing windows)

   b) Night ventilation cooling

   c) Insulation and thermal insulation glazing (optimal qualities depending on the climate zone)

   d) Measures to improve airtightness

   e) Compact building design, moderate proportion of window area (=> new buildings)

   f) High thermal storage masses (=> new constructions)
2. Renewable energy supply from on-site energy sources

   a) Installation of PV on roofs, possibly with battery storage, designed to limit maximum demand (goal in subtropical climate: self-sufficient power supply)

   b) Solar thermal water heating (e.g., via thermosiphons in subtropics or evacuated tube collectors in temperate climates)
3. Use of sustainable building materials (natural stones, timber construction, insulation from renewable raw materials) (=> new buildings)

Special measures for subtropical climate regions (Southern Europe, North Africa)

a. Efficient active cooling (without fluorinated refrigerants)

   A) Cooling of the most important usage zones via decentralized or central (reversible) air conditioning units/systems with natural refrigerants (e.g., propane), which are fed by

[9] Trees native to subtropical regions have low levels of transpiration.

PV systems depending on the supply.
B) Alternative for larger new buildings or as a supplement to existing systems using solar heat-driven chillers (solar collectors in combination with sorption chillers)

C) Climate-neutral district cooling (=> new buildings)
e.g. fed from solar energy, waste heat or seawater

D) Central ventilation systems with cold- and moisture recovery (=> new buildings)

Special measures for temperate climate regions (Germany)

a. Measures to reduce heating energy demands

A) High insulation standard (target U-values: Roof: <0.1 W/m²K; facade: <0.15 W/m²K; floor/basement: <0.25 W/m²K), good window qualities (U_W - value < 1 W/m²K and g-value[10]> 0.55[11]).

B) Efficient ventilation

Refurbishment

If additional ventilation measures are required after checking the requirements of German standard DIN 1946-6, possibly decentralized fans with heat recovery in the bedroom and living room[12].

New buildings

Mechanical ventilation system with heat recovery (recommend degree of heat recovery > 80%, fan efficiency with nominal ventilation: SFP < 0.45 Wh/m³)[13]

C) Compact building design; mainly south-facing window areas that are not shaded in winter (=> new building))

b. Efficient, climate-neutral heating and water heating

New buildings

Floor heating (and cooling) fed by a heat pump powered by green electricity without fluorinated refrigerants, possibly as a hybrid system with (gas) peak load boiler. Hot water preparation via a PV supply-controlled central system with storage tank, in apartment buildings with a circulation system (system temperature 45 °C, to avoid legionella, heat transfer stations and, if necessary, reheaters in the kitchens)

Existing buildings

Renewable district heating *(if available); alternative: see new buildings;* as for retrofitting floor heating does not make sense, it may be necessary to retrofit convector heaters in some areas to ensure the necessary low flow temperatures.

c. Efficient active cooling

[10] Total energy transmittance as a measure of the usable portion of the heat-active solar radiation
[11] A good g-value is particularly important for winter energy gains with unshaded south-facing windows
[12] Retrofitting a central ventilation system is usually difficult. In detached houses it is usually possible to keep the window ventilation (test according to German standard DIN 1946-6 required), in which without permanent tilt window ventilation the air exchange rate of approx. 0.2/h is usually well below that of a mechanical ventilation system. Although this is associated with a loss of air quality, it is definitely advantageous from an energy and economic point of view.
[13] A possible automatic requirement control (air volume control according to humidity, air quality and temperature) makes sense from an energy perspective, but is currently not (yet) economical

Especially in regions with cool summers, efforts should be made to achieve sustainable summer comfort through measures to improve summer heat protection. Proof of thermal insulation in summer is mandatory for new buildings in Germany.

If it is not possible to do without active cooling, so-called silent surface cooling systems (e.g., floor cooling) should preferably be used in new buildings. The high system temperatures that are possible here for cooling enable high efficiency of the chiller or, in the case of ground and groundwater heat pumps, even direct use of the groundwater or groundwater as a heat sink. In addition, the energy required for distribution (between the generator and the transfer system) is significantly lower in water-based distribution systems than in air-based distribution systems.

2.2 Simulation -supported proof of effectiveness of the packages of measures for selected quarters

2.2.1 Modelling basics

The quarters are analyzed on two different, interconnected levels:

(a) at quarter level (simulation of the microclimate within the quarter) and

(b) at the building level (building simulation to determine the thermal dynamics of the buildings in the quarter and to quantify the energy demand for cooling and heating).

2.2.1.1 Simulation of the microclimate

The simulation of the microclimate has two tasks within this project:

- the localization of the general reference climate data, generalized to a large area, to the special investigation area with a building-resolving accuracy as framework conditions for the building simulations, and
- the presentation and analysis of the microclimatic and bioclimatological conditions outdoors over the course of the day.

The microclimate simulations are carried out with the microclimate model ENVI_MET (Version 5.0; www.envi-met.com). ENVI_MET has been used for the high-resolution simulation of the microclimate in urban areas worldwide for over 25 years and has been independently validated in well over 300 scientific papers for a wide variety of climate zones.

As part of the project, microclimate simulations are carried out on two different levels:

- The framework level (framework-level simulations) with a coarser spatial resolution (5 m) of the quarters in a continuous simulation of a complete annual cycle
- The level of detail (detail-level simulations) with a high resolution (2 m) performed for selected days.

2.2.1.1.1 Overview of the procedure for annual simulations (framework-level simulations)

The main task of the annual simulations is the generation of adjusted input data for the building simulation. The simulations are also suitable for obtaining a seasonal overview of the changes in temperature distribution, especially under the influence of different sun angles.

The annual simulation calculates the microclimate in the various study areas with a spatial resolution of 5 x 5 m. In addition, the simulations are adjusted every 30 minutes to the externally specified weather data.

To analyse the microclimate, the distribution of the air temperature for the **status quo** in the various seasons is first considered for each area and compiled in an overview table. For this purpose, the air temperature [°C] at a height of 1.8 m at 4 a.m. and 4 p.m. in **January** (partial figures A & B), **March** (partial figures C & D), **July** (partial figures E & F) and in **September** (Partial Figures G & H) shown and analysed. Here, the same days in the corresponding month are not always taken for the different cities, but those are selected that have a clear daily amplitude and little cloudiness, so that the microclimatological properties are clearly evident (see Table 10).

Table 10: Overview of the selected simulation days

	January	March	July	September
Tunis	01/14	03/11	07/22	09/02
Madrid	01/21	03/20	07/07	09/21
Cologne	01/18	03/21	07/25	09/21
Hamburg	01/22	03/22	07/09	09/22
Frankfurt a. M	01/22	03/22	07/01	09/22

Exemplarily, not the existing climate reference data were used as input for Frankfurt, but the climate projections for 2050.

The illustrations of the status quo are compared with the results of the **optimisation** measures. The differences are usually shown as difference images (optimisation minus status quo), except for the Cologne study area, since the building structure has changed fundamentally here or the changes were locally based on the building structure, so that an area-based difference formation makes little sense. The absolute temperature values were therefore shown for Cologne.

To get a detailed insight into the microclimate of the different areas, detailed simulations were then created for the selected winter and summer days. The data generated in the annual simulation was used as the framework for the high-resolution simulations (see next section). However, the spatial resolutions between the very well resolved annual simulations and the detailed simulations are quite close together (5 m vs. 2 m). Since the redesign measures envisaged in this project are of a more general nature and locally limited, the results of both types of simulation do not differ significantly and no additional information can be gained from the detailed simulations in this project on a general level. However, as a basis for further use planning of the open space (residence functions, small-scale design e.g., with street furniture, etc.), a high resolution of the microclimate is a necessary planning basis.

2.2.1.1.2 Overview of the procedure for detailed simulations (detail-level simulations)

The detailed simulations essentially cover the same study area as the overview simulations, but with a higher spatial resolution of 2 x 2 m. This results in small changes in the building structure in places and sometimes buildings are added at the edges, which are omitted in the overview simulation because they were cropped unrealistically.

The detailed simulations adopt the framework conditions of the overview simulations, so that longer-term effects are considered despite the short simulation period.

In contrast to the overview simulations, the wind direction and wind speed for the detailed simulations were set to typical values for the day under consideration and were not changed during the simulation period. This is a useful specification for a high-resolution analysis of the microclimate, since the focus here is not on the exact depiction of a given weather pattern, but on the interpretation of the effects of the planned measures. This is made considerably more difficult if the wind varies in direction and strength over the analysis period.

By considering the annual simulation and detailed simulation together, it is therefore possible to consider the effect of measures both in general (detailed simulation) and applied to specific weather data (annual simulation).

2.2.1.1.3 The thermal comfort indicator PET

The thermal comfort index PET is used to assess the thermal comfort outdoors. Like many other indicators (e.g. PMV, UTCI, felt temperature), PET is an attempt to transfer complex microclimatological outdoor conditions into a simpler, intuitively understandable indoor situation. A comprehensive description of PET, including the existing vulnerabilities, can be found in Walther and Goestchel (2018).

The PET value is defined here as a theoretical interior temperature at which, without direct exposure to radiation and without wind movement, people experience the same heat perception as under the outdoor conditions considered.

In a windless, sunny outdoor situation (1 m/s wind, 70°C radiation temperature) at an air temperature of 30°C, for example, the PET value can quickly be 37°C and more.

The PET limit values between the sensitivity levels entered in the figure are only to be understood as a guide. The heat perception of humans varies over the year, among other things due to the thermal adaptation of humans and there are regional and cultural differences.

Since the PET scale is based on the simulated human energy balance, it is theoretically open at the top and bottom and can be freely expanded with additional attributes such as "extremely hot" or "extremely cold". As with all model results, the spatial distribution of the values and their changes due to planning measures are more relevant than the exact numerical value of PET.

The PET value is a static thermal index, i.e. it calculates the heat perception of a person based on the assumption that the person stays in one place until the energy balance of his body is balanced. This can take up to 20 minutes, especially in summer.

Strictly speaking, the PET value is therefore only valid for lingering people or very homogeneous microclimate situations, since moving people are usually exposed to a wide variety of microclimates within a few minutes. The calculation of the thermal sensation of moving people is complex, as this requires information about the movement patterns of the individual passers-by (cf. Bruse, 2007). The static PET value is therefore used for practical application, although the above must be considered when interpreting the values.

The consideration of the PET value only makes sense during the daytime hours, after sunset PET roughly corresponds to the air temperature with a slight dependency on the wind speed.

The results of the microclimate simulations are shown on the one hand in the figures in the corresponding chapters. Further representations can be found in the form of so-called colour tables in the appendix (see corresponding text references).

2.2.1.2 Building simulations

Dynamic thermal simulations were carried out with the TRNSYS software for the investigations of the indoor climate and the building's energy demands. The buildings and the apartments in the buildings were mapped using multi-zone models.

The simulations were carried out based on the local hourly temperature, humidity and radiation data determined by the microclimate simulations for selected points in front of the facades of the buildings/apartments in the quarters. The underlying annual reference climate data also included hot summer periods, which made it possible to verify indoor climate comfort even under extreme conditions. For the building simulation, the individual buildings were divided into usage areas, each with several zones (e.g., living- and dining room, bedroom and children's room or retail). A reference climate point of the microclimate simulations was assigned to each area of use. In this way, the different temperature and climate conditions on different facade sides and elevations could be considered for a building. This made it possible to realistically depict the individual buildings and apartments in the quarter. Sunlight/shadowing of the individual areas of use was also considered. Similarly, the radiation data was differentiated according to orientation and shadowing (position and height) and considered according to the location of the areas of use.

To determine the total energy demands and energy gains (i.e., to prove climate neutrality) of the buildings and the quarter, the sum of the energy demands and gains was calculated for each building and quarter using the different usage type models, reference climate points and radiation data.

For selected usage types (e.g., extremely unfavourable and "normal" usage areas), comfort statistics (e.g. frequency of temperature excesses or Predicted Percentage of Dissatisfied (PPD)) were created, which together with the energy demand (for heating, cooling, humidification and dehumidification, and ventilation) enabled a comparison of the concepts and provided a functional proof. An example of unfavourably located areas of use are roof apartments, which tend to overheat in summer due to their exposure and low thermal storage mass.

By considering a representative selection of the buildings, it was possible to examine the impact of the measures implemented in the quarter on the indoor thermal comfort of the residents and the efforts to achieve climate neutrality in the selected area. For this purpose, the energy demands for cooling, heating, hot water and household electricity of the buildings in the quarter were determined. In addition, the resulting operative temperatures in the buildings were determined and characteristic values for quantifying the thermal comfort were derived from them.

2.2.1.2.1 Model coupling

Both scale levels are carried out by passively coupling the programs ENVI_MET and TRNSYS. The hourly annual and daily changes of the climate parameters relevant for the building simulation (air temperature, humidity and long- and short-wave radiation) calculated in ENVI_MET are transferred to TRNSYS as a base data for the simulation. The location of the zones in the apartments/buildings in the quarter as well as the respective facade orientation and height are considered.

2.2.2 Quarter selection

When selecting the quarters, an attempt was made to cover as wide as possible a range of real existing and future residential quarters. The focus was on urban quarters with high residential densities, as can be found in the central quarters of many large cities. In the case of the German quarters, an attempt was made to cover regions that are cool in summer as well as regions that are hot in summer. In addition, both new and existing quarters and densification should be considered.

2.2.2.1 Existing quarter Tunis, Tunisia

The selected quarter in Tunis can be used in many ways as a representative of numerous quarters in hot or subtropical regions. The quarter is characterized by a highly diversified development structure of mostly simple one-, two- or three-family houses in setback areas and larger building complexes on main streets. Due to the increasing availability, but not least also the increasing need, it can be assumed that the currently low proportion of air-conditioned buildings will increase sharply in the near future. Financial leeway and thus also the awareness of climate-friendly solutions are very limited among the residents there. As part of the investigation, suitable solutions for such quarters are to be identified and their effectiveness demonstrated.

2.2.2.2 New building quarter Madrid, Spain

The quarter studied in Madrid is a typical new-build quarter with high-rise apartment buildings, such as are currently being built in many suburbs or conversion areas of international metropolises. As part of the investigations for this quarter, the effect of improvement measures compared to the usual building standard on the energy demand should be shown and at the same time it should be checked to what extent a climate-neutral energy supply through PV systems on the roofs is possible. The main question of the microclimatic investigations was whether and how much the shadowing can be increased by densifying the building structure and more intensive tree planting and thus improves the microclimate.

2.2.2.3 New building quarter Cologne, Germany

Like the quarter in Madrid, the quarter in Cologne is also a typical metropolitan new-build quarter with multi-storey apartment buildings. Here, too, an attempt is made to positively influence the microclimate by changing the building structure. In contrast to Madrid, however, in addition to the intensification of tree planting, the building structure will be loosened up. Regarding the building investigations, it should be clarified which indoor climate conditions can be achieved in summer without cooling and which sustainable solutions are the most suitable for ensuring optimum comfort.

2.2.2.4 Existing quarter Hamburg, Germany

The quarter in Hamburg is characterized by a perimeter block development with multi-storey existing buildings. As in many existing quarters of German and European cities, the street facades (e.g. for reasons of monument protection) cannot or should not be insulated. Due to the comparatively mild climate, the intense vegetation and, finally, the massive construction of the buildings, this quarter is the least critical of the quarters examined in this project, both in terms of the outside and the indoor climate. The focus of the investigations is therefore to show whether and through which measures comfortable conditions can be achieved in summer. In addition, climate-friendly renovation and energy supply solutions should also be shown for this climate region and this type of quarter. Due to the comparatively low availability of solar radiation, the on-site supply of renewable energies is limited.

2.2.2.5 Densification quarter Frankfurt, Germany

Due to the fact that both existing buildings (with high thermal storage masses and comparatively poor thermal envelope qualities) and new buildings (with low thermal storage masses and good thermal envelope qualities) are present in the model area, a direct comparison of climate resilience and solution approaches for different years of construction and building qualities is possible. An extreme climate (climate forecast 2050[14]) was considered in the calculations, so that climate-resilient solutions with active cooling had to be found for all buildings.

[14] IPCC scenario B1 (+2.8 °C)

2.2.3 Existing quarter Tunis - El Aouina

2.2.3.1 Location and description

Tunisia, with a population of 11 million, has moved towards democracy following the events of the Arab Spring. During this development, a number of measures in the field of sustainable energy and energy efficiency were implemented. This is related to a growing population and the significant dependence on energy imports. In a regional comparison, the country is characterized by the most comprehensive energy efficiency policy and has, for example, adopted an energy efficiency action plan for 2013-2020.

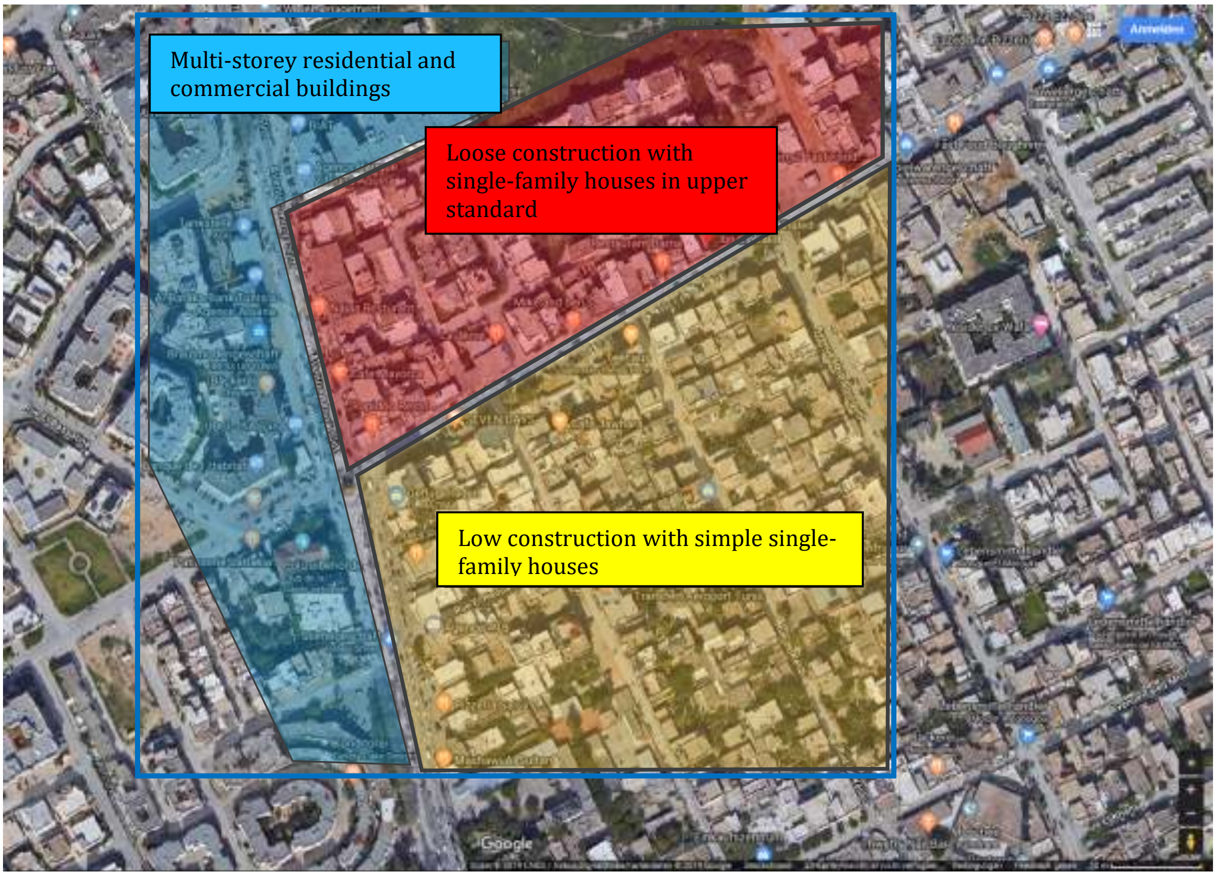
The El Aouina quarter is part of the residential area surrounding Tunis downtown and is close to the airport. The buildings have one to three floors and are mainly occupied by the owners. Many buildings have been and will continue to be raised to accommodate additional family members. Typical is the dense, solid construction with a central, narrow courtyard that is shaded by the surrounding parts of the building. The roof areas have so far hardly been used due to the heat stress and the lack of privacy.

The area contains different relevant building types (simple and upscale single-family homes as well as multi-storey residential and commercial buildings). There are opportunities for greening and shadowing (especially along the main streets and the central square, as well as in the peripheral areas).

Figure 3: Location of the El Aouina quarter in Tunis

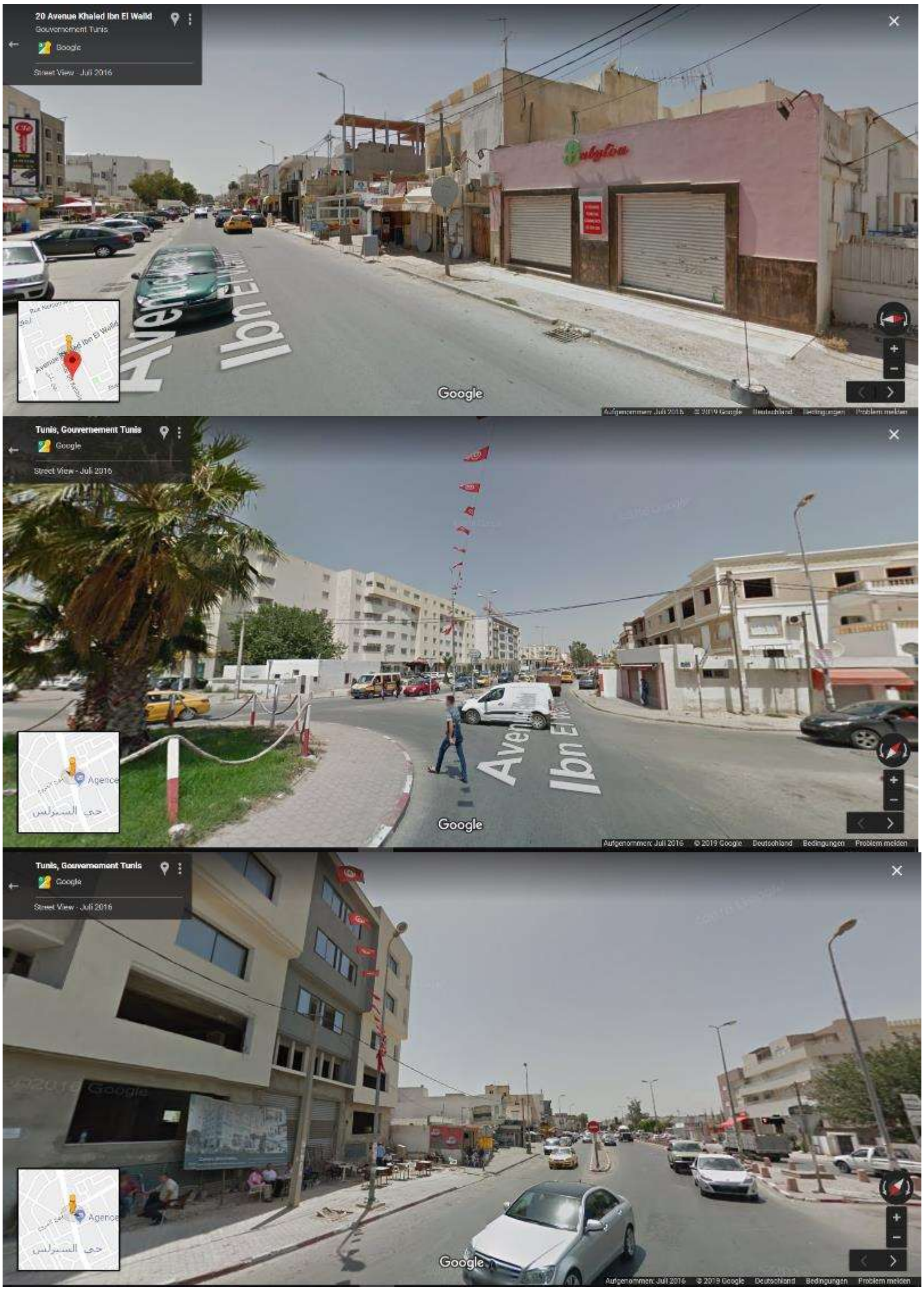
Source: Google

Figure 4: Building types of the El Aouina quarter in Tunis



Source: Own illustration, Guidehouse based on Google (background)

Figure 5: Street views of the quarter - El Aouina in Tunis

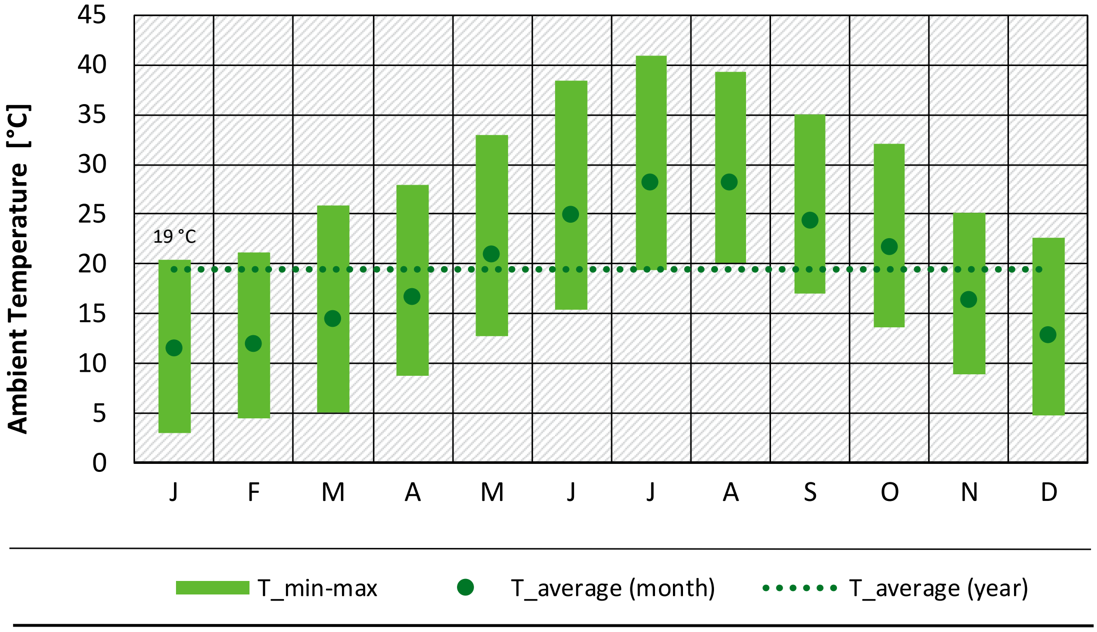


Source: Google

2.2.3.2 Climate

The reference climate data for the Tunis location[15] was used as the basis for the calculations. According to Figure 6, the annual mean value of the ambient temperature is approx. 19 °C. The monthly mean values of the ambient temperature are in the range of approx. 12 °C (January) to 28 °C (July, August). The summer peak values reach over 40 °C.

Figure 6: Monthly ambient temperature Tunis (airport)

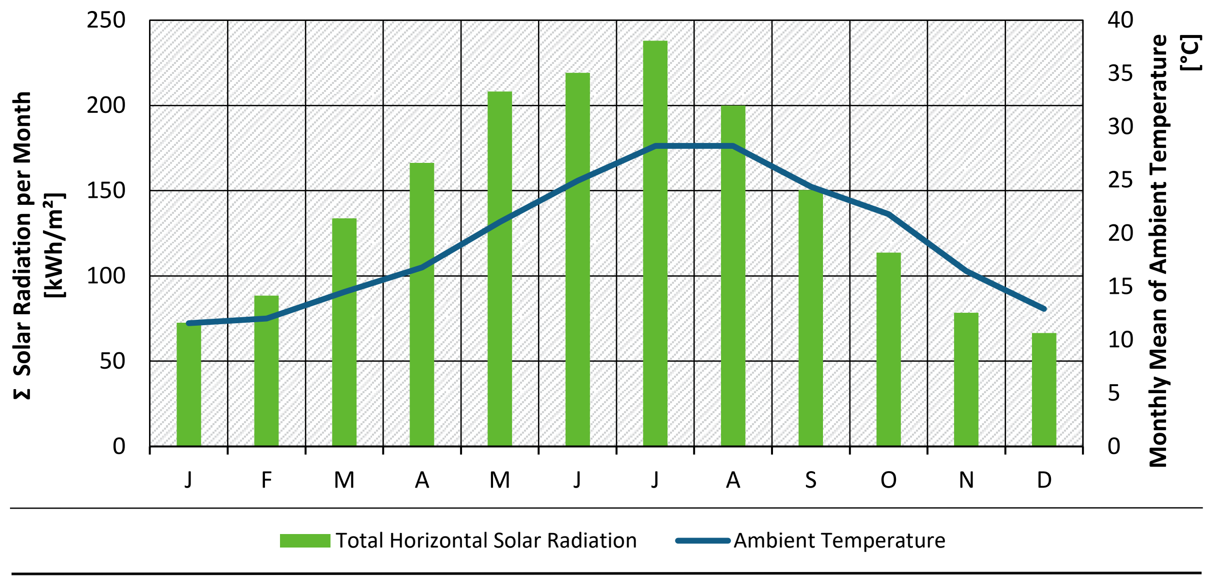


Source: Own illustration, Guidehouse

The annual global radiation total is 1,736 kWh/m^{2}a. It is highest in July with approx. 240 kWh/m^2 and lowest in December with approx. 70 kWh/m^2.

[15]Source: Meteonorm software , version 7, most recent weather data set (period 2000-2009)

Figure 7: Monthly values of global radiation and outside temperature Tunis (airport)



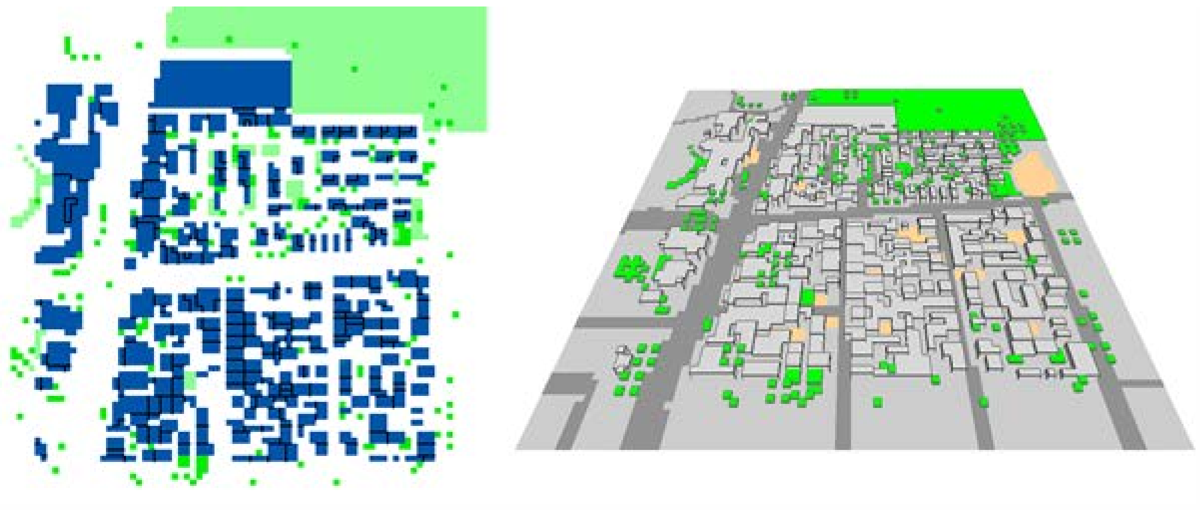
Source: Own illustration, Guidehouse

2.2.3.3 Microclimate simulation

2.2.3.3.1 Variant current state

The division of the area was realistically mapped in the microclimate model ENVI_MET with three different building types (see Figure 8). The building density and general urban structure were taken from the aerial photographs and implemented with standardized building types. The Northeastern area with upscale single-family houses has a much lower building density than the area with simple family houses in the southeast. With increasing distance to the main roads of the area, the building density increases and the vegetation density decreases.

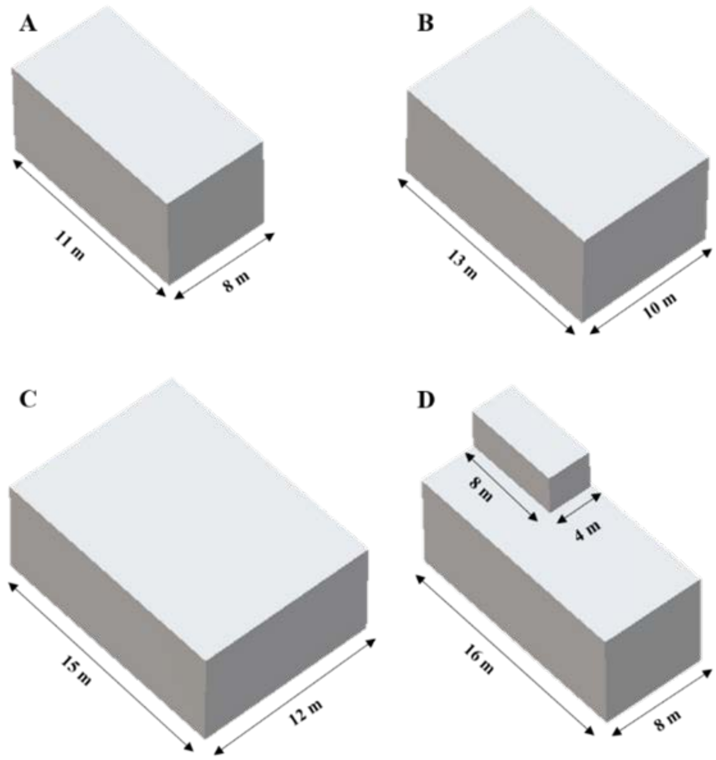
Figure 8: Model area of the El Aouina quarter (status quo) in Tunis as top view and 3D view



Source: Own illustration, ENVI_MET

To ensure a general applicability of the results to other areas in the MENA region, the building geometries were standardized (Figure 9). The areas marked in yellow in Figure 4 were digitized with building types A to C at two different heights (6 m and 9 m). Type D applies to the more upscale area marked in red in Figure 4. The area marked in blue in Figure 4 and the residential buildings directly bordering the main streets have been digitized according to reality.

Figure 9: Standardized building geometries



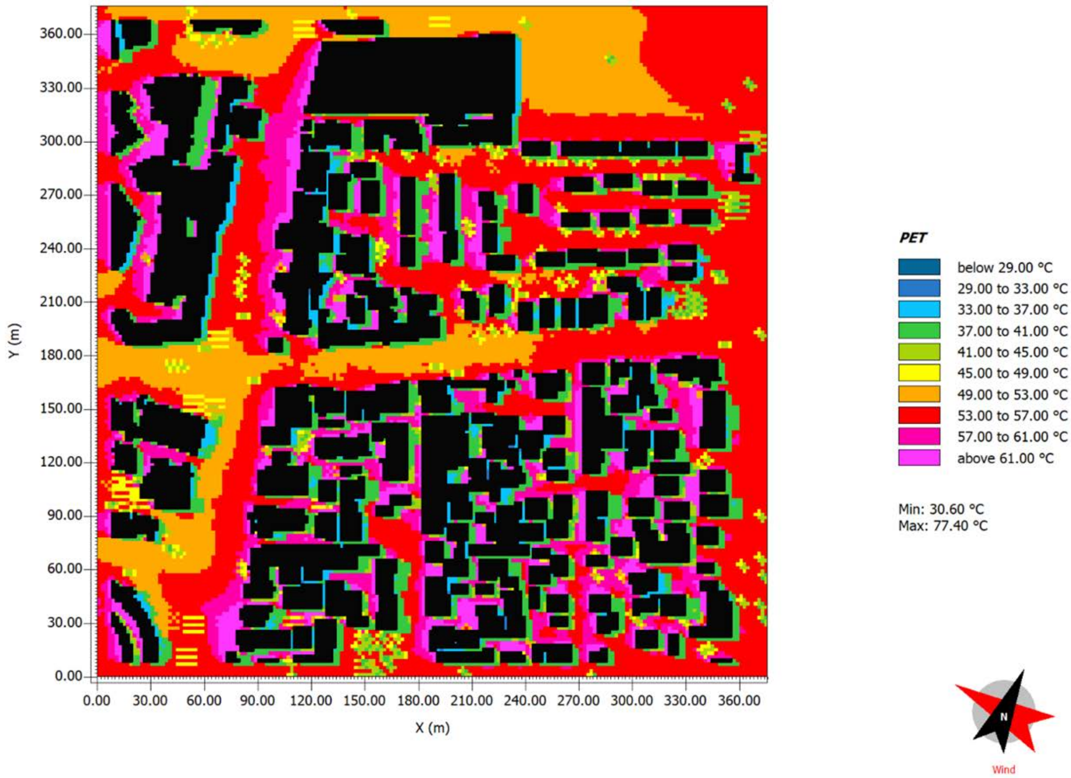
Source: Own illustration, ENVI_MET

2.2.3.3.2 Results of current microclimate simulations

Based on the annual overviews in Appendix A.3 (Panel_1_a_Tunis_SQ) and the detailed simulations (Panel_1_c_Tunis_Detail), it can be seen that the areas with the consistently highest warming compared to the rest of the area can be found along the main streets, the central square and within the elevated area . This can be explained by the fact that, in contrast to the lower standard areas, there is a high sky view factor (proportion of the area of the sky that is visible from one point) and thus the high level of solar radiation. Since more radiation can reach street level, the heating of the surfaces and thus the air is comparatively higher.

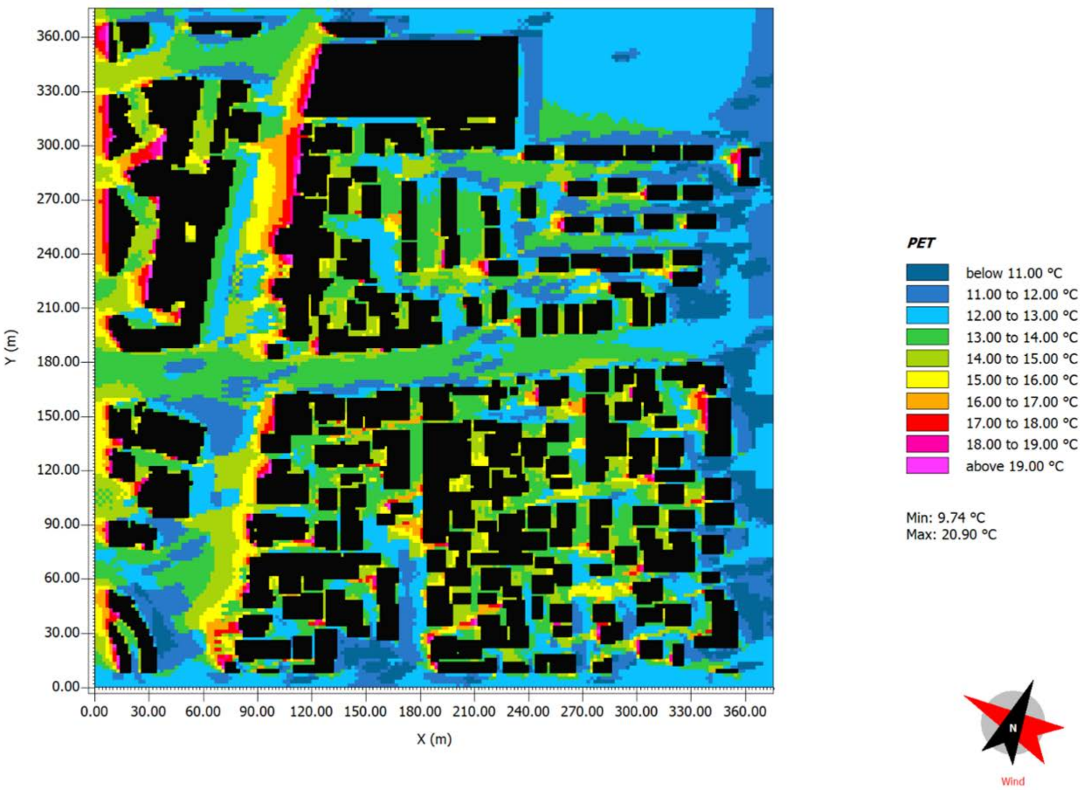
Figure 10 shows the distribution of the PET value on July 22 at 4:00 p.m. In addition to the distribution of the air temperature, the influence of the short-wave solar radiation on the temperature perception can be observed here. As it can clearly be seen in the figure, the reflection behaviour of the building facades also has an influence on the thermal perception of pedestrians. Especially in the vicinity of west-facing facades, the thermal load caused by light-coloured facades can be higher than with darker building surfaces.

Figure 10: Distribution of the PET value in Tunis on July 22 at 4:00 p.m. for the status quo



Source: Own illustration, ENVI_MET

Figure 11: Distribution of the PET value in Tunis on January 14 at 4:00 p.m. for the status quo



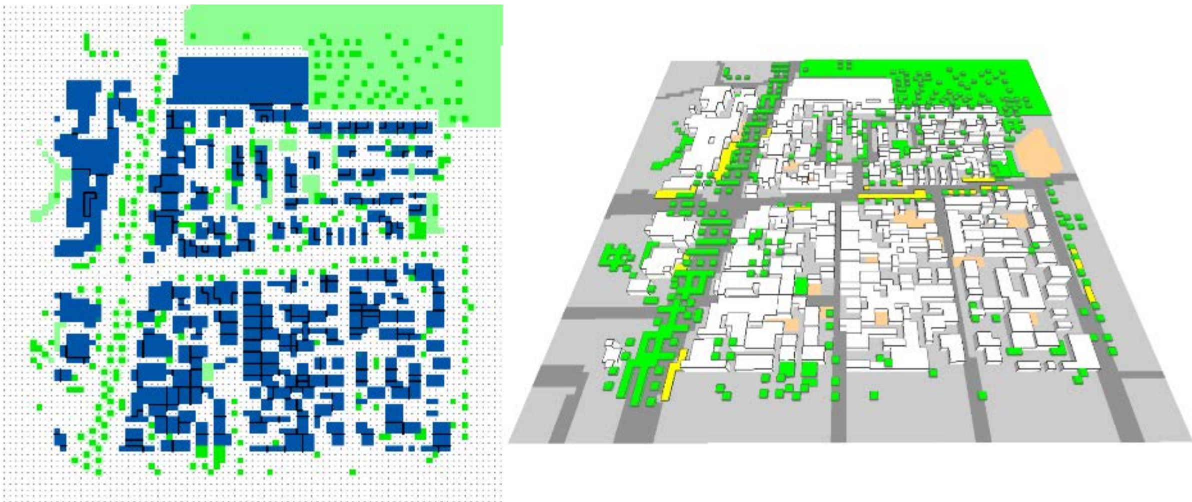
Source: Own illustration, ENVI_MET

Figure 11 shows the distribution of the PET value in January. All areas are in the thermally comfortable, sometimes slightly cool area. On the western street, a differentiation can still be seen between the areas with the still sunlit facades and the shaded side of the street.

2.2.3.3.3 Optimised variant

The planned measures for the optimised variant were developed based on the results of the current situation. For this purpose, trees typical of the country were integrated along the main roads to simulate higher shadowing and a possible cooling effect of the trees. Furthermore, shadowing elements (yellow in Figure 12) were installed where densification of the vegetation was not possible due to the proximity to buildings.

Figure 12: Model area of the optimised variant as top view and 3D view



Source: Own illustration, ENVI_MET

Another adjustment to improve the energy balance of the simulation area is the adjustment of material properties. To ensure the least possible intervention in the existing structural conditions, these were limited to an adaptation of the paintwork. Since the walls of the buildings are already light and thus the warming of the materials is kept low by a high degree of reflection, this measure was applied to the roofs.

2.2.3.3.4 Results of microclimate simulations optimised variant

Panel_1_b_Tunis_OPT and Panel_1_c_Tunis_Detail in Appendix A.3 show the air temperature changes caused by the changes over the course of the year (Panel_1_b_Tunis_OPT) and for the detailed simulations (Panel_1_c_Tunis_Detail). Negative values mean a reduction in air temperature compared to the reference condition.

The absolute reductions vary throughout the year and throughout the day. In winter, the effects are naturally rather small, since the angle of the sun is small and the initial temperatures are also relatively low.

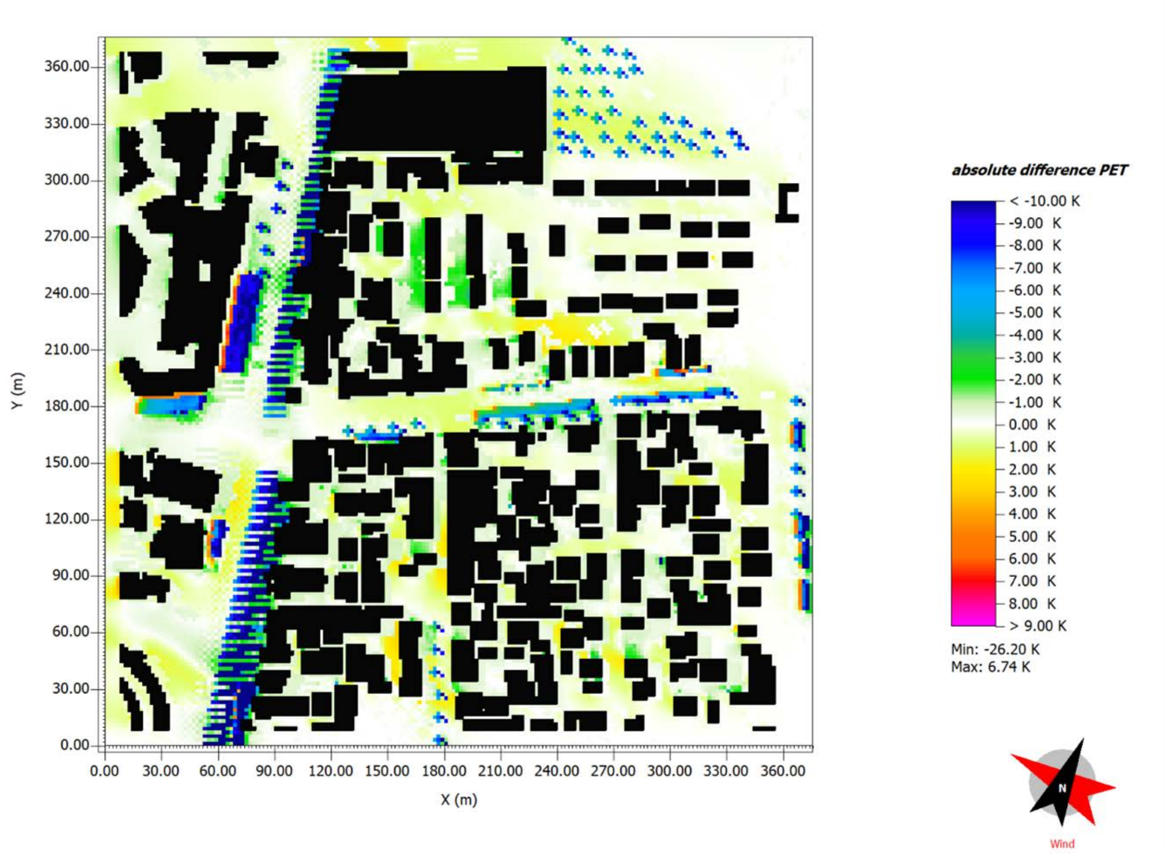
On the spring-, summer- and autumn days, on the other hand, an areal reduction in air temperature by 1 K and more can be observed, with the effect of the wind building up as it passes through the model area and the maximum effect being observed in the lee of the model area.

During the night hours, slightly higher air temperatures can be observed locally. These warmer regions are where the shadowing elements have been placed. During the night, the heat accumulates a little under the elements and cannot escape upwards, which leads to higher temperatures of a maximum of +0.14 K in these areas in contrast to the initial situation (SQ simulation).

Figure 13 shows the change in the PET value at 4 p.m. due to the optimization measures.

Additional shadowing zones are particularly noticeable in the distribution of PET, since the absence of direct solar radiation immediately reduces the perception of heat and the PET value falls by 10 K and more as a result. However, it must be considered that the PET represents the static thermal perception. In particular, the small-scale structures that can be observed are only relevant if they bring about a change in the microclimatological conditions over a longer period or have an effect on moving people again and again.

Figure 13: Change in the PET value in Tunis on July 22 at 2:00 p.m. duet to the optimization measures



Source: Own illustration, ENVI_MET

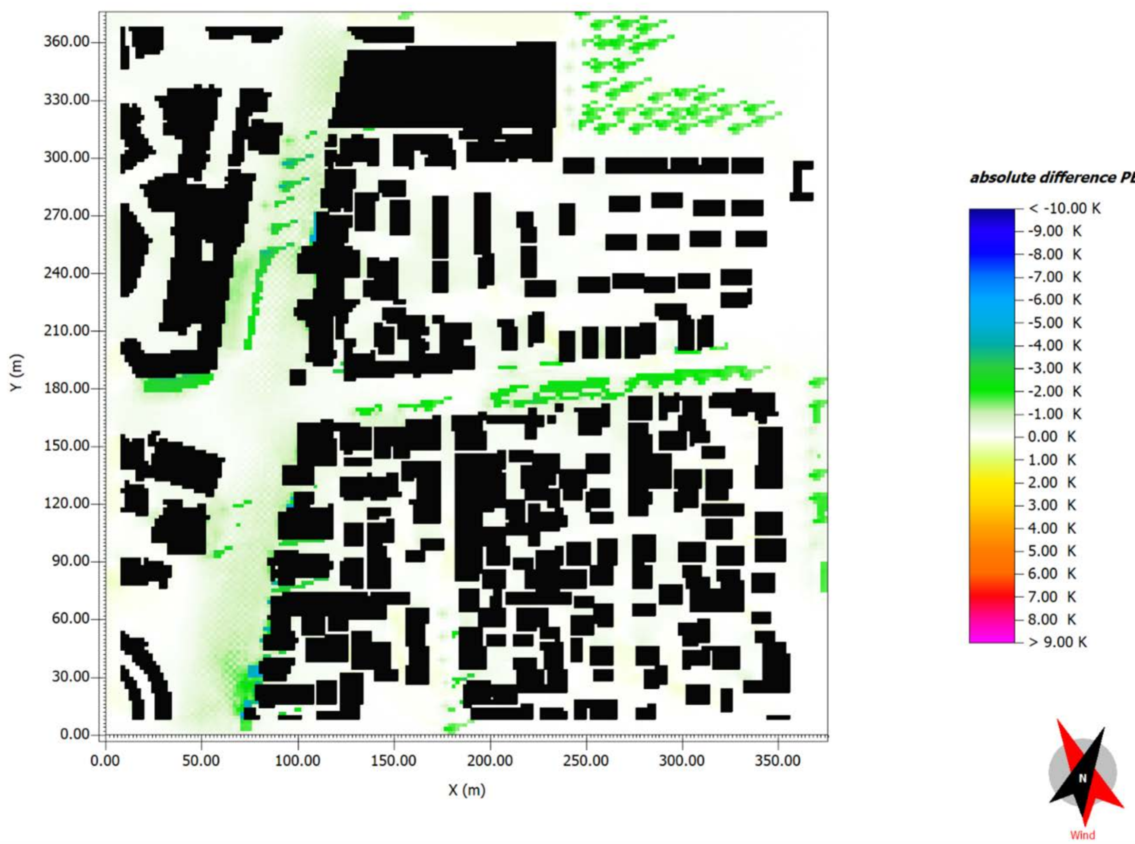
Under this premise, continuous rows of trees like the one in the road running North-South is an important element for reducing thermal loads.

Another factor in determining the thermal load is the local wind speed. Although this factor does not dominate the perception of heat as much as short-wave radiation, it can improve thermal comfort, especially in the case of high heat loads.

In Panel_1_c_Tunis_Detail in Appendix A.3, the wind vectors and the local wind speed are shown in the top figures. Especially in the afternoon hours, the local wind speeds are low with a westerly or easterly flow in the North-South running streets and thus further increase the thermal stress caused by the sun.

An improvement in ventilation is only possible through invasive measures (removal of buildings) and is excluded from this study as an instrument.

Figure 14: Change in the PET value in Tunis on January 14 at 4:00 p.m. due to the optimization measures



Source: Own illustration, ENVI_MET

Figure 14 shows the changes in the PET distribution for January. There are only small changes here, which are mainly due to the shadows cast by the newly added trees.

2.2.3.3.5 Summary assessment

Based on the microclimate simulations, the optimization measures can be used to achieve improvements in both air temperature and thermal comfort (PET), which lead to increased comfort when staying outside.

The optimizations examined can therefore be seen as sensible measures to improve the thermal comfort in the outdoor space of the MENA region, also when planning a new quarter. Overall, a reduction in the incidence of radiation and an increase in the latent heat flow (evaporation of water) are considered suitable measures in dry, hot climates.

In areas with high levels of solar radiation, however, conflicting measures can arise between ones that are favourable for the outside area and those that are favourable for the energy balance of the building. This includes, above all, the use of light-coloured building materials. Although the energy input into the building is reduced due to the increased reflection of the radiation, at the same time the energy input into the street system and onto people in the street space increases due to multiple reflections. In these cases, alternative measures such as facade greening should be examined.

2.2.3.4 Building simulation

2.2.3.4.1 The simulation model

There are many different buildings in the study area. To reduce the number of individual buildings to be modelled to a manageable level, they were first classified. A reference building type was then defined for the class. A reference building type is a standardized building or part of a building which in geometry, building physics and use represents a number of similar buildings.

The essential characteristic values of the reference building types derived for the quarter are listed in Table 11.

Table 11: Reference building types in Tunis

No.	Type	Net floor area	Floors	Window area	Area (external) facade + roof	Air change [1/h]
1	Two-family house	260 sqm	2	26.4 sqm	406 sqm[16]	0.4 (infiltration) 1.0 (night ventilation)
2	Retail trade	65 m²	1	12.2 sqm	39 m²	0.4 (infiltration) 5.0 (daytime)
3	Flats in apartment blocks	4x75 m²	2	8.8 m²	120 / 250 m²[17]	0.4 (infiltration) 1.0 (night ventilation)

In addition to the geometry, building physics and type of use, solar radiation and the local ambient temperature are the main influencing factors on the thermal behaviour of the building. Both the solar radiation and the local ambient temperature are largely determined by the location of the building (either free-standing, e.g., on a street or open space, or built-in into the quarter).

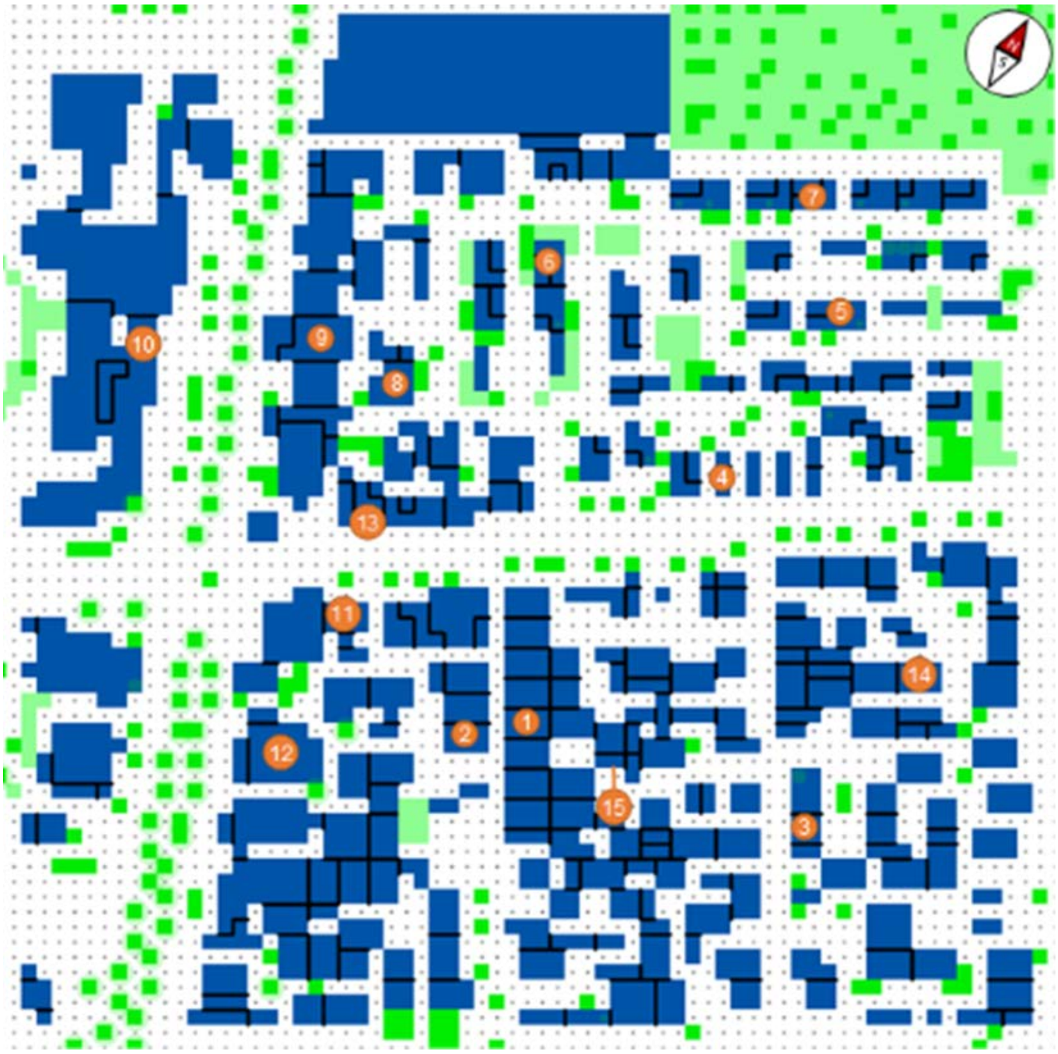
Therefore, site-specific reference buildings were developed based on the three reference building types mentioned above, which consider the individual local conditions.

A reference building is a standardized building or part of a building that represents a number of similar buildings in terms of geometry, building physics, use and location.

Figure 15 shows the location of the 15 selected reference buildings.

[16] basic geometry; when the building is attached, the area is reduced accordingly.
[17] Apartment in block / top floor apartment

Figure 15: Selection of the reference buildings based on the digitized building structures

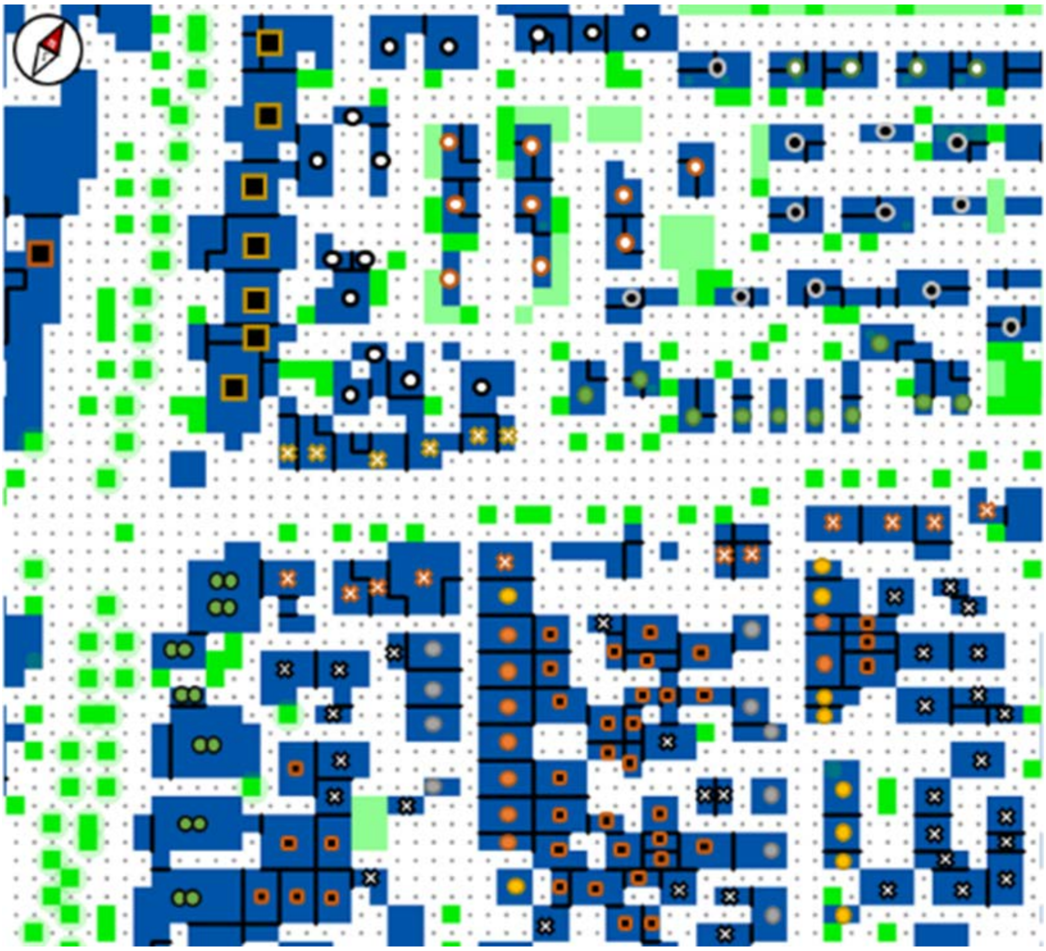


Source: Own illustration, Guidehouse and ENVI_MET

The following Figure 16 shows the selected assignment of the 15 reference buildings to the buildings in the study area.

Each reference building is marked with a different symbol.

Figure 16: Assignment of the reference buildings to the digitized buildings



Source: Own illustration, Guidehouse and ENVI_MET

The assignment of numbers and symbols as well as a description of the characteristics and the number of individual buildings represented by the reference building can be found in Figure 17 below.

Figure 17: Overview of the assignment of numbers and symbols including a description of the characteristics[18]

1) Street West (enclosed) – 9
2) Street East- 10
3) Street West (2-bound) - 10
4) Street South (upper) - 9
5) Block (upper, EW) - 7
6) Block (upper, NS) - 9
7) Park North - 4
8) Block North - 15
9) Main street WN (incl. 1 apartment, 1 shop ground floor) - 7
10) Main street East (incl. 1 top floor, 1 middle, 1 shop ground floor) - 1
11) Main street North - 11
12) Main street WS - 7
13) Main street South - 6
14) Block South (free) - 33
15) Block south (enclosed) - 37

The numbers indicate the number of individual buildings represented by the reference building

Source: Own illustration, Guidehouse

2.2.3.4.2 Variants

2.2.3.4.2.1 Status quo

The current state is described by the status quo scenario. The results of the corresponding scenario of the microclimate simulations were used as the basis for the thermal calculations. It was also assumed that the buildings are only partially heated according to local custom in winter, i.e. that only 50% of the building area is heated to at least 20°C in winter.

Regarding the air conditioning, a differentiated analysis was carried out. This should consider the current situation, according to which the vast majority of buildings are not air-conditioned. In the future, however, it can be expected that the proportion of air-conditioned areas in residential buildings will increase significantly. Therefore, two variants were defined in this regard (see Table 12).

Table 12: Definition of the variants – status quo (SQ)

Status quo	SQ1 (no cooling)	SQ2 (with cooling)
Cooling setpoint (T_{set})	-	2 rooms (24°C)
Heating setpoint (T_{set})	2 rooms (20°C)	2 rooms (20°C)
Cooling system	-	Split AC device (low efficiency)
Heat generator	Gas ovens	Gas ovens

2.2.3.4.2.2 Optimization

The results of the corresponding microclimate simulation scenario were used as the basis for the variants in the optimised quarter described below. The optimised quarter is to be examined with regard to three essential aspects:

1. Improvement of the indoor thermal comfort,

[18] For the multi-storey reference buildings (Nos. 9 and 10), further subtypes were taken into account, depending on the location of the apartments in the building (with or without attic or ground floor).

2. Reduction of energy demand and
3. Transformation to a climate-neutral quarter.

Six variants were defined for this, of which the main parameters are summarized in Table 13. The parameters of the first two variants correspond to the calculations with the status quo. Based on these variants, the influence of the improved microclimate on the optimised variant is to be shown. The following variants (Opt3 to Opt6) examined the path towards a climate-neutral energy supply through constant improvement of technology and the use of renewable energies. The step-by-step adjustment allows the effect of individual measures to be assessed separately.

Table 13: Definition of the scenarios – optimised quarter

Variant	opt1	Opt2	Opt3	Opt4	opt5	Opt6
Designation	None cooling gas	D 24 gas	D 24 fully electric	A++ 24 fully electric	A++ 26 fully electric	A++ 26 PV + battery
Cooling (T_{set})	-	2 rooms (24°C)	2 rooms (24°C)	2 rooms (24°C)	2 rooms (26°C)	2 rooms (26°C)
Heating (T_{set})	2 rooms (20°C)	2 rooms (20 °C)	2 rooms (20°C)	2 rooms (20°C)	2 rooms (20°C)	2 rooms (20°C)
Cooling	-	Split devices (low efficiency)	Reversible split devices (low efficiency)	Reversible split units (refrigerant R290[19], high efficiency)	Reversible split units (refrigerant R290, high efficiency)	Reversible split units (refrigerant R290, high efficiency)
Heat generator	Gas ovens	Gas ovens	Reversible split device see above	Reversible air conditioners see above	Reversible air conditioners see above	Reversible air conditioners see above
Hot water preparation	Gas flow-heater	Gas flow-heater	Electric instantaneous water heater	Electric instantaneous water heater	Electric instantaneous water heater	Electric instantaneous water heater
Renewable energies	-	-	-	-	-	PV with battery[20]

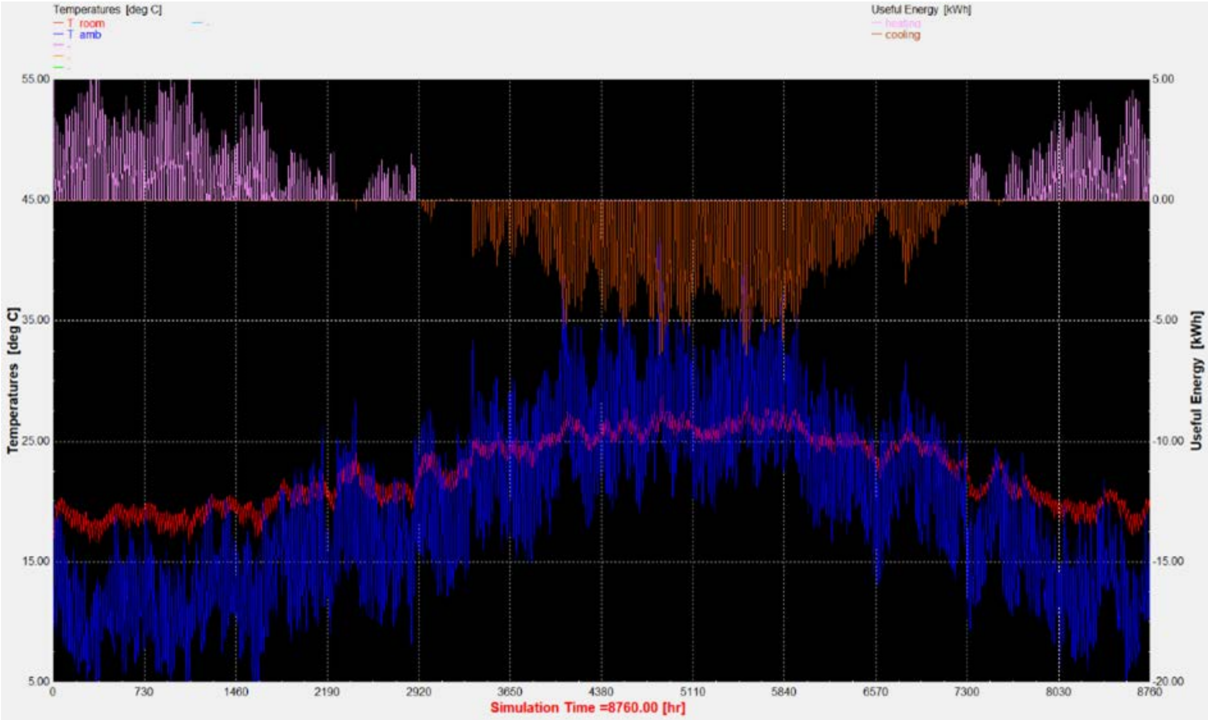
2.2.3.4.3 Results

2.2.3.4.3.1 Status quo

A complete year thermal simulation with hourly resolution was carried out for each of the 15 (18 incl. subtypes) reference buildings and each variant. The heating and cooling energy demands and the resulting temperatures in the individual rooms were calculated. Figure 18 shows an example graphic of the main results of such a simulation. According to this, heating is required in the months from November to April and cooling is required in the remaining months.

[19] Split air conditioners with natural refrigerants are currently only available in a few countries (status October 2021). However, it can be assumed in the medium term that worldwide availability will improve. In Germany, devices have already been awarded the Blue Angel for air conditioning devices.
[20] Dimensioning according to the requirement to achieve climate neutrality => see results

Figure 18: Graphic of the results of the building simulation

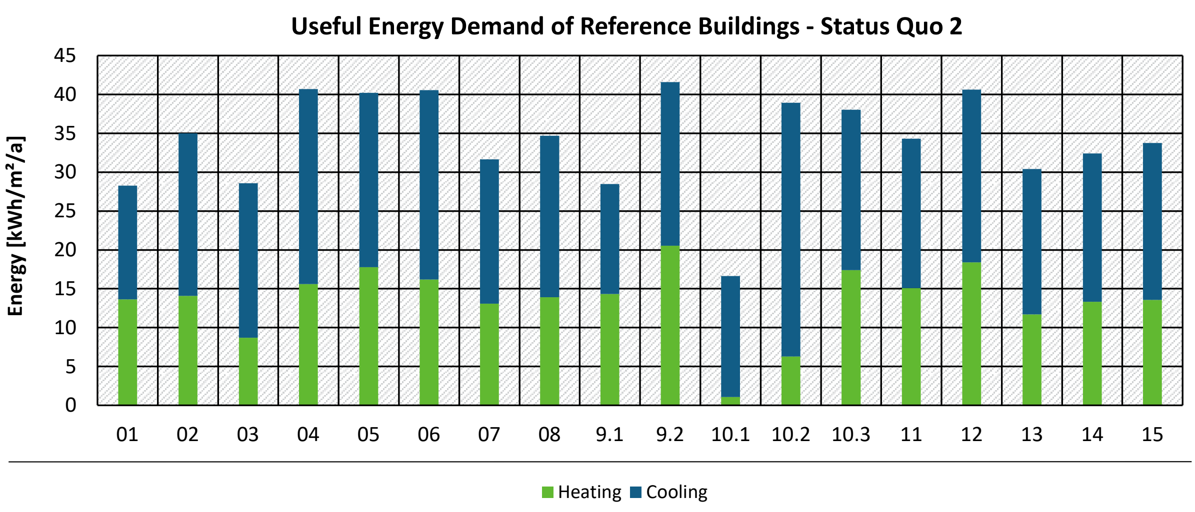


Building location type 02 in the Status Quo 2 scenario (SQ2, with air conditioning); Heat demand (pink bars), cooling energy demand (orange bars), outside temperature (blue line), mean room temperature (red line).

Source: Own representation, Guidehouse (screenshot TRNSYS simulation window)

The results of the calculated useful energy demand (heating + cooling) for all reference buildings in the Status Quo 2 (SQ2) scenario are shown in Figure 19 as specific values per m^2 of floorspace. The annual energy demands in the quarter examined range between 17 kWh/m^2 for apartments (see reference building 10.1) and up to 42 kWh/m^2 for retail shops (see reference building 9.2). The cooling energy demand easily outweighs the heating energy demand.

Figure 19: Useful energy demand of all examined reference buildings of the Status Quo 2 variant

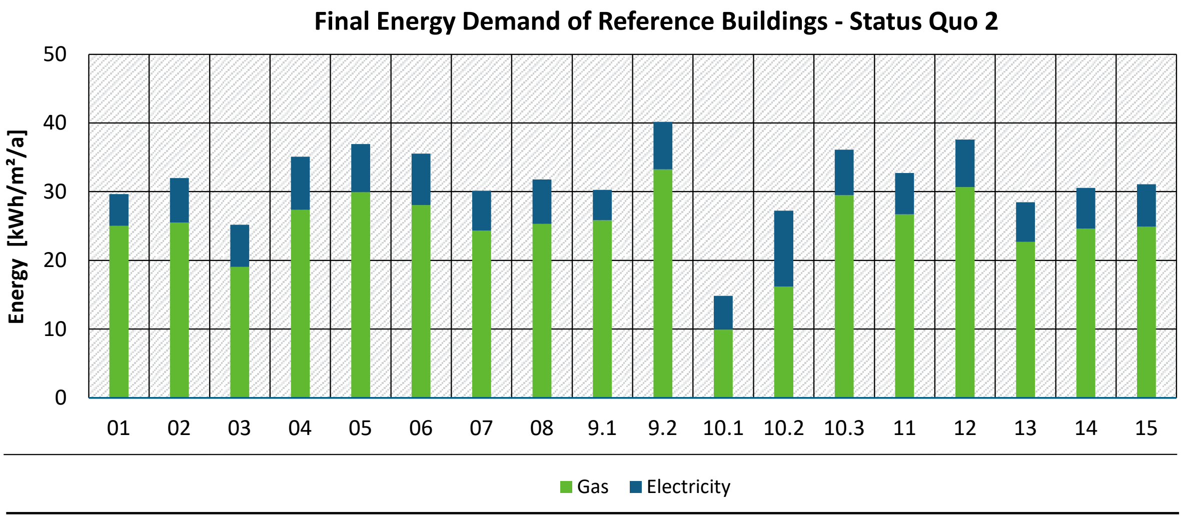


Source: Own illustration, Guidehouse

The retail stores (reference buildings 9.2 and 10.2) have the highest useful energy demand, mainly due to the higher air exchange rate. They are also located on the North-South main road, on which other reference buildings with high useful energy demands for cooling (10.3, 12) are also located. An exception to this is reference building 10.1, which is a ground floor apartment. In addition, it can be observed that the buildings in the Northwestern area (reference buildings 4, 5, 6) also require a relatively large amount of useful energy, especially for cooling.

Figure 20 shows the final energy demand broken down by the energy sources electricity and gas. On the one hand, due to the additionally calculated need for hot water preparation, but also due to the generator expenditure numbers[21], a different picture emerges for the final energy demand: The gas requirement (final energy demand for heating and hot water) clearly predominates in this analysis.

Figure 20: Final energy demand of the reference building for heating, hot water and cooling of the Status Quo 2 variant



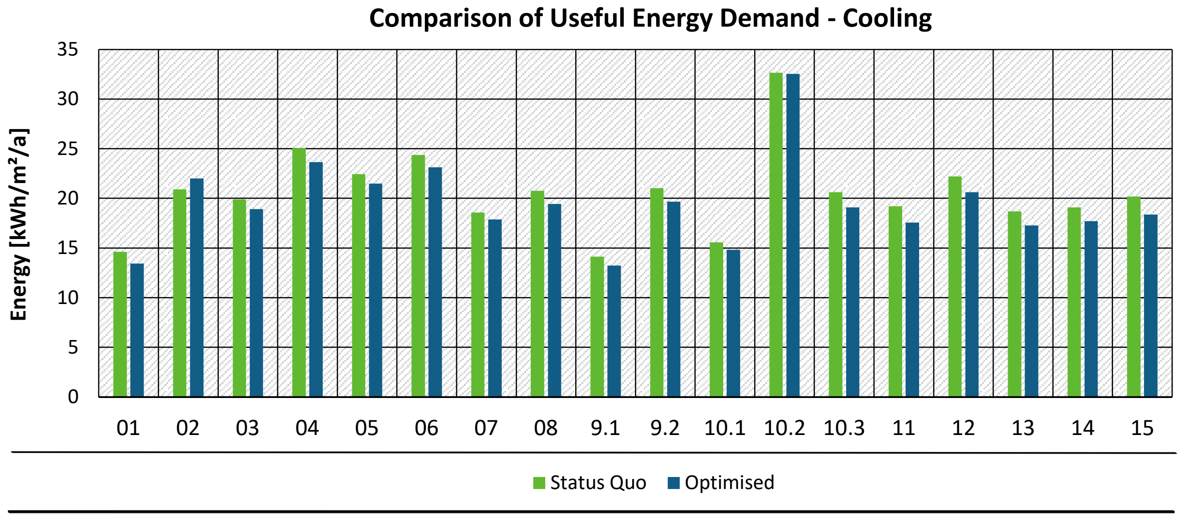
Source: Own illustration, Guidehouse

2.2.3.4.3.2 Optimised quarters

By implementing the measures in the quarter to contain the heat island effect, a reduction in the cooling energy demand is achieved. Figure 21 shows that the useful energy demand for cooling decreases in almost all reference buildings. The average reduction across the reference buildings is around 5%.

[21]Generator expenditure numbers: Ratio of final energy to useful heat or cold. This is 1.2 for gas and approx. 0.3 for air conditioning (powered by electricity; an hourly EER value dependent on the current operating conditions was calculated by the model).

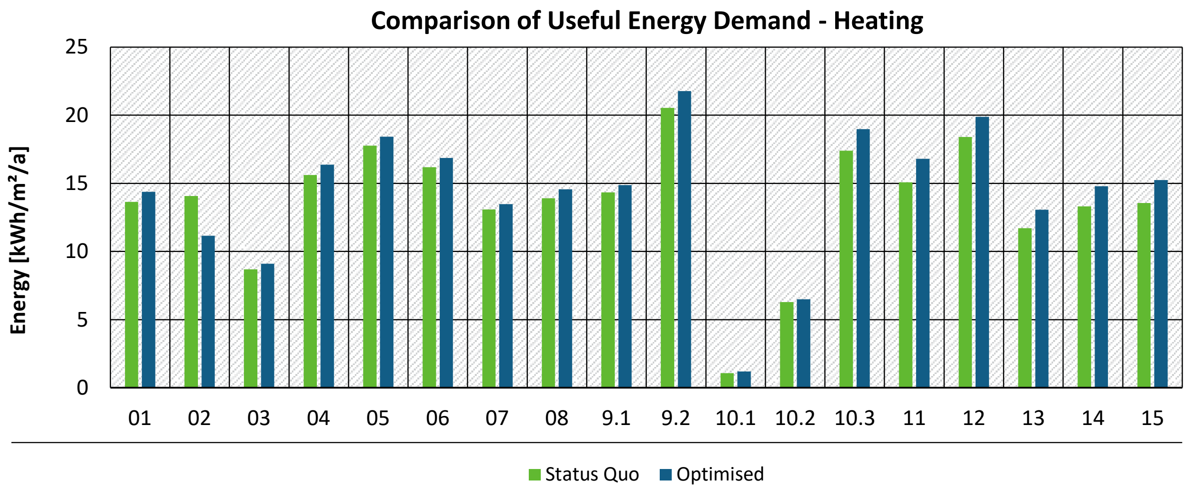
Figure 21: Comparison of the cooling energy demands of the Status Quo (SQ2) and Optimised (Opt2) scenarios



Source: Own illustration, Guidehouse

At the same time, according to Figure 22, it can also be observed that the average heating energy demand increases to the same extent.

Figure 22: Comparison of the heating energy demands of the Status Quo (SQ2) and Optimised (Opt2) scenarios

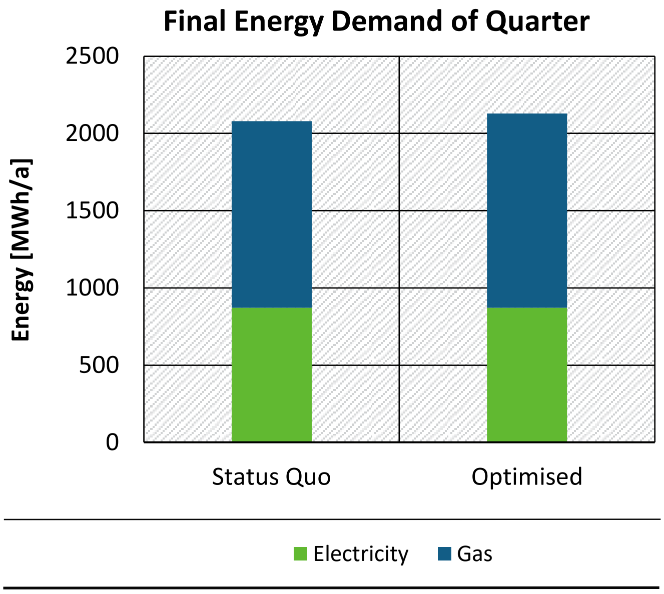


Source: Own illustration, Guidehouse

Considering the frequencies of the individual reference buildings in the quarter (see Figure 16) and the generator expenditure numbers, it can be observed that in the optimised quarter approx. 1% [22] more final energy is required over the year (see Figure 23).

[22] including household electricity requirements

Figure 23: Comparison of final energy consumption (incl. heating, cooling, hot water and household electricity requirements[23]) of the Status Quo (SQ2) and Optimised (Opt2) scenarios



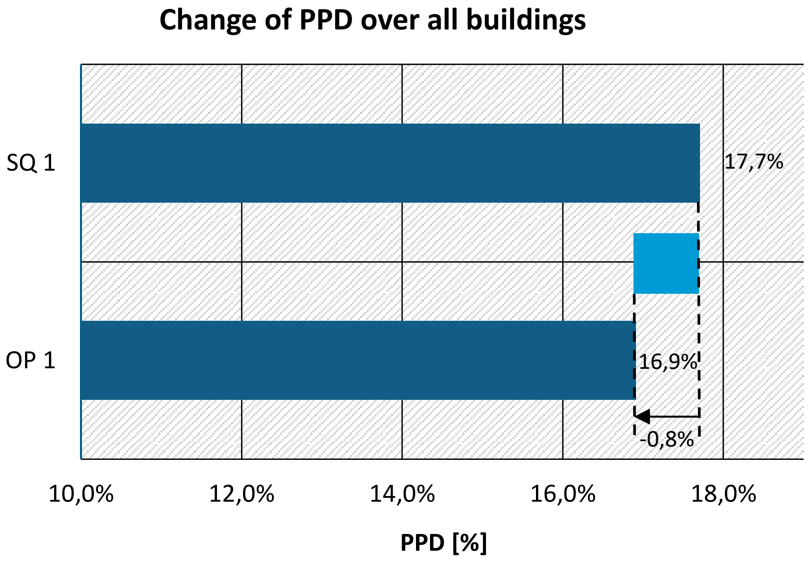
Source: Own illustration, Guidehouse

In addition to the energetic aspects, the thermal comfort must also be considered. This is particularly important given that most of the apartments in the quarter are not yet air-conditioned. The so-called PPD[24] value is used to quantify thermal comfort. This quantifies the proportion of people who find the prevailing room climate statistically uncomfortable. The scenarios without cooling (variants SQ1 and Opt1) were used for this analysis. The retail stores (9.2, 10.2) were not considered in this evaluation, as it can be assumed that those are always cooled.

Figure 24 shows the mean values of the PPD in the interior spaces over the period of use and all buildings in the quarter, as well as its change, which is achieved through the optimization measures in the quarter. On average, the PPD in the buildings in the optimised quarter improves by 0.8 percentage points compared to the status quo. Overall, however, the proportion of dissatisfied people of around 17% can be classified as very high.

[23] A specific household electricity requirement of 18 kWh/m^2 was assumed (e.g. 4,680 kWh for the 260 m^2 two-family houses). In relation to German conditions, this value can be classified as rather low.
[24] Predicted Percentage of Dissatisfied according to DIN EN ISO 7730

Figure 24: Average change in the PPD factor after the optimization measures in the quarter (variant Opt1, without cooling)



Source: Own illustration, Guidehouse

2.2.3.4.3.3 Optimised scenario

In the following, it is to be examined to what extent a climate-neutral supply of the buildings in the quarter is possible and through which measures this could be implemented in concrete terms.

Photovoltaic on the roofs is considered as the available renewable energy source on site. To be able to use PV electricity to supply the building, the heating and hot water supply must be operated electrically. For this reason, the four fully electric variants listed in Table 13 were defined. Such a conversion is considered feasible from both a technical and financial perspective. Cooling was also considered in all scenarios in order to take into account the likely future increase in comfort requirements. Other measures such as improved insulation, were not taken into account, since the relationship between effort and benefit was assessed as insufficient or impractical.

Reversible air conditioning units for heating and cooling were considered for the all-electric variants, as well as an electric instantaneous water heater for hot water preparation. The path to climate neutrality should be achieved on the one hand by efficiency and sufficiency measures and on the other hand by covering the remaining energy consumption with PV. Based on variant D24 (Opt3), a highly efficient heating and cooling device (variant Opt4: A++ 24) was initially used as efficiency measures, and as a sufficiency measure, an adjustment of the cooling temperature from 24°C to 26°C (variant Opt5: A++ 26) considered[25].

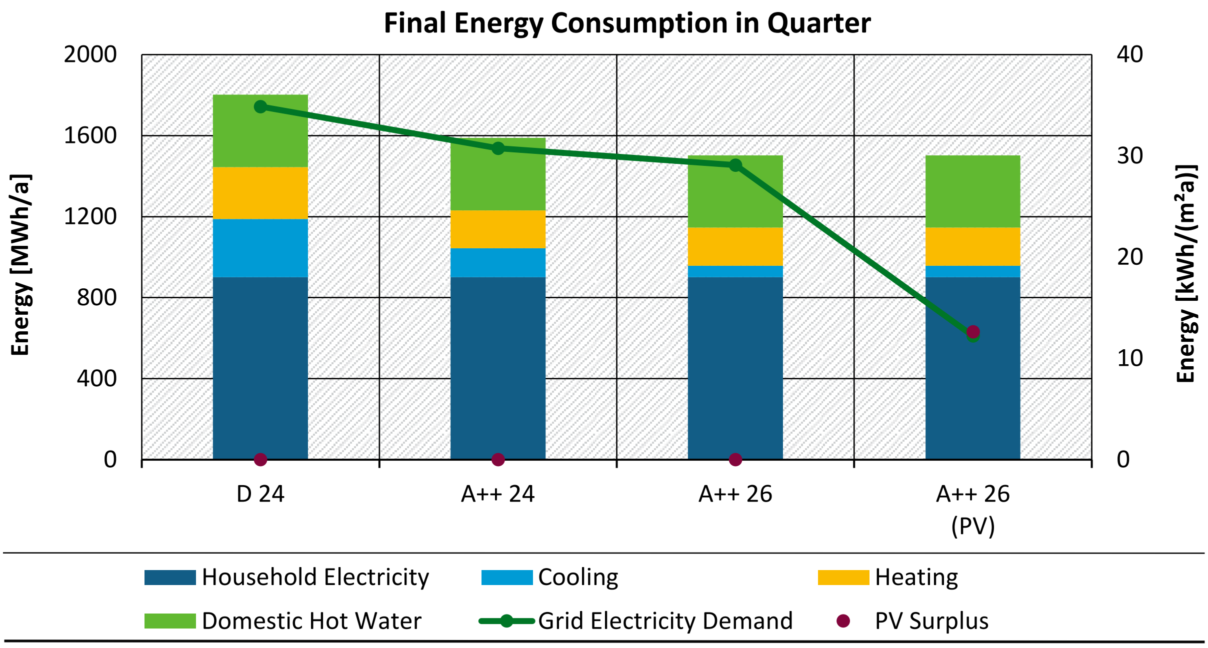
Under the above conditions and a suitable dimensioning of PV and battery storage (see variant Opt6: A++ 26 PV), it is possible that over 90% of the heating, cooling and hot water requirements are covered directly by the own energy generation [26]. The output of the PV systems can be designed in such a way that enough electricity is produced in the annual balance to supply the examined quarter with heating and cooling energy and at the same time to cover

[25] This measure makes sense, but is not necessary, as can be seen from the figure.

[26] A 100% direct self-coverage of the electricity requirement would be technically possible but would mean a disproportionate additional investment in generation and storage capacity. The economically achievable share of coverage, including household electricity, is around 50%.

the household electricity demand and the electricity demands of the retail trade. On average, there is a PV system with 4 kWp and a battery with 6 kWh per residential unit storage capacity required [27]. The final energy consumption (electricity) of the corresponding optimised variants is shown in Figure 25.

Figure 25: Transformation to a climate-neutral quarter: specific final energy consumption (electricity) of the quarter



Graphics of the final energy consumption by application (bar) as well as the total resulting electricity demand from the grid (incl. PV feed-in, green line) and the excess PV generation (red dots).

Source: Own illustration, Guidehouse

The Figure shows that the final energy consumption (electricity) of approx. 1,800 MWh/a (approx. 35 kWh/m^{2}a) in the all-electric initial case 'D24' has been reduced to approx. 1,500 MWh/a (approx. 30 kWh /m^{2}a). It can be further reduced to around 600 MWh/a (around 11 kWh/m^{2}a) thanks to the local rooftop PV systems and battery storage. This remaining energy demand corresponds to the surplus of the PV systems in summer, so that the annual demand is balanced. In order to be able to guarantee a climate-neutral power supply at all times, further measures are required, but these must go beyond the quarter level (e.g., seasonal electricity storage concepts such as power to gas to power or wind turbines). However, the proposed measures for the buildings in the quarter can make an important contribution to the decarbonisation of the Tunisian electricity grid, whose emission factor was 447 g/kWh in 2019 (Irena 2021).

2.2.3.4.3.4 Summary assessment

The measures considered to reduce the heat island effect in the quarter have a small but measurable positive influence on the indoor comfort in the buildings if there is no cooling. Regarding energy aspects, the slight reduction in the cooling energy demand is neutralized by the slight increase in the heating energy demand.

[27] For the blocks of houses with several apartments and shops, only 2 kWp per apartment was assumed, taking into account the limited roof areas.

A climate-neutral supply of the building, at least on an annual basis, is possible through appropriate conversions to reversible instead of cooling only split air conditioning units and electric hot water preparation as well as the provision of PV on the roofs and battery storage. To avoid direct greenhouse gas emissions, air conditioning systems with natural refrigerants must be used for the conversion.

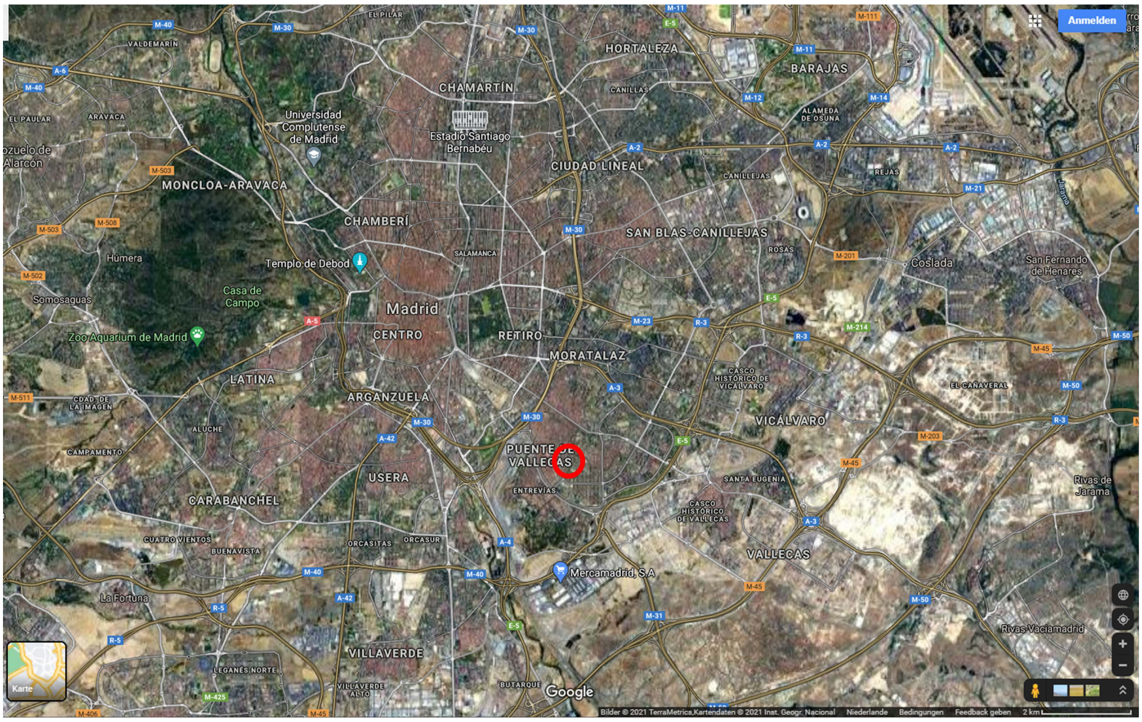
The efficiency and sufficiency measures described make economic and ecological sense and are ensuring an annual climate-neutral supply. Due to the high proportion of self-use of the generated PV electricity, the electricity requirement (including household electricity) can be reduced by two thirds to 11 kWh/m^{2}a, and thus make an important contribution to the decarbonisation of the Tunisian electricity grid.

2.2.4 New building quarter *Ecobarrio San Francisco Javier y Nuestra Sra. de los Angeles* in Madrid

2.2.4.1 Location and description

The new development *Ecobarrio San Francisco Javier y Nuestra Sra. de los Ángeles* is located about 4 km southeast of the centre of Madrid and is intended to replace an existing area that was built in the late 1960s. The project is being realised based on urban planning with the help of public funding. The quarter is to be supplied with heat via district heating, which is generated using biogas from municipal waste.

Figure 26: Location of the new Ecobarrio San Francisco Javier y Nuestra Sra. de los Ángeles in Madrid (see red circle)



Source: Own illustration, Guidehouse based on Google (background)

The following figure shows the planned development structure of the new development area, although only a few buildings were realized at the time of the study (2019).

Figure 27: Map of the new construction quarter Ecobarrio San Francisco Javier y Nuestra Sra. de los Ángeles in Madrid, model area (blue border)

Source: Own illustration, Guidehouse based on Google (background)

The following illustrations show views of buildings that have already been realized, which were used as templates for the reference buildings.

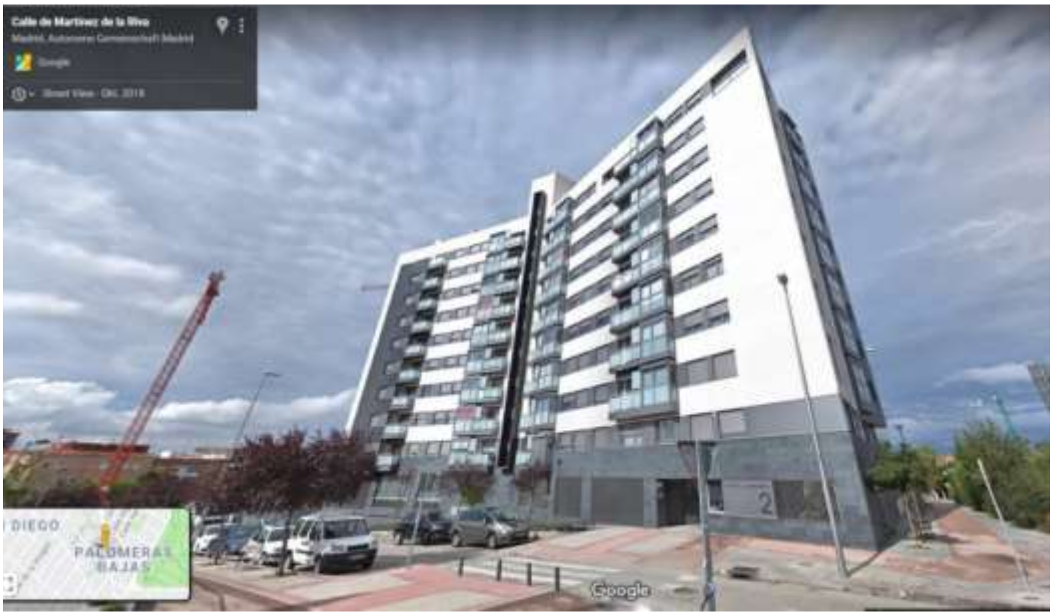
Figure 28: View of building No. 1

Source: Google

Figure 29: Reference building No. 2

Source: Google

Figure 30: Reference building No. 3

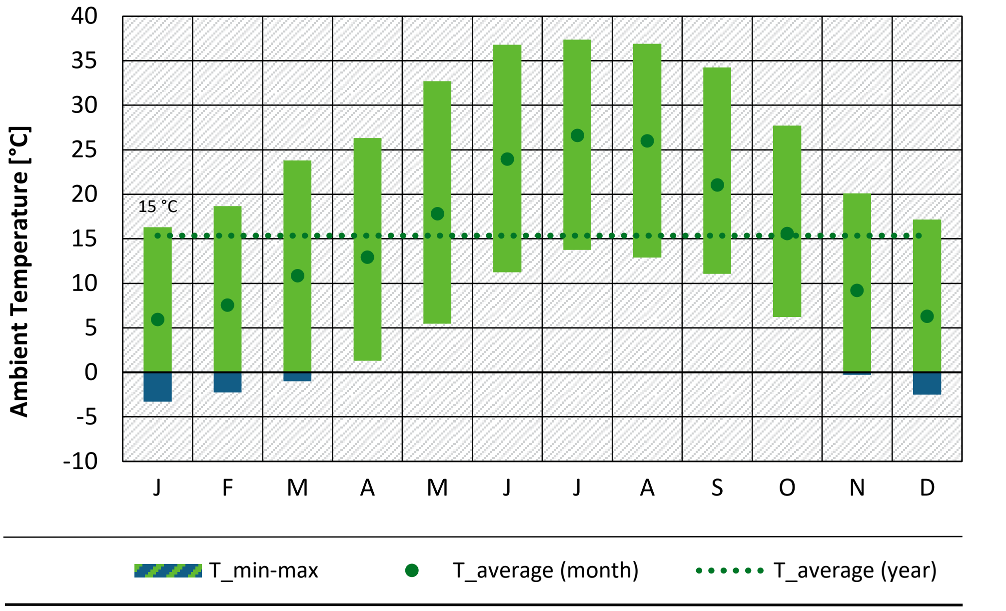


Source: Google

2.2.4.2 Climate

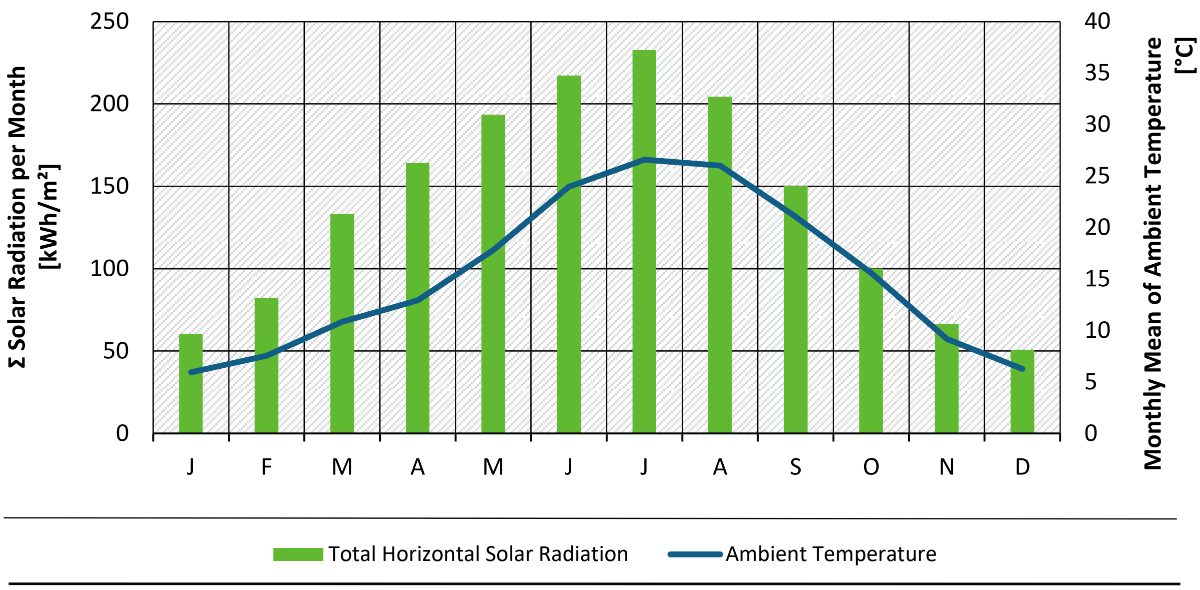
The reference climate data for the Madrid location was used as the basis for the calculations [28]. The average annual ambient temperature is therefore 15 °C. The monthly mean values for the ambient temperature range from approx. 12 °C (December, January) to 26 °C (July, August). The peak values in summer reach well over 35 °C.

Figure 31: Monthly ambient temperature values in Madrid



Source: Own illustration, Guidehouse

Figure 32: Monthly values of global radiation and outside temperature Madrid



Source: Own illustration, Guidehouse

[28]Source: Meteonorm software , version 7, most recent weather data set (period 2000-2009)

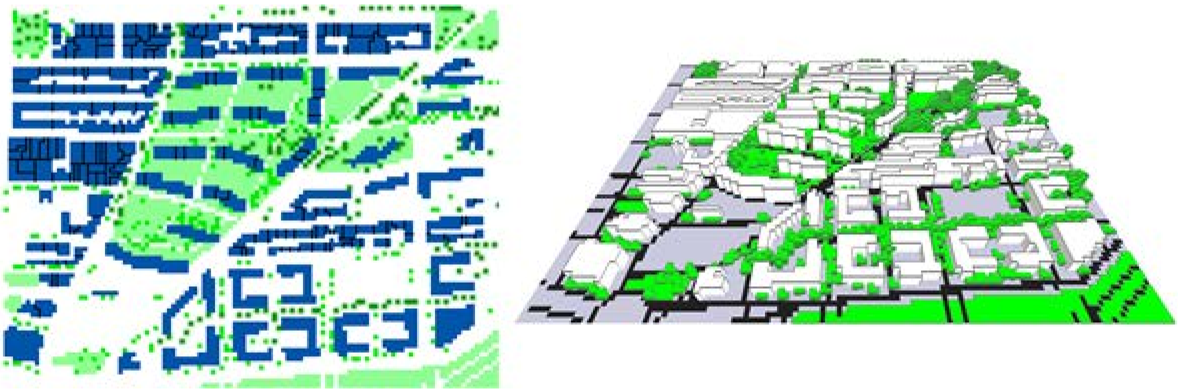
2.2.4.3 Microclimate simulation

2.2.4.3.1 Variant current state

The new development Ecobarrio San Francisco Javier y Nuestra Sra. de los Ángeles in Madrid was digitized in the microclimate model ENVI_MET based on the existing development plan (hereinafter referred to as status quo).

The qualities of the building materials correspond to those described in Section 2.2.4.4. The degree of sealing and vegetation of the model in its current state roughly corresponds to the planning and the actual vegetation (Figure 33).

Figure 33: Model of the current state of the new development area Ecobarrio San Francisco Javier y Nuestra Sra. de los Ángeles in Madrid as top view and 3D view



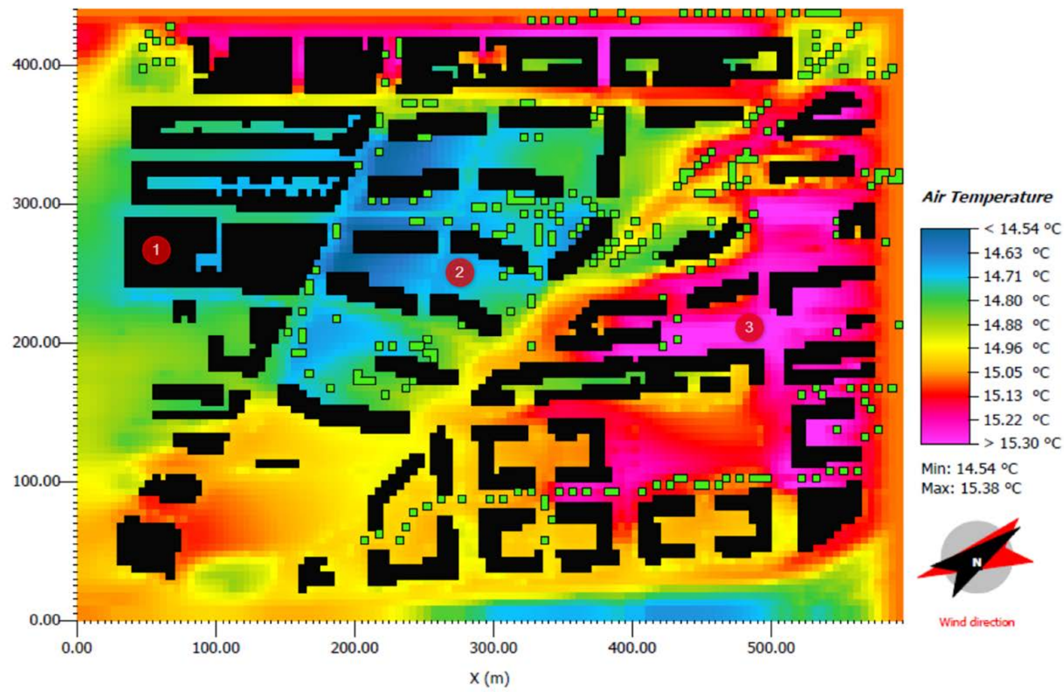
Source: Own illustration, ENVI_MET

2.2.4.3.2 Results of current microclimate simulations

Panel_2_a_Madrid_SQ in Appendix A.3 shows the distribution of air temperatures in the current state over the various seasons. Clear differences can be seen between three thermal areas, which are shown as examples in Figure 34: The original block perimeter development in the west of the new development area (1), the new development area itself (2) and the loosened-up development with green areas in the east (3). The differences are particularly evident at night, when the new development area is up to 1 K cooler than the two adjacent areas (see, for example Panel_2_a_Madrid_SQ - Fig. E). This is mainly due to the open construction in the new development area, which allows the structure to cool down at night.

During the daylight hours, the differences are less noticeable since the open building structure is also accompanied by increased solar radiation.

Figure 34: Different thermal areas in Madrid (status quo) using the example of July, 4:00 a.m



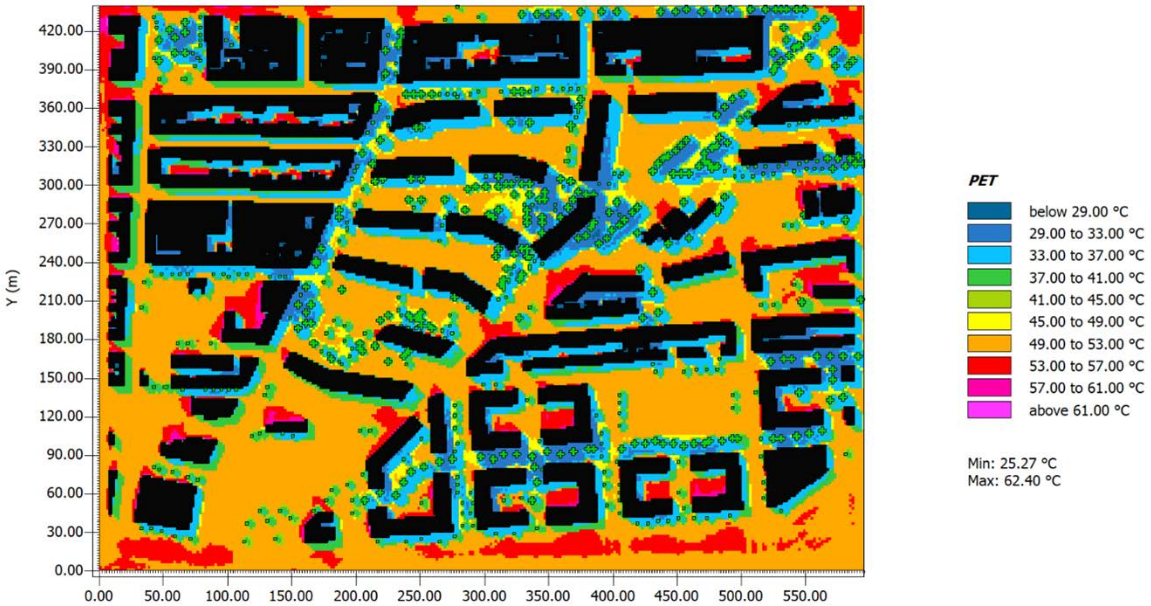
Source: Own illustration, ENVI_MET

The detailed simulations (Annex A.3, Panel_2_c_Madrid_Detail) show the initial situation in July with a higher resolution and a southerly wind direction. Since the building structure due to the lack of a barrier effect in the Northern building blocks, the thermal differences between the areas are blurred.

The daytime air temperature here is determined by the local arrangement of building and vegetation elements without any characteristic features.

This thermal structure can also be found in the PET distribution for July at 4 p.m. (Figure 35). The distribution of the PET shows perceived temperatures around 50 °C in the sunlit areas, which are assigned to the 'very hot' sensitivity level. PET values of up to 60 °C can be observed in the lee of the buildings. In the shaded areas, the PET values are around 33 °C, so they can be classified as 'warm'.

Figure 35: Distribution of the PET value in Madrid on July 07 at 4:00 p.m. for the status quo

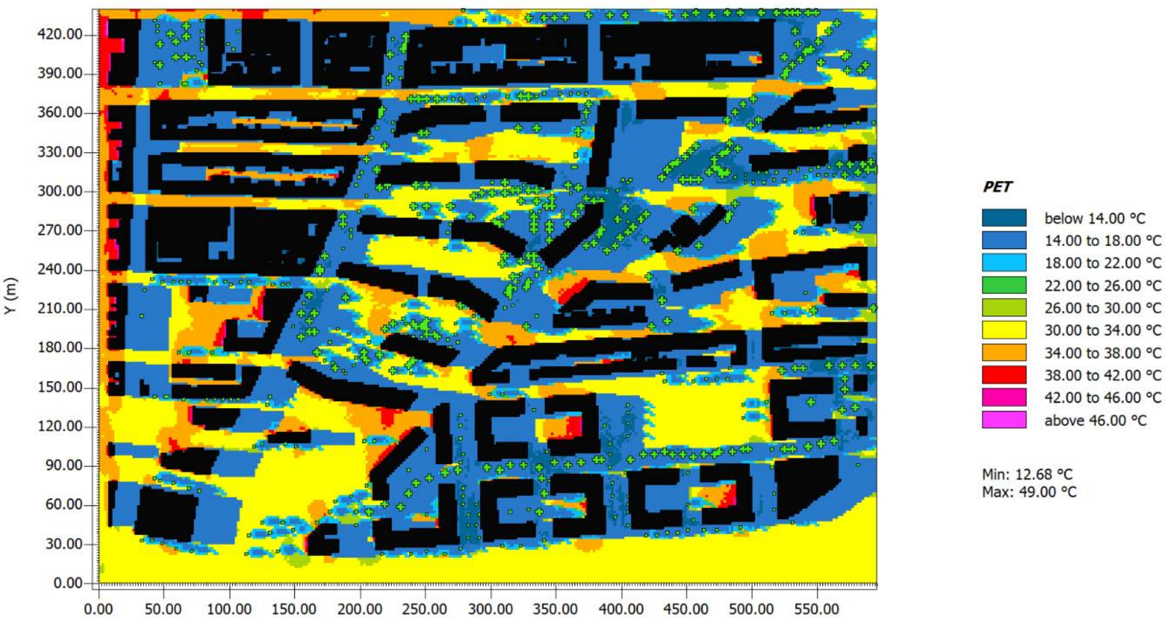


Source: Own illustration, ENVI_MET

The PET distribution for 4 p.m. in January (Figure 36) is significantly more inhomogeneous than in July due to the lower position of the sun and the associated longer shadows.

In the shadowed areas, the thermal comfort is still good on the border to the cool range. In the sun, on the other hand, the well-ventilated areas can be assigned to the warm environment, but in the areas with little wind can rise to over 37 °C even in January and are therefore perceived as hot.

Figure 36: Distribution of the PET value in Madrid on January 21 at 4:00 a.m. for the status quo



Source: Own illustration, ENVI_MET

2.2.4.3.3 Optimised variant

Only slight changes were made to the area to analyse the microclimatic conditions in terms of outdoor thermal comfort (see Figure 37).

Since the traditional building style in historic cities in Southern Europe is primarily characterized by narrow streets and closed courtyards that guarantee optimal shadowing, the effects of building based on the traditional building style are to be examined in the new development area. To do this, simple changes are made, and the inner courtyards are closed by adding building wings to the open sides. This increases the shadowing within the yard but may reduce the possibility of ventilation. The extent to which this influences the thermal comfort in the inner courtyards can be determined in the following analyses. A change in the vegetation density in the model area and other measures were not taken into account.

Figure 37: Model of the optimised scenario of the new development area Ecobarrio San Francisco Javier y Nuestra Sra. de los Ángeles in Madrid as top view and 3D view

Source: Own illustration, ENVI_MET

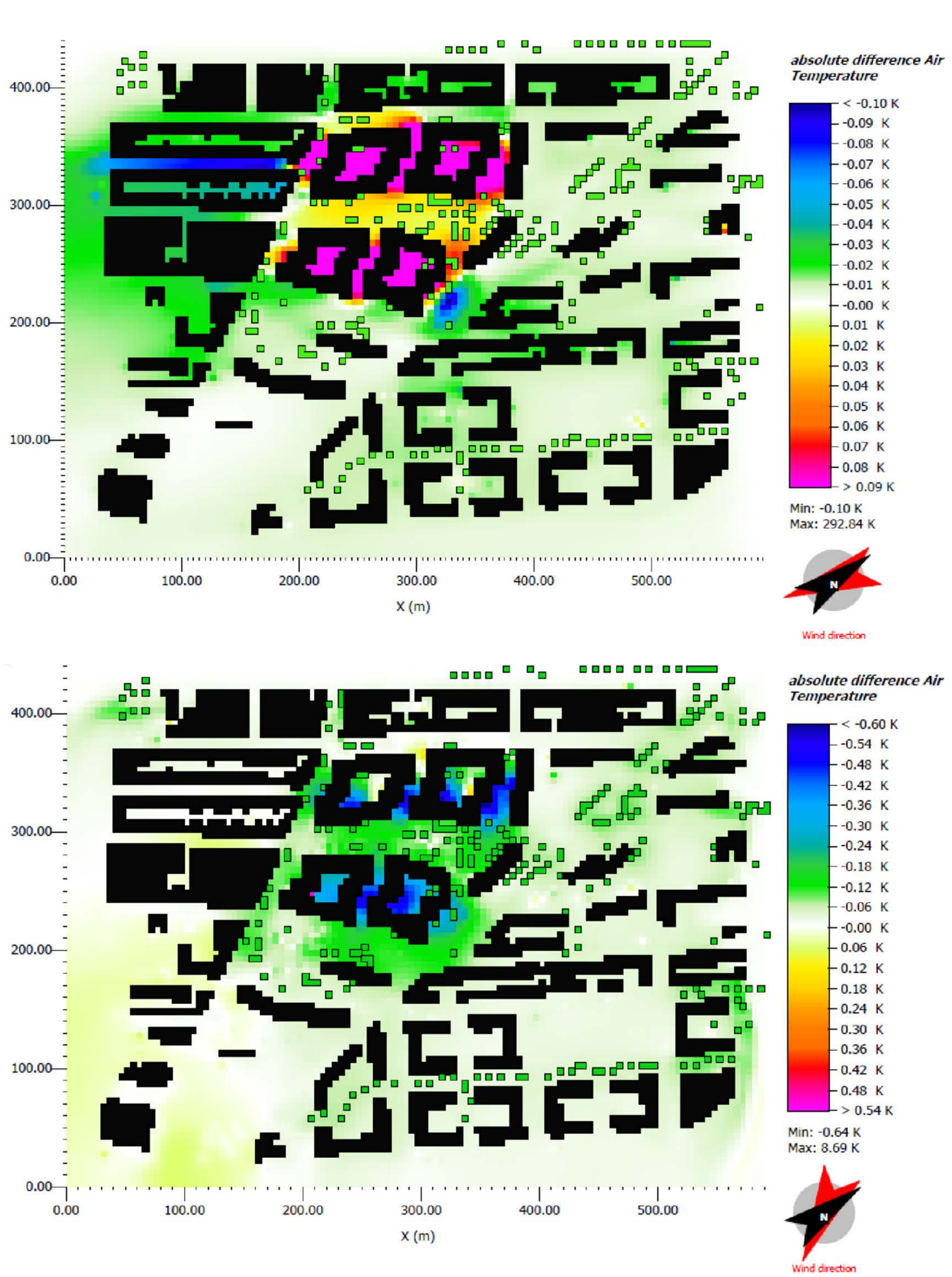
2.2.4.3.4 Results of microclimate simulations optimised variant

Panel_2_b_Madrid_OPT in Appendix A.3 compares the air temperatures over the course of the year between the status quo and the optimised variant.

Due to the minimal adjustments, the main changes are to be expected in the area of the newly created inner courtyards or in the shadow area of the modified building blocks. This assumption is confirmed when looking at Panel_2_b_Madrid_OPT. However, more far-reaching effects can also be observed since the wind flow is changed by changing the building fabric. This was examined for January, March and July as examples. The closure of the block edges results in a change in ventilation, which is also noticeable at a somewhat greater distance from the building block.

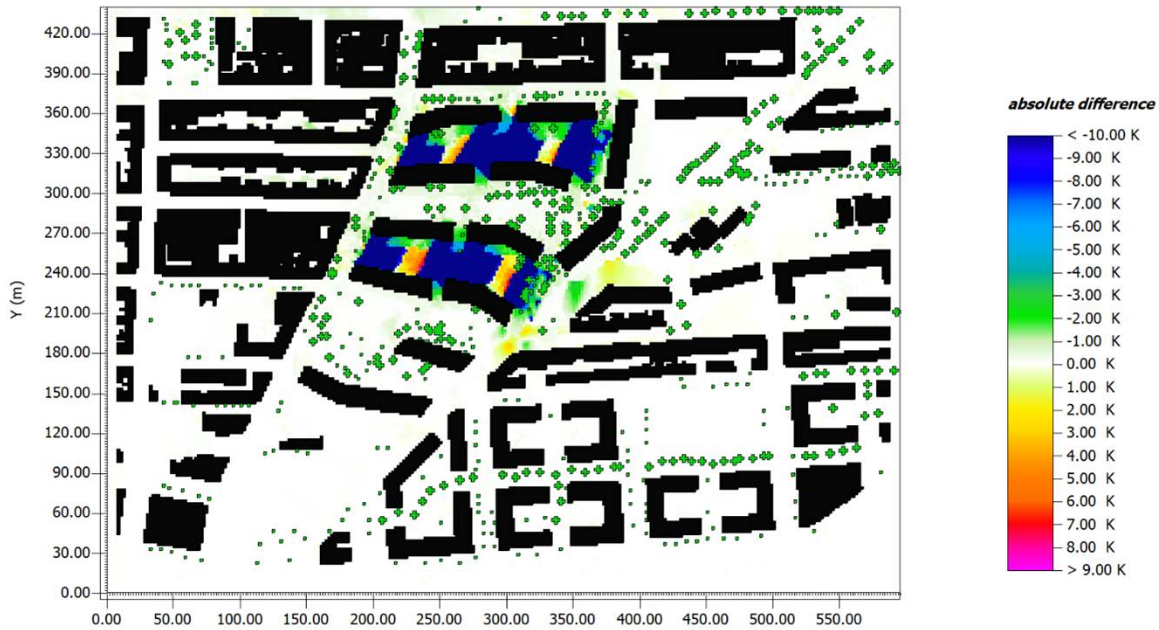
Due to the lateral closure of the building clusters in the new development area, the microclimatological conditions within the building blocks are somewhat decoupled from the ambient conditions. This is particularly evident during the daylight hours: The building blocks are slightly warmer here in March, while they have lower air temperatures in July (cf. Appendix A.3, Panel_2_b_Madrid_OPT and Panel_2_c_Madrid_Detail). Although the absolute differences are small, the high specific heat of the air and the turbulent exchange in the atmosphere must also be considered. Thus, even small differences in air temperature can provide indications of significant changes in energy flows.

Figure 38: Thermal behaviour of the building blocks in Madrid in March (top) and July (bottom) at 04:00 a.m.



Source: Own illustration, ENVI_MET

Figure 39: Change in the PET value in Madrid on July 7 at 4:00 p.m. due to the optimization measures

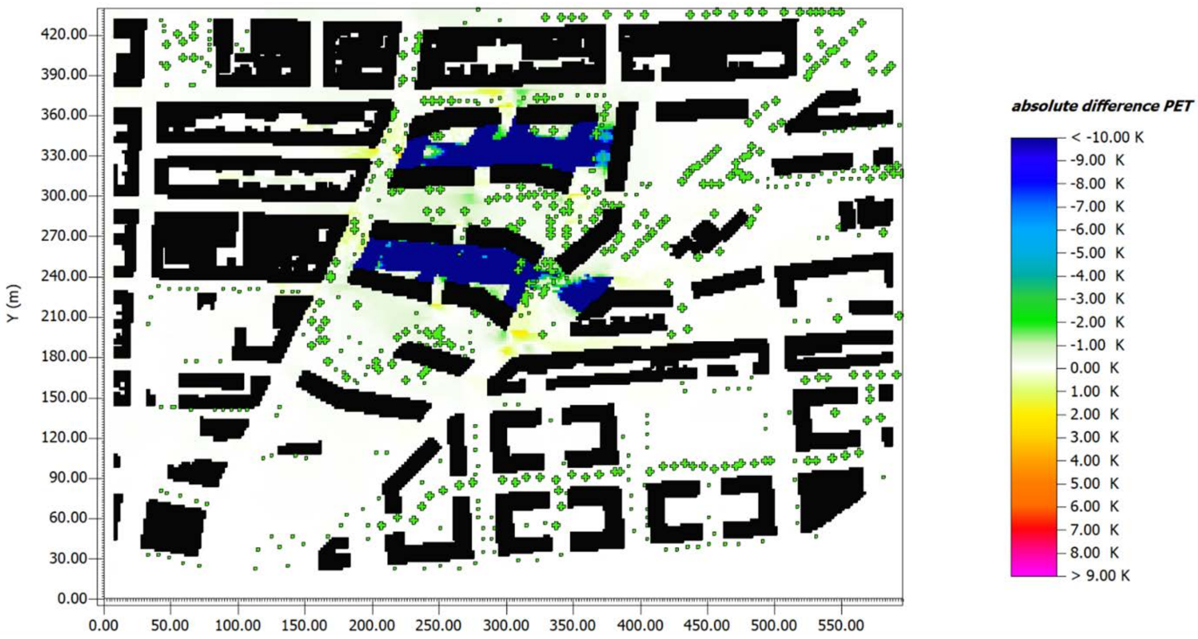


Source: Own illustration, ENVI_MET

Figure 39 shows the change in PET values in July compared to the status quo. Since the thermal sensation is primarily dominated by the radiation flows, the changes are limited to the area of the redesigned building blocks. A clear division can be seen in the inner courtyards: On the shaded side of the inner courtyard, the PET is noticeably lower than in the reference case, but on the side that can still receive direct solar radiation, the values are sometimes higher than in the initial situation. This effect is due to the reduced wind speed in the now closed inner courtyards, which lead to increased thermal stress in the sunny areas.

The change in the PET distribution in January (Figure 40) is similar to the July results. Due to the lower position of the sun, the inner courtyards are now almost completely shaded and thus, like the other shaded zones, can also be assigned to the comfortable thermal area.

Figure 40: Change in the PET value in Madrid on January 21 at 4:00 p.m. due to the optimization measures



Source: Own illustration, ENVI_MET

2.2.4.3.5 Summary assessment

The comparison of the air temperature and the PET shows the example of the new development area Ecobarrio San Francisco Javier y Nuestra Sra. de los Ángeles in Madrid, an improvement in thermal comfort while adapting the new development areas to the closed block construction traditional in these areas.

To a certain extent, this intervention leads to a decoupling from the microclimate of the surroundings, in that a separate, local microclimate can be created through shadowing, modified ventilation and the use of the building mass as thermal storage. This effect can be used in winter and in the transitional phases of the year to locally generate a slightly warmer microclimate outdoors, while in summer it can be used to reduce the thermal load, provided that windless and at the same time sunny zones are avoided.

2.2.4.4 Building simulation

2.2.4.4.1 The simulation model

The evaluation area consists of seven to ten-storey buildings, which were assumed to be the same for the simplified modelling with regard to building physics. The evaluations regarding consumption and comfort were carried out at apartment level. Depending on the location and orientation of the apartments in the building and area, there are differences in energy demands and indoor comfort.

Regarding the geometry of the apartments, a representative floor plan with 100 m^2 of floorspace was taken into account, which was divided into two zones (living- and dining room as well as bedroom and children's room) for the modelling.

The living- and dining rooms were always oriented to the south as far as possible. The location of the 39 reference apartments in the initial state (status quo) can be seen in the following figure.

Figure 41: Location of the reference apartments in the quarter in the initial state (status quo)

For each of the 13 locations shown, one apartment was taken into account on the top floor, middle floor and ground floor.

Source: Own illustration, Guidehouse and ENVI_MET

As part of the quarter optimization, the existing buildings were closed to blocks with inner courtyards (see chapter microclimate simulations). To also be able to assess the conditions in the apartments of the resulting additional building blocks, six additional apartments were taken into account for the optimised quarter (see Figure 42).

Figure 42: Location of the reference apartments in the quarter in the optimised quarter

For each of the 15 locations shown, one apartment was taken into account on the top floor, middle floor and ground floor.

Source: Own illustration, Guidehouse and ENVI_MET

In total, the quarter has 348 apartments in its initial state.

The qualities of the building envelope were adopted according to local minimum standards. Accordingly, the following U-values were considered:

- Facades: 0.46 W/m²K
- Flat roof: 0.4 W/m²K
- Window: 3.0 W/m²K (g= 0.7)
- Floor to unheated basement: U=0.7 W/m²K

Deviating from the realization, no climate-neutral district heating was considered for the heating in the initial state, but central reversible multi-split air conditioning systems with fluorinated refrigerants in the apartments. These systems can also be used for cooling in summer. The hot water is provided by central electric instantaneous water heaters per apartment, ventilation by ventilation systems in the bathrooms. These and other characteristic values can be found in the following table in the variants chapter.

2.2.4.4.2 Variants

Variants considered are summarized in Table 14.

The initial state is represented by the Status Quo 1 (SQ1) variant. As part of the SQ2 variant, the optimization of the quarter (including closed development) was considered, while the building qualities remained unchanged. In the following variants, based on the SQ2 variant, the envelope quality and air conditioning were improved (Opt1 variant). In the Opt2 variant, effective sun protection was assumed. In the last variant (Opt3), a maximum occupancy of the free roofs with PV (assumption of the possible occupancy density: 50%) and corresponding battery storage to increase the proportion of electricity self-use was taken into account.

The specifics of the variants considered are summarised in the table below.

Table 14: Overview of the variants examined for the quarter in Madrid

	SQ1	SQ2	Opt1	Opt2	Opt3
Microclimate	Current state (open development structure)	Optimised (closed development structure)	See SQ2	See SQ2	See SQ2
Heat protection	New-build standard: Facades: U= 0.46 W/m²K Flat roof: U=0.4 W/m²K Window: U=3.0 W/m²K, g= 0.7 Floor to unheated basement: U=0.7 W/m²K	See SQ1	Improved: Facades: U: 0.23 W/m²K Flat roof: U=0.2 W/m²K Window: U=1.5 W/m²K, g= 0.64 Floor to unheated basement: U=0.35 W/m²K	See Opt1	See Opt 1
Heating	Reversible split air conditioners -	See SQ1	Reversible split air conditioners with high	See Opt1	See Opt1

	SQ1	SQ2	Opt1	Opt2	Opt3
	with average - efficiency		efficiency and natural refrigerant propane		
Water heating	Electric instantaneous water heater	See SQ1	See SQ1	See SQ1	See SQ1
Cooling	See heating	See SQ1	See heating	See Opt1	See Opt1
Ventilation	Exhaust air system, air exchange 0.4 1/h, additional ventilation for cooling in summer[29]	See SQ1	See SQ1	See SQ1	See SQ1
Sun protection	Fixed elements (fc=0.5)	See SQ1	See SQ1	Automatically operated effective sun protection[30]	See Opt2
Renewable energies on site	-	-	-	-	50% of the roofs are covered with PV modules (10% inclination): arithmetically 1 kWp [31]+ 2 kWh battery storage per apartment[32]

2.2.4.4.3 Results

2.2.4.4.3.1 Status quo

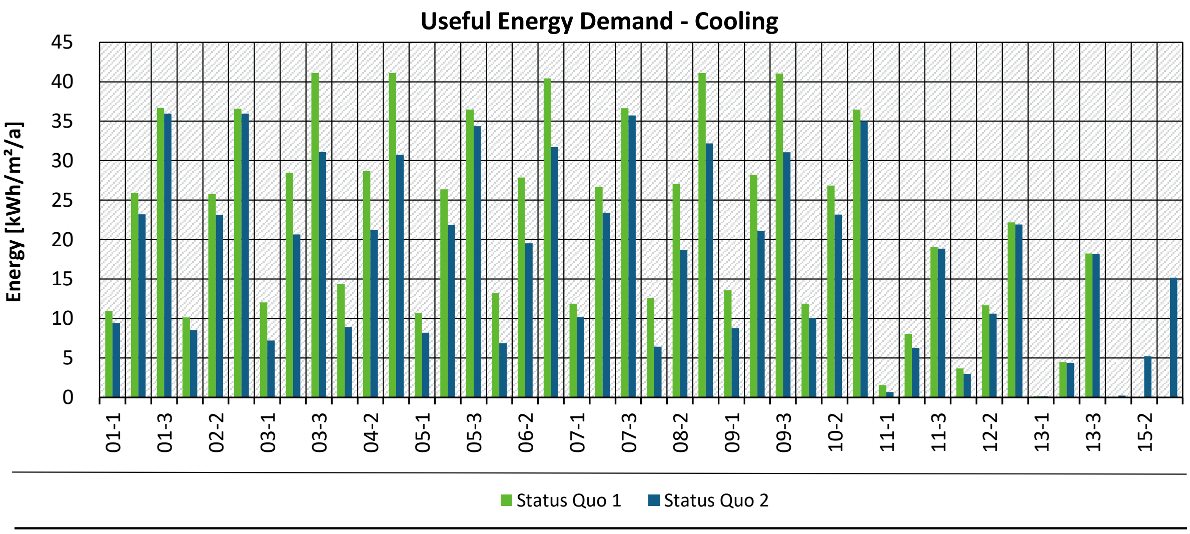
As can be seen in the following two figures, the useful energy demand for cooling clearly outweighs that for heating in most apartments. The highest cooling energy demands, sometimes over 40 kWh/m^{2}a, are observed in the attic apartments (apartments with the last code -3). On the other hand, the highest heating energy demands of up to 27 kWh/m^{2}a occur in the ground floor apartments (apartments with the final code -1). In the case of the ground floor apartments,

[29]Summer (shock) ventilation at room temperatures above 24 °C and cooler outside temperature as well as the presence of the residents: in the morning from 7-8 a.m. with an air exchange rate of 6 1/h; afternoons/ evenings from 4 p.m. to 10 p.m. with an air exchange rate of 4 1/h; Night ventilation via a tilted window in the bedroom from 10 p.m. to 6 a.m. with an air exchange rate of 0.4 1/h
[30]Assumption of mean Fc value of 0.2
[31]Considering an eight-storey building, the roof area per apartment is 15 m^2 (=120 m^2/8); For the study area with 348 apartments, this results in an installed total capacity of 348 kWp
[32]As central building battery storage. Note: It was not checked whether this solution is also practicable under the current local conditions.

the cooling and heating energy demand is due to the bigger shadowing and cooling through the ground approximately at same order of magnitude.

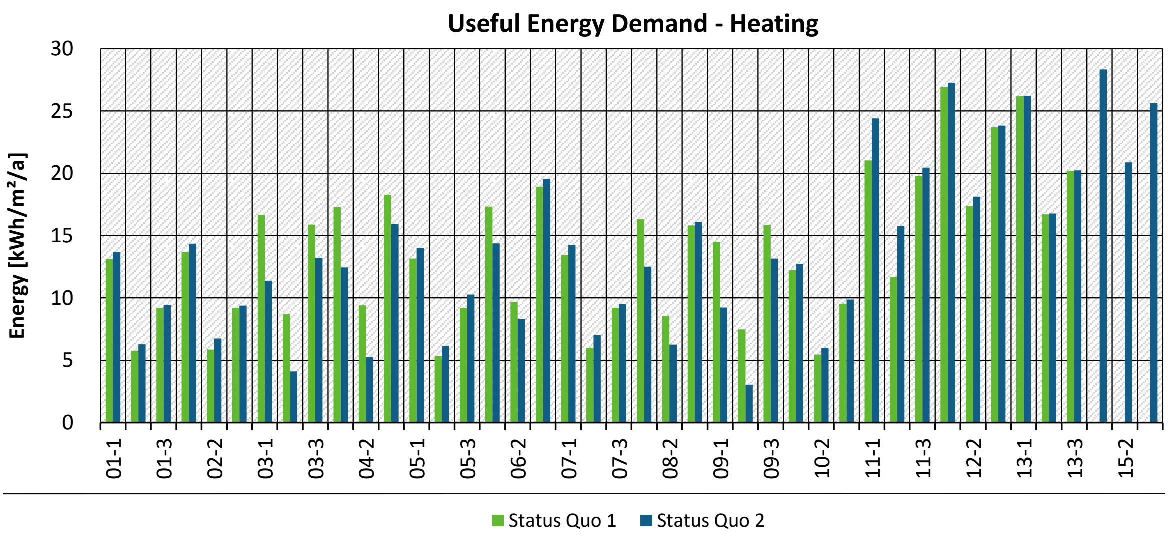
Overall, the improved shadowing in the optimised quarters leads to a significant reduction in the cooling energy demand. In numerous apartments, the cooling energy demand drops by almost 10 kWh/m^{2}a. The effect of the quarter measures on the heating energy demand is indifferent. Here, too, there are buildings (e.g., buildings 3 and 4) in which the heating energy demand drops significantly. However, this is mainly due to the elimination of one facade due to the closure of the building.

Figure 43: Comparison of the useful energy demand for cooling the reference apartments of variants SQ1 (initial state) and SQ2 (optimised quarter)



Source: Own illustration, Guidehouse

Figure 44: Comparison of the useful energy demand for heating the reference apartments of variants SQ1 (initial state) and SQ2 (optimised quarter)

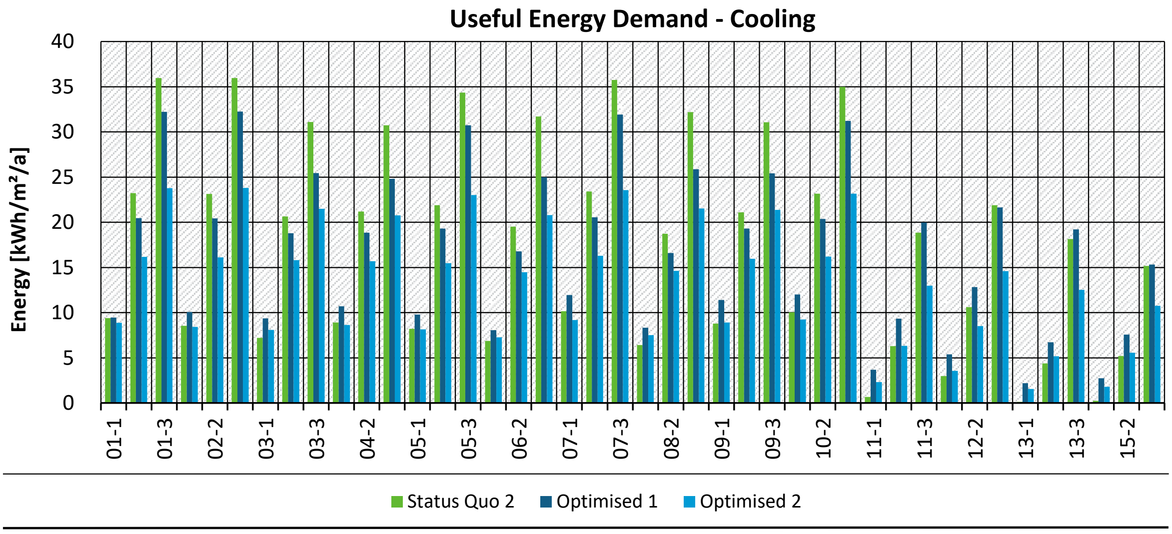


Source: Own illustration, Guidehouse

2.2.4.4.3.2 Optimised scenario

Improvements of the building envelope reduce the useful energy required for heating by around a third in most apartments. According to the following Figure 45, the effect on the cooling energy demand in relation to the heating energy demand is lower and most evident in the attic apartments. The effect of the additional improvement in sun protection on the cooling energy demand is greater. Overall, the cooling energy demand in the apartments on the top floor and the middle floors can be reduced by around a third thanks to the two measures considered. With consideration of good automatic control, the influence of the sun protection on the heating energy demand is negligible.

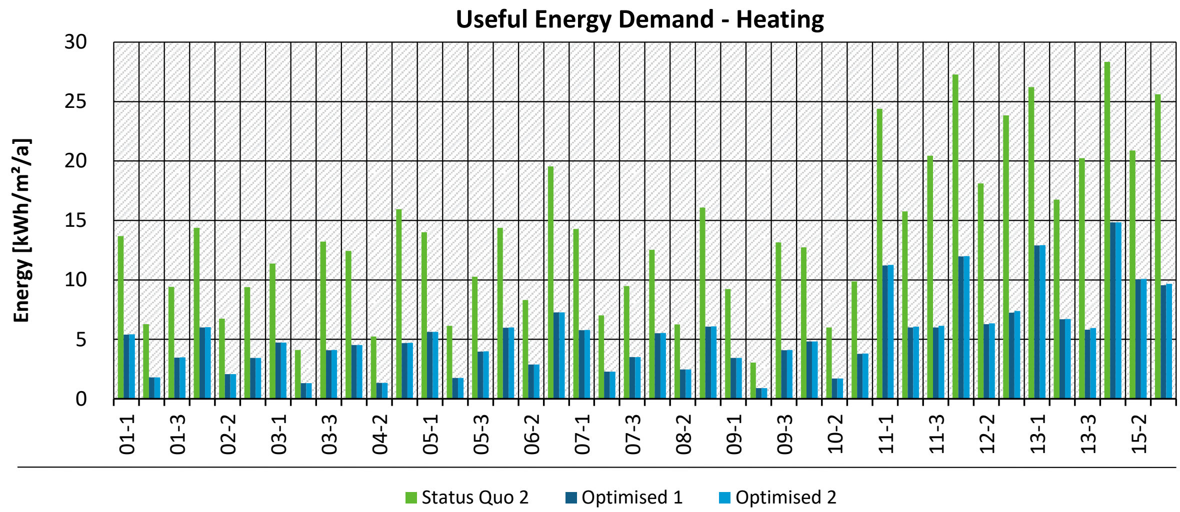
Figure 45: Comparison of the useful energy demand for cooling the reference apartments of the Satus Quo 2, Optimised 1 and Optimised 2 variants



Variant SQ2 is the closed building structure with otherwise unchanged building properties. With Opt1 the envelope quality has also been improved, with Opt2 sun protection has been improved.

Source: Own illustration, Guidehouse

Figure 46: Comparison of the useful energy demand for heating the reference apartments of the Status Quo 2, Optimised 1 and Optimised 2 variants

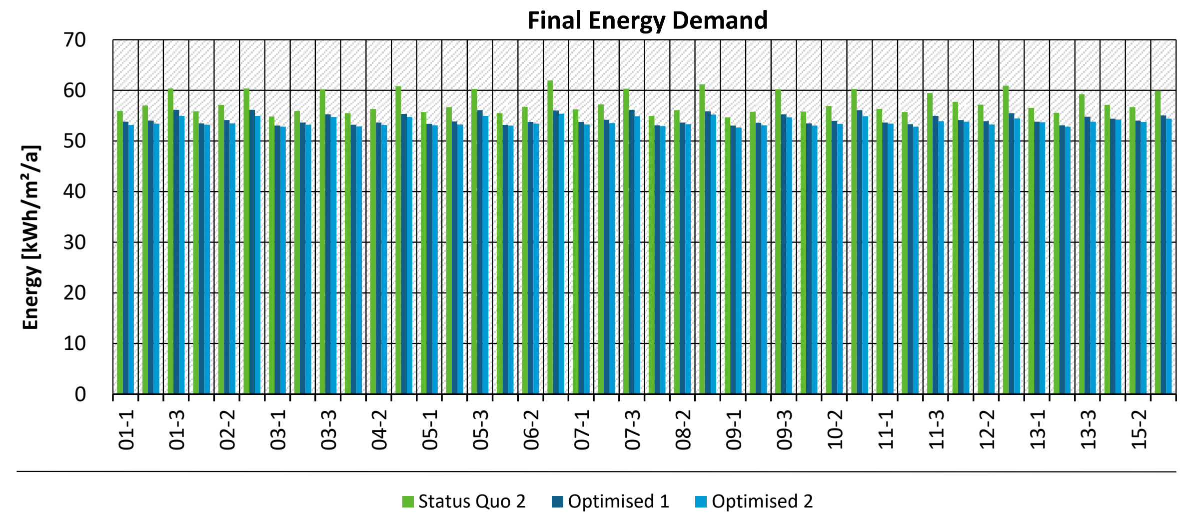


Variant SQ2: closed building structure with otherwise unchanged building properties; Opt1: additionally improved envelope quality; Opt2: additionally improved sun protection.

Source: Own illustration, Guidehouse

If the final energy demand of the examined variants is looked at (Figure 47), it appears that the relative differences are small.

Figure 47: Comparison of the final energy demand of the reference apartments of the Status Quo 2, Optimised 1 and Optimised 2 variants



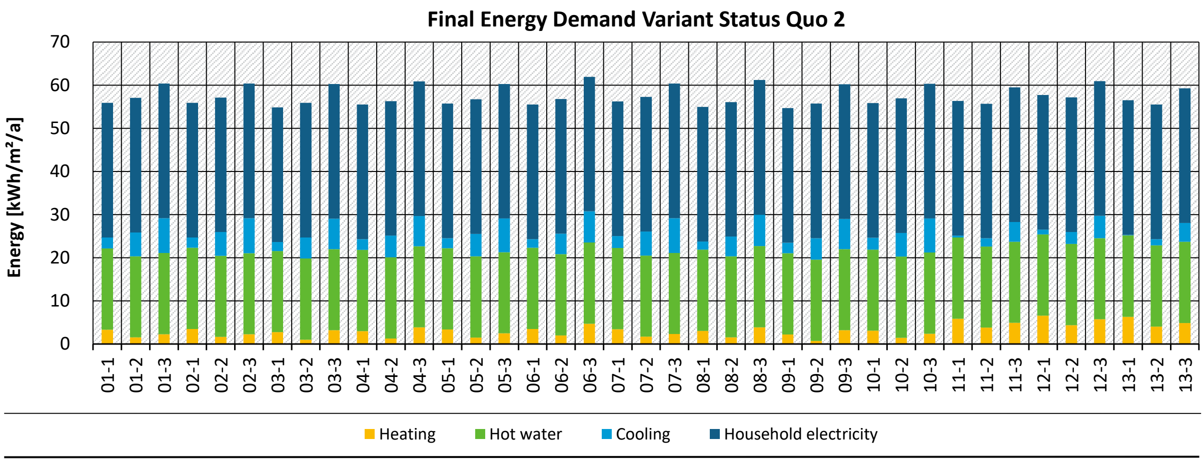
Variant SQ2: closed building structure with otherwise unchanged building properties; Opt1: additionally improved envelope quality; Opt2: additionally improved sun protection.

Source: Own illustration, Guidehouse

This is due to the fact that the household[33] electricity demand and the electricity demand for domestic water heating are relatively high.

[33] 3100 kWh/a (=> 31 kWh/m²a) was assumed for the household electricity requirement of the apartments

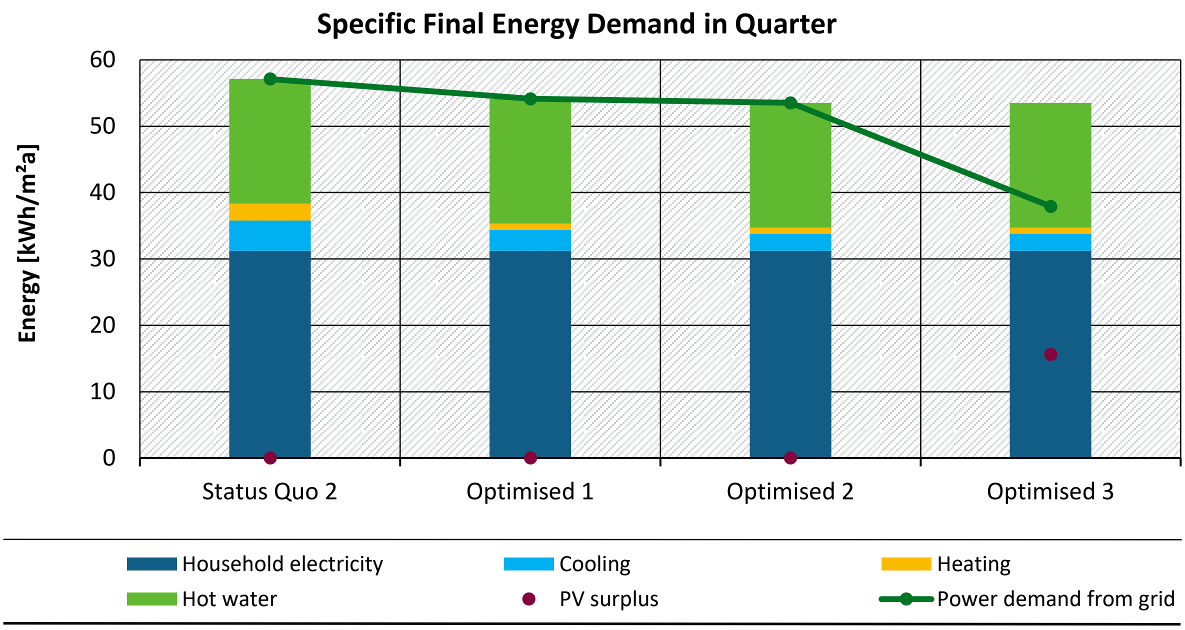
Figure 48: Distribution of the final energy demand using the example of the Status Quo 2 variant



Source: Own illustration, Guidehouse

This is also reflected in the following figure of the final energy demand of these variants. Only through the PV systems on the roofs the electricity demand (final energy) of the quarter can be significantly reduced (by approx. 30% in a comparison between the Optimised 2 and Optimised 3 variants).

Figure 49: Comparison of the final energy demand[34] of the quarter variants



Variants Status Quo 2 (optimised quarter, building unchanged), Optimised 1 (additionally improved envelope quality), Optimised 2 (additionally improved sun protection) and Optimised 3 (additionally PV and battery).

Source: Own illustration, Guidehouse

A climate-neutral supply from renewable energies at the location alone is not achieved. That is primarily due to the unfavourable relationship between the roof and the total floor space, which

[34] To ensure comparability, only the apartments in the initial state (SQ1 and SQ2) were used. The energy demands of the additional apartments in the optimised quarter were not taken into account.

is due to the height of the building (eight storeys). For a climate-neutral supply, additional electricity from renewable sources, e.g., from regional PV power plants, would be necessary.

2.2.4.4.3.3 ***Summary assessment***

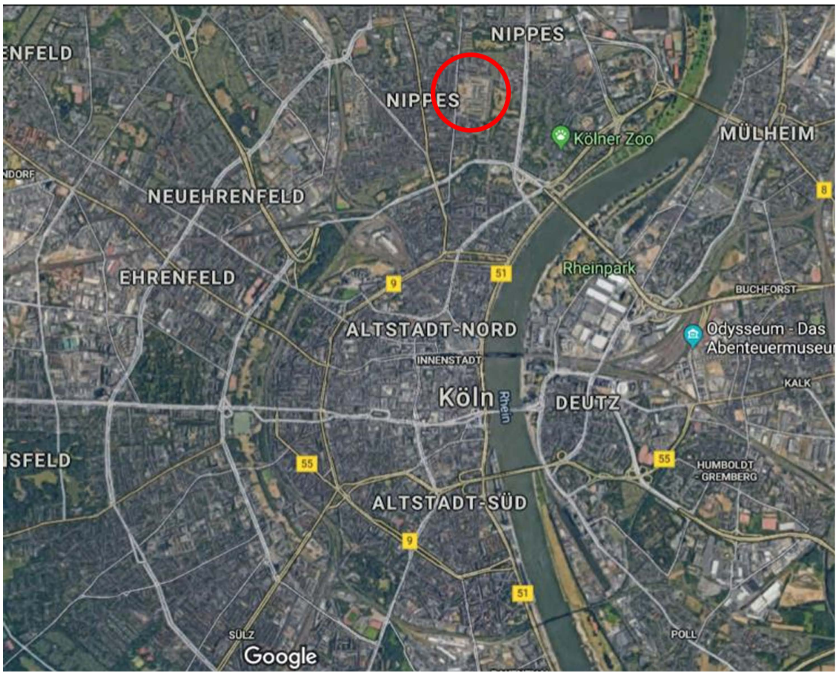
The improved shadowing of the closed development in the optimised quarter significantly reduces the energy demand in the quarter. This is mainly due to the reduction in the significant cooling energy demand, which can be reduced by more than 20% in many apartments. Through the additional improvement of the envelope qualities and the sun protection (see variants Optimised 1 and Optimised 2), the cooling energy demand in the middle and top floor apartments can be reduced by about a further third. However, the total energy demand is dominated by the household electricity demand and the demand for water heating. By providing PV systems on the roofs and battery storage, the total electricity requirement can be reduced by around 30%. Due to the eight-storey building, however, it is not possible to compensate the annual energy demand by renewable energy production.

2.2.5 New construction quarter Cologne-Clouth

2.2.5.1 Location and description

The Clouth quarter is located on the Northern edge of downtown Cologne.

Figure 50: Location of the Clouth quarter in Cologne (see red circle)



Source: Own illustration, Guidehouse based on Google (background)

The project development company of the city of Cologne - Moderne Stadt - developed the new urban quarter for 3,000 inhabitants.

The site covers 14.5 hectares. The naming is based on the former rubber goods factory "Clouth Werke". After the demolition and development work, the first high-rise buildings (mainly four-storey apartment buildings) began in mid-2014, and the majority of the buildings have been completed in 2020.

The buildings in the Clouth quarter are heated with climate-neutral district heating[35].

[35]Climate-neutral according to the calculation method before the introduction of the German GEG (Bundesanzeiger 2020). A review and, if necessary, adjustment of the calculation method is planned in the GEG. With a switch to the so-called Carnot calculation method, the CO_2 emissions would no longer be zero.

Figure 51: Clouth quarter site plan

Model area (outlined in orange) and evaluation area (outlined in blue); Basic source: Modern City – Cologne

Source: Own illustration, Guidehouse based on Google (background)

Figure 52: Street view in the Clouth quarter

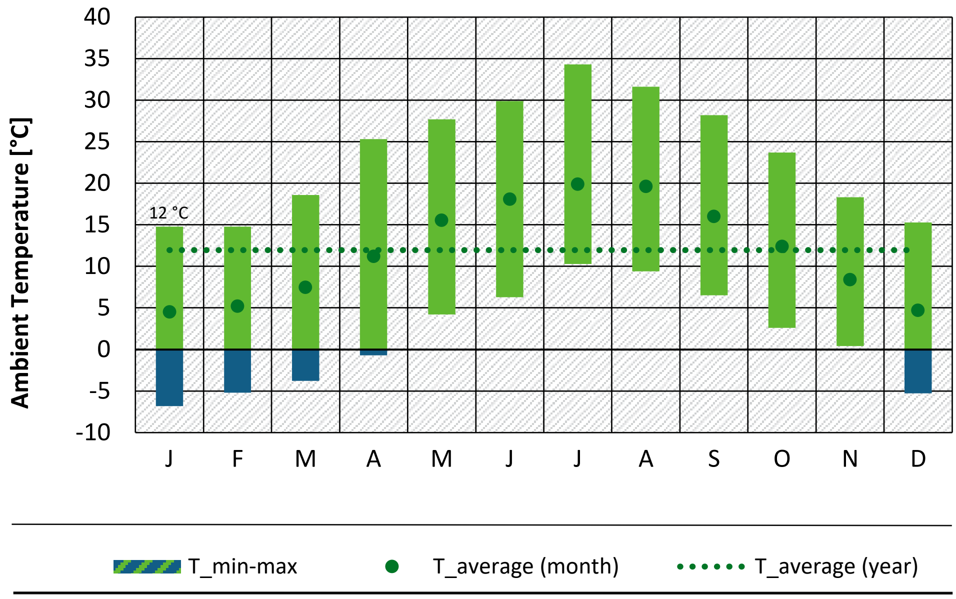
Source: Google

The quarter was adapted for the modelling. For the status quo scenario a closed perimeter block development was assumed. The green areas were almost completely eliminated (see Chapter 2.2.5.3.1 Microclimate model status quo).

2.2.5.2 Climate

The reference climate data for the Cologne location[36] was used as the basis for the calculations. The average annual ambient temperature is therefore 12 °C. The monthly mean values for the ambient temperature range from approx. 4 °C (January) to 20 °C (July). The summer peak values reach almost 35 °C.

Figure 53: Monthly values for the ambient temperature in Cologne

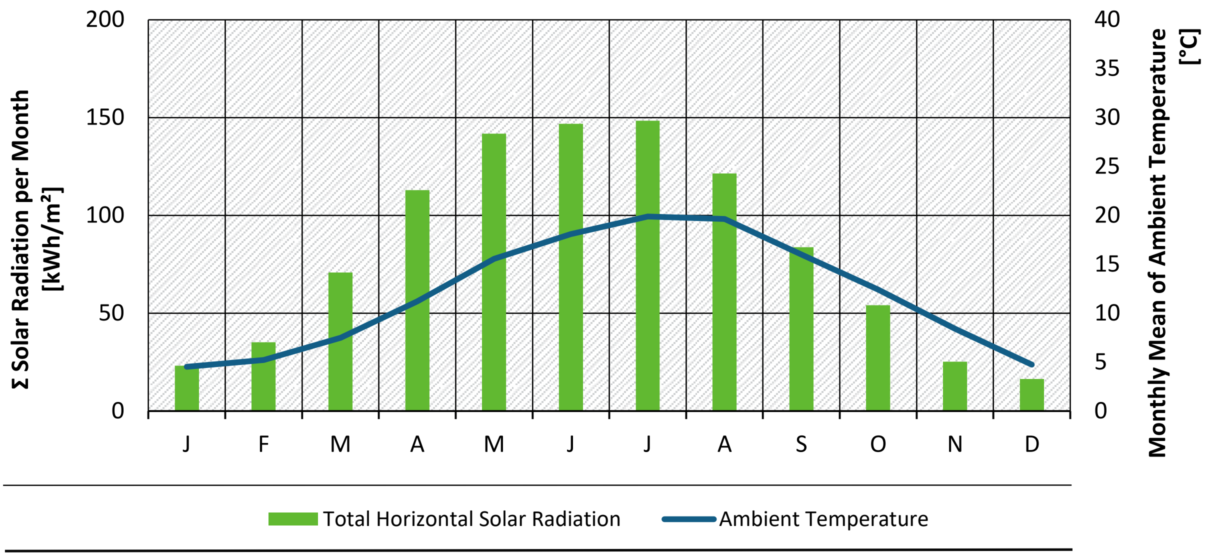


Source: Own illustration, Guidehouse

The annual global radiation total is 980 kWh/m²a. It is highest in July at around 150 kWh/m² and lowest in December at around 20 kWh/m².

[36] Source: Meteonorm software , version 7, most recent weather data set (period 2000-2009)

Figure 54: Monthly values for global radiation and outside temperature in Cologne



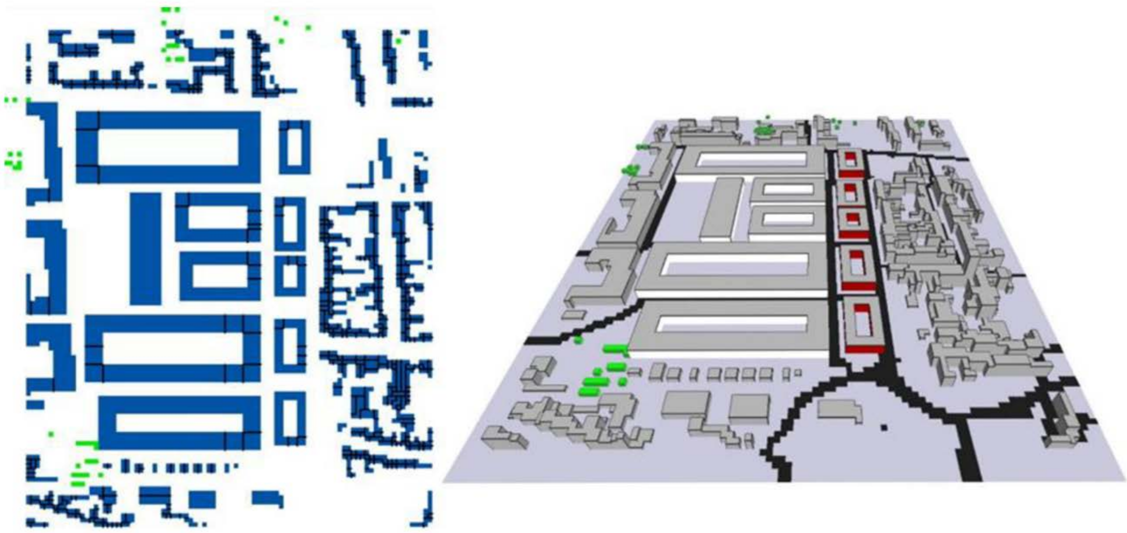
Source: Own illustration, Guidehouse

2.2.5.3 Microclimate simulation

2.2.5.3.1 Variant current state

The Clouth quarter in Cologne was digitized in the ENVI_MET microclimate model with minor changes to the existing building structure. The park, which is actually located in the east of the area, was replaced by a housing estate that is typical for the area in order to take current densification into account and also to make the examined area more universally comparable. The individual buildings were connected to form a block of buildings with an inner courtyard.

Figure 55: Cologne model area (status quo) as top view and 3D view



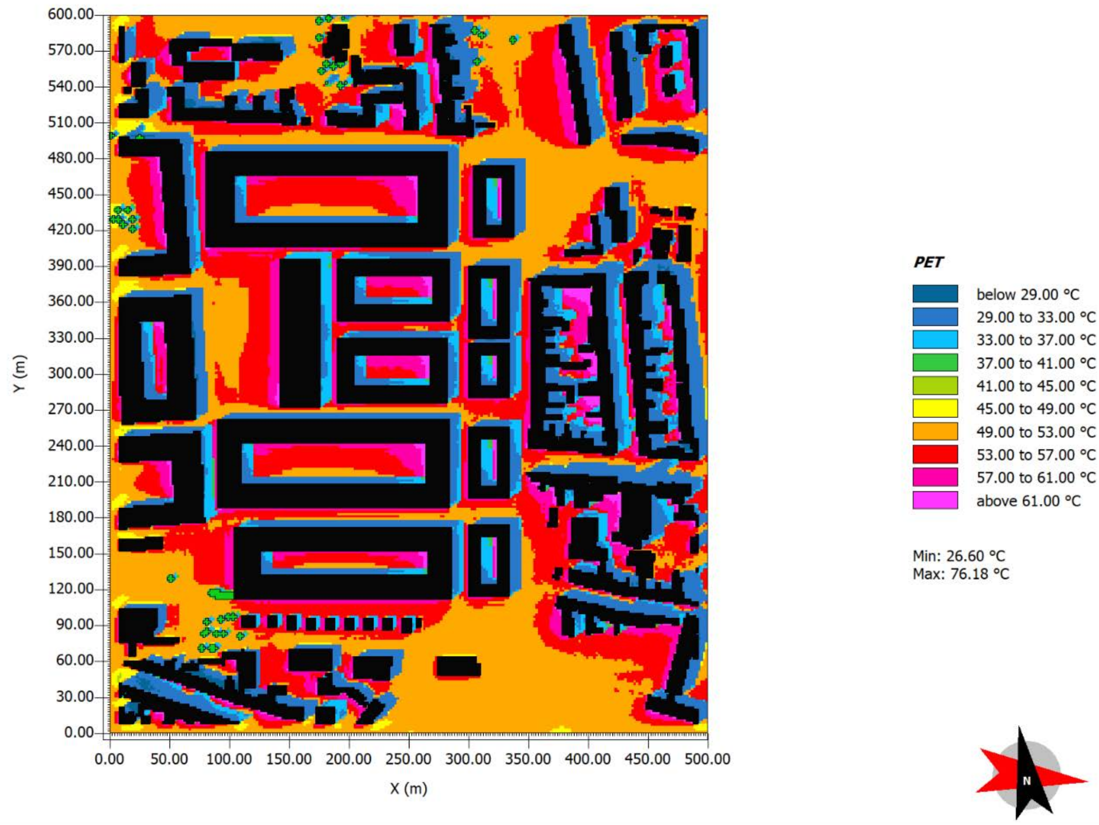
Source: Own illustration, ENVI_MET

2.2.5.3.2 Results of current microclimate simulations

As already mentioned at the beginning, due to the major changes in the building structure, there is a deviation from the previous scheme of the illustration boards. For the Cologne study area, the simulation results for 4:00 a.m. are compared in Appendix A.3 in Panel_3_a_Koeln_04h for the status quo and the optimised case, while Panel_3_b_Koeln_16h provides the results for the 4:00 p.m. situations. The detailed simulations (Panel_3_c_Koeln_Detail) are processed in the same way. In the present case, direct differences are not shown due to the intervention in the building structure.

The distribution of air temperatures in the Status Quo case shows a relatively even structure over the area, with temperature differences rarely exceeding 1 K between the warmest and coldest areas. The building blocks show only a weak differentiation in the inner courtyards both at 4:00 p.m. and at 4:00 a.m., which is because they are structurally closed, but only have a low building height of 12 m. This allows the wind to intervene well in the structure and blur local temperature differences.

Figure 56: Distribution of the PET value in Cologne on July 25 at 4:00 p.m. for the status quo

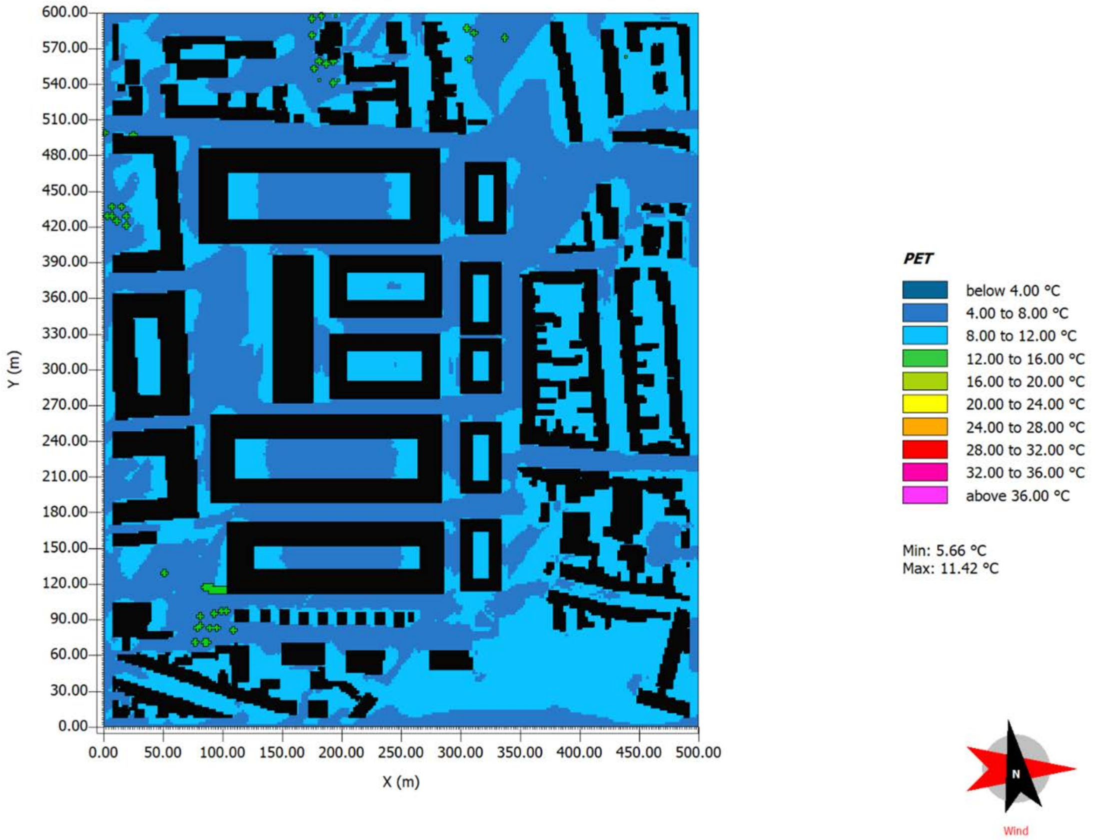


Source: Own illustration, ENVI_MET

The thermal comfort distribution (Figure 56) reflects both the high absolute air temperature and the strong structuring of the study area.

Within the building blocks, the thermal areas can be differentiated into the shaded and the sunny courtyard side, whereby both with approx. 35 °C in the shade and over 57 °C in the sun can be assigned to the hot and very hot area. These extreme values are due to a combination of several unfavourable factors: on the one hand, the air temperatures are very high according to the model assumptions, on the other hand, the wind speeds in these backyard areas are very low, so that no physiological cooling effect can occur on the skin. Another factor, especially near the facades and in the corner areas of the inner courtyards, is the short-wave radiation reflected from the facades as an additional burden.

Figure 57: Distribution of the PET value in Cologne on January 18 at 4:00 p.m. for the status quo



Source: Own illustration, ENVI_MET

The thermal situation on January 18 at 4:00 p.m. is shown in Figure 57. At this time, the angle of the sun is already too small to affect the PET distribution. The small differences observed in the PET distribution are due to differences in air temperature and wind speed. The wind-protected areas in the inner courtyards are slightly warmer than those that are a little more exposed to the wind, but they can all be assigned to the 'cool' or 'slightly cool' sensitivity range.

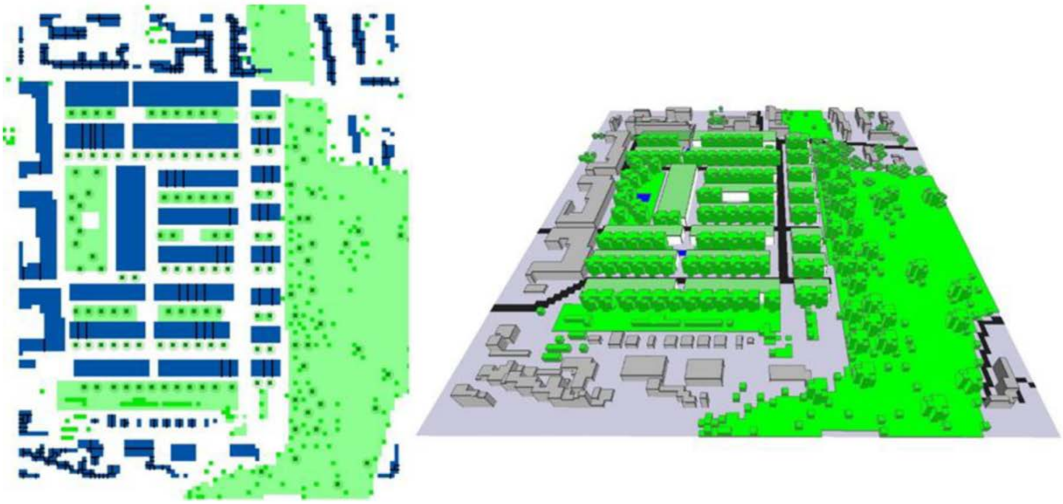
2.2.5.3.3 Optimised variant

In the Northern latitudes, in contrast to more southern areas such as the MENA region, there is no perennial heat stress problem. There is much more tension between heat and cold stress, which makes it much more difficult to select suitable measures that improve the microclimatic conditions outdoors in both the winter and summer months. Here it is important to find measures that reduce both the heat stress in summer and the cold stress in winter to which people are exposed outdoors.

To optimise the ventilation of the area, the building blocks were broken up and converted into terraced houses. The roofs and east walls of the buildings were provided with extensive green roofs and facades. Trees have been integrated between the rows of buildings to take advantage of the positive effects of vegetation on the local microclimate. In addition, passive water elements (water without water movement or fountains) were also integrated between the buildings.

The vegetation density in the model area was significantly increased overall. As a result of these measures, the proportion of green areas was greatly increased and thus the degree of sealing was significantly reduced.

Figure 58: Model area of the optimised variant as top view and 3D view



Source: Own illustration, ENVI_MET

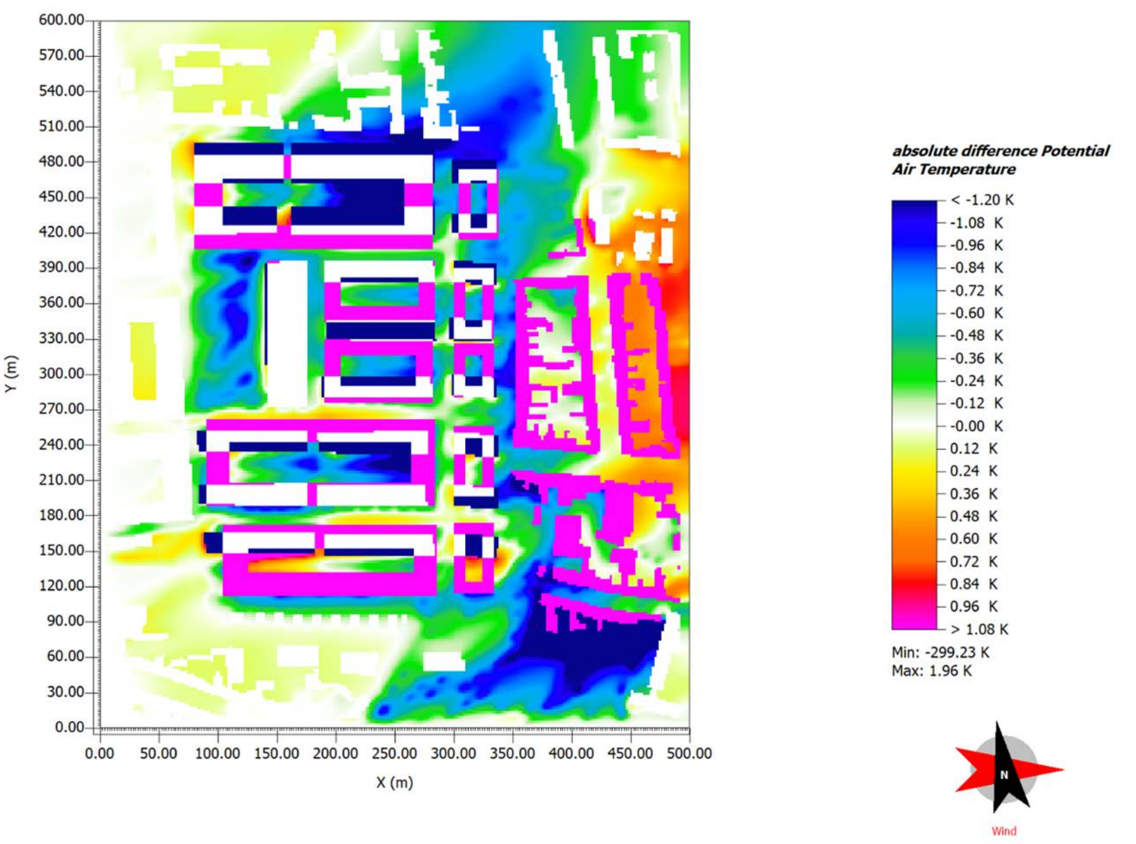
2.2.5.3.4 Results of microclimate simulations (optimised state)

The illustrations on Panel_3_a_Koeln_04h, Panel_3_b_Koeln_16h and Panel_3_c_Koeln_Detail in Appendix A.3 initially show the distribution of the air temperature as absolute values. Due to the major changes in both the building structure and the vegetation, the variants can only be directly compared to a limited extent.

By breaking up the building blocks, the entire area becomes much more permeable to the wind, which is also reflected in a significantly lower differentiation of the air temperature than in the status quo case. Due to the creation of the green area in the east, the air temperature changes significantly here. In winter and spring, the air temperature in this area is now higher than in the status quo case, since the sun can reach the ground unhindered. In summer, the cooling effect of the grassy area and trees has an effect, so that lower temperatures are observed here.

Figure 59 shows the changes in air temperature directly. The complex structure between cooling and warming areas is clearly evident, as is the dynamic distribution of temperature due to the better flowability of the area. The increased proportion of green reduces the air temperatures in the western part by up to 1.5 K, whereby the places where buildings used to stand cannot be interpreted. In the area of the new green area in the east, an increase in air temperature of up to 0.8 K can be observed. As already noted, this is due to the increase in solar radiation, since there is no shadowing from distant buildings. In the after hours, however (see Appendix A.3, Panel_3_c_Koeln_Detail), the cooling effect of the newly created open space can be clearly seen.

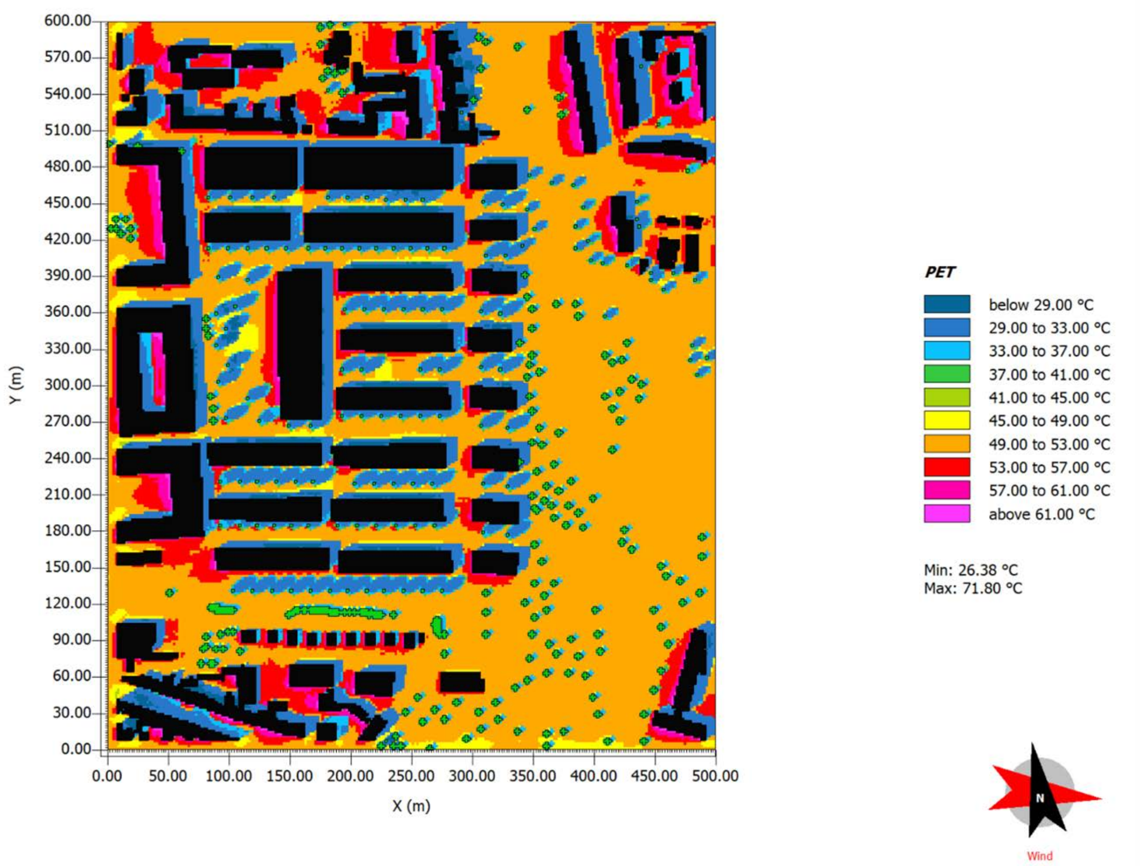
Figure 59: Difference in air temperature between the status quo and the optimised variant in July



Source: Own illustration, ENVI_MET

Figure 60 shows the distribution of the absolute PET value for the optimised scenario. You can clearly see that due to the high air temperature, very large areas can still be assigned to the 'very hot' sensitivity level, but the extreme areas that can still be observed in the status quo with a PET of 60 °C and more are only directly in front of the sunlit facades are found. PET temperatures around 30 °C now dominate in the shaded areas, which can be assigned to the comfortable to slightly warm range. This was only very rarely observed in the shadow areas of the status quo scenario. Both the reduced air temperature and the better ventilation of the areas have a positive effect here.

Figure 60: Distribution of the PET value in Cologne on July 25 (4:00 p.m.) for the optimised scenario

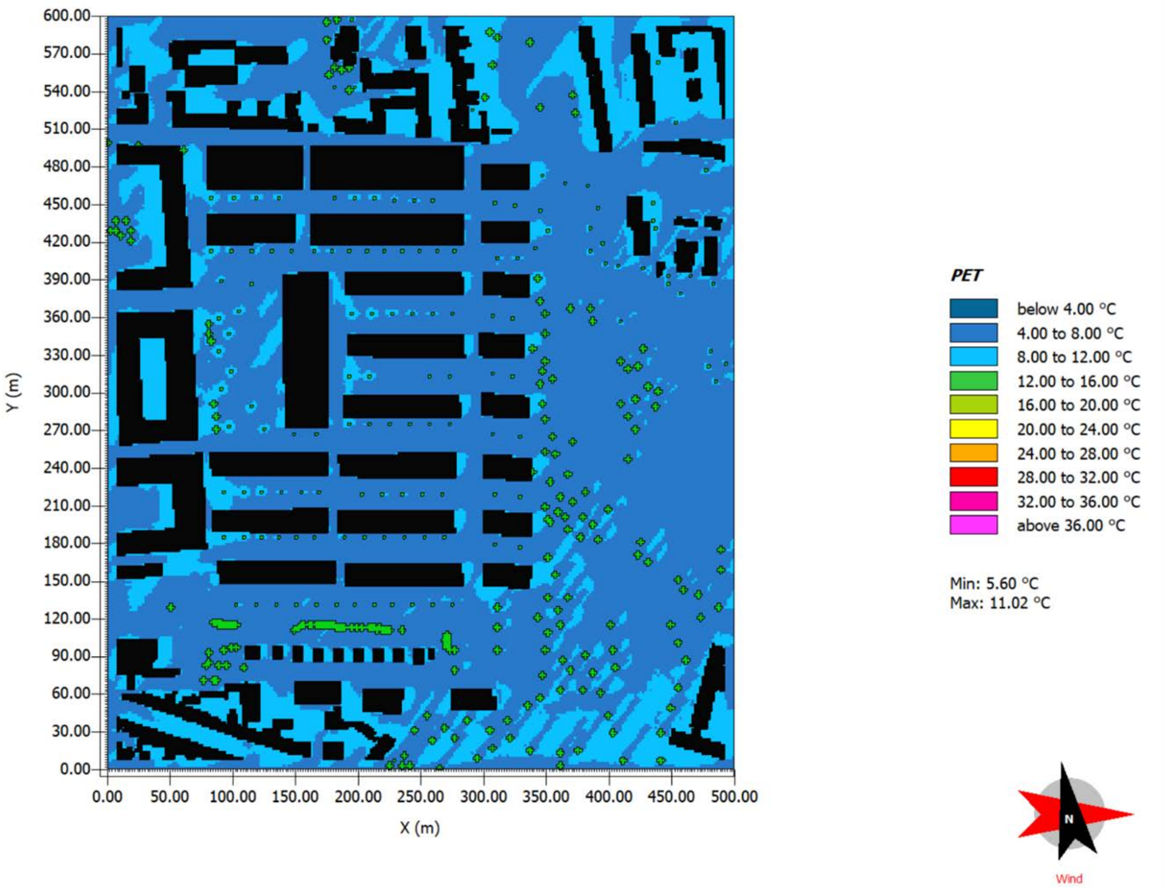


Source: Own illustration, ENVI_MET

As already indicated in the description of the optimisation measures, there is a certain tension between the optimisation of the outdoor space for summer use and the resulting consequences for winter use. In the following, this is to be presented once for the example of Cologne. However, the interpretation must be viewed against the background that the use of outdoor space in winter and to a certain extent also in the transition months is less climate-sensitive than in summer. On the one hand, the use of outdoor space to linger is of secondary importance at this time of year, at least in the more Northern countries since the weather is generally too cold and unstable. On the other hand, you can easily adapt to cooler conditions by wearing suitable (warmer) clothing, which is only possible to a limited extent regarding heat stress in summer.

Figure 61 shows the PET distribution for the optimised scenario in January. The distribution of colours already shows that the size of the dark blue areas has increased.

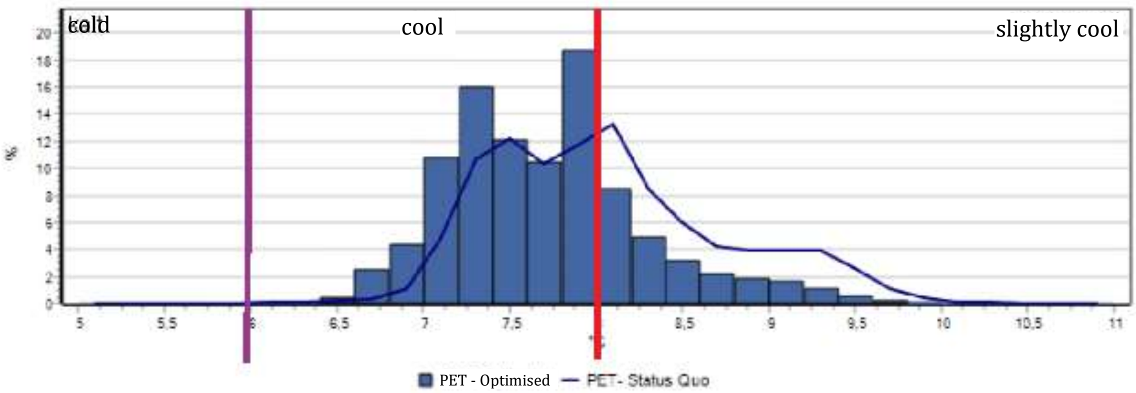
Figure 61: Distribution of the PET value in Cologne on January 18 (4:00 p.m.) for the optimised scenario



Source: Own illustration, ENVI_MET

This is an inevitable consequence of the improved ventilation of the study area, which leads to higher local wind speeds than in the more densely built-up status quo. Figure 62 shows the frequency distribution of the various PET values for the status quo and the optimised scenario. In addition, the areas of the comfort classes 'cold', 'cool' and 'slightly cool' marked with the limit values 6 °C and 8 °C. One can clearly see that in the optimised scenario the number of slightly cool areas decreases and the number of areas perceived as cool increases slightly.

Figure 62: Comparison of the PET distribution between the status quo (blue line) and the optimised scenario (bars) in winter



Source: Own illustration, ENVI_MET (screenshot from software: ENVI-MET)

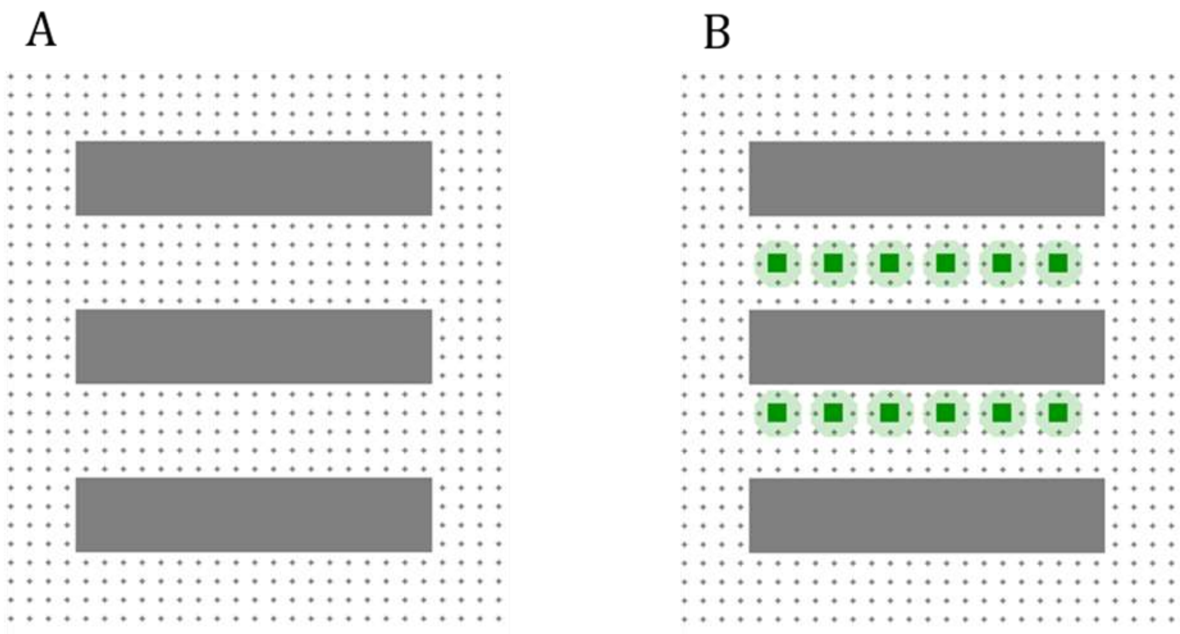
2.2.5.3.5 Summary assessment

For the Cologne study area, it was shown how the microclimate and thermal comfort, especially in summer, can be positively influenced by massive restructuring measures. The abandonment of closed structures such as building blocks leads to improved ventilation of the area, which, together with various greening measures, can significantly improve thermal comfort. It could be shown that the PET value depends primarily on the solar radiation, but fine differentiations can be observed due to the effects of wind and air temperature.

2.2.5.3.5.1 Excursus air temperatures in front of the facades

When evaluating the simulation data for transfer to the building physics simulation, it was noticeable that the air temperature of the optimised scenario in summer sometimes showed higher air temperatures on the facade elements observed than in the actual state. However, this cannot be attributed to the trees digitized in front of the buildings, but rather to the general differences in the development structure between the model areas. To investigate the effects of large-canopy trees in front of facades in isolation, one-month simulations were carried out, which showed a reduction in air temperature. The arrangement of the buildings and the trees in the green scenario in the one-month simulations can be seen in Figure 63. Similar to the year-round simulations, the buildings are aligned in an east-west direction, all other parameters such as resolution, materials and climatic input data were selected according to the quarter simulations.

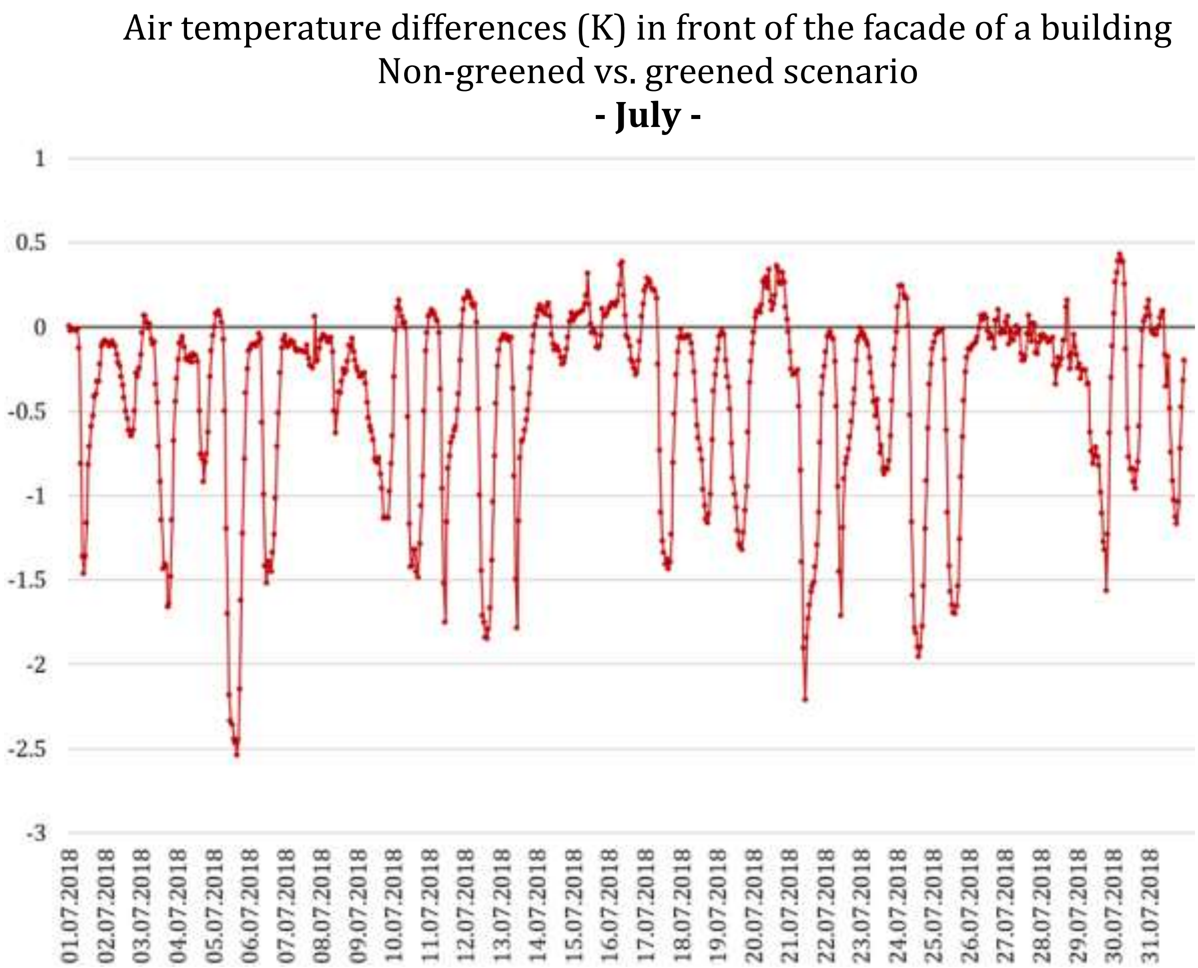
Figure 63: Section of the model area for partial simulation without vegetation (A) and with vegetation (B)



Source: Own illustration, ENVI_MET

Comparing the air temperatures in front of the buildings (Figure 64) an overall air temperature-reducing effect due to the added vegetation of around -0.4 K on average can be observed. There are strong daily fluctuations, which can be explained by photosynthesis and the influence of transpiration associated with it: Since photosynthesis only takes place during the day and thus a flow of transpiration is created, a latent heat flow is generated, which leads to a massive reduction in air temperature. At night, when there is no photosynthesis due to the lack of short-wave radiation, either no or very small increases in air temperature can be observed due to the introduced vegetation. This in turn can be explained by the reduction in the sky view factor: the long-wave radiation transport is slightly impeded by the large-canopy trees, which can slightly reduce the nocturnal cooling rate.

Figure 64: Air temperature differences [K] in front of the facade of a building



Source: Own illustration, ENVI_MET

2.2.5.4 Building simulation

2.2.5.4.1 The simulation model

The evaluation area consists mainly of apartment buildings with a moderate window area of 25%, which can be assumed to be similar in terms of geometry and building physics. The evaluations regarding consumption and comfort were carried out at apartment level. Depending on the location and orientation of the apartments in the building and area, there are differences in energy demands and interior comfort.

Regarding the geometry, a representative apartment with 112 m² of living space was initially chosen, which was divided into two zones for the modelling (Z1: living- and dining room, Z2: bedroom and children's room).

The living and dining rooms were always oriented to the south as far as possible.

Figure 65: Qualitative positioning and orientation of the apartments and zones in the building blocks in the status quo scenario

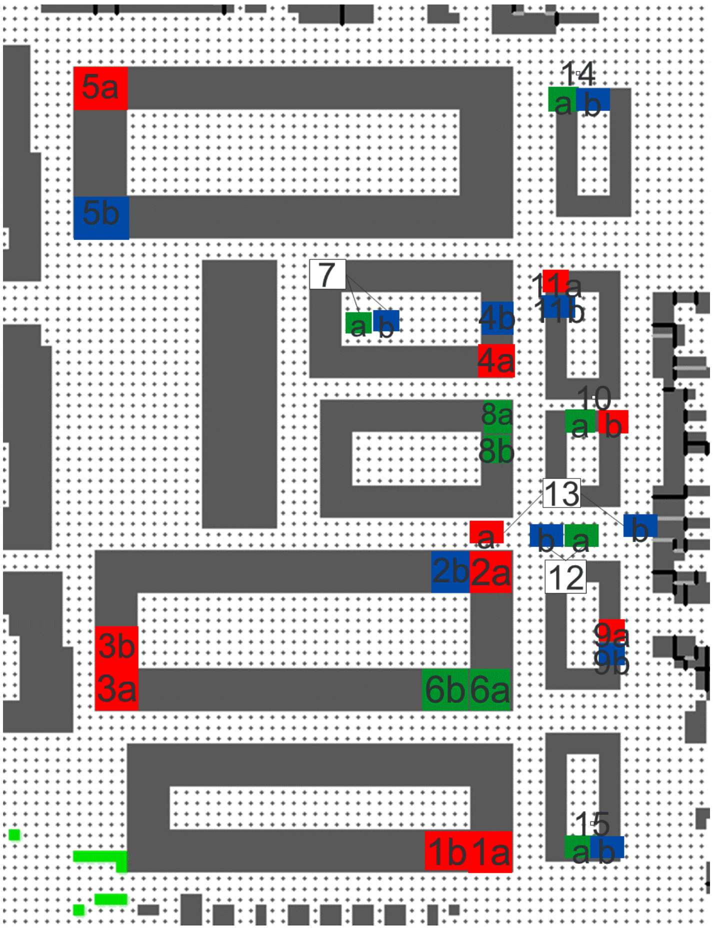
Above: North; Z1: Living- and dining room; Z2: Bedroom and children's room.

Source: Own illustration, Guidehouse

When distributing the representative reference apartments, care was taken to ensure that all orientations and all locations in the building and in the quarter were suitably considered.

The locations of the reference apartments in the quarter are shown in the following illustrations.

Figure 66: Location of the reference apartments in the quarter in the initial state (status quo)



Red: Top floor, blue: Middle floor, green: Ground floor

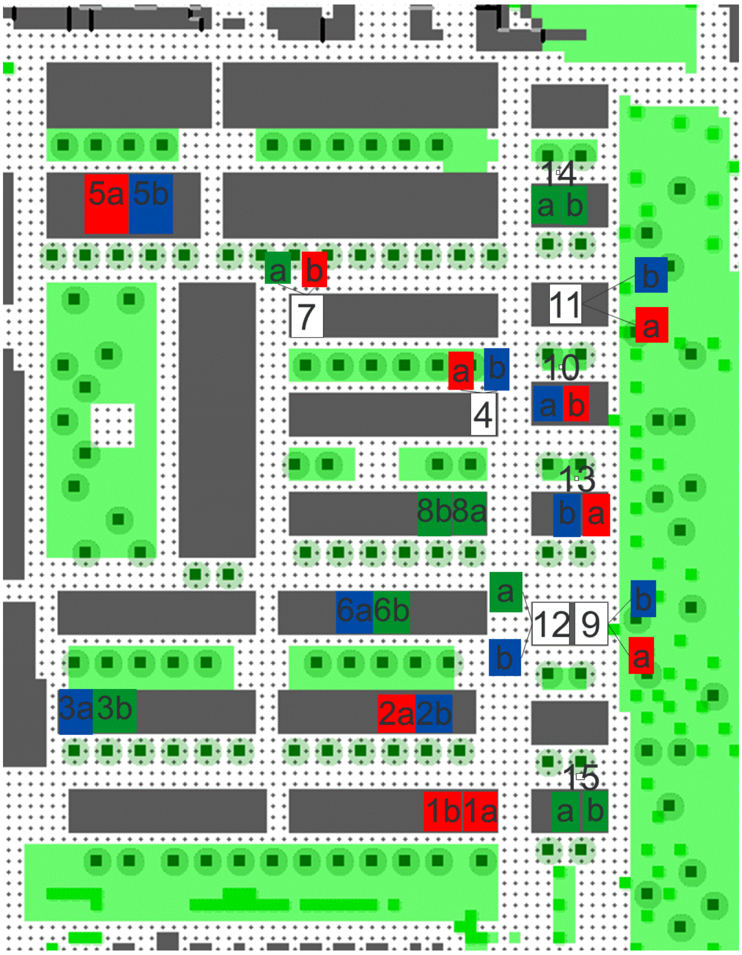
Source: Own illustration, Guidehouse and ENVI_MET

In the initial state (status quo), the 30 reference apartments represent a total of 903 apartments with a total living space in the quarter of approx. 100,000 m^2. The most relevant are the middle-floor apartments on the long sides of the apartment blocks (1b, 2b and 6b), each representing 15% of the total living space.

Since the building geometries were also changed during the quarter optimization, the locations of the apartments are different for the optimised scenario.

The optimization reduces the number of apartments to 555 and the living space to 62,000 m^2 i.e. almost 40% less than in the initial state.

Figure 67: Location of the reference apartments in the optimised quarter



Red: Top floor, blue: Middle floor, green: Ground floor
Source: Own illustration, Guidehouse and ENVI_MET

2.2.5.4.2 Variants

The following table summarizes the variants considered in the building simulation.

In the basic variants, heat supply via central gas boilers was assumed instead of district heating. Climate-neutral quarter heating was provided in the Optimised 3 variant. Natural ventilation cooling via windows was considered in all variants[37]. Furthermore, an effective external sun protection (external venetian blinds in the so-called cut-off position[38]; fc=0.2) was also assumed as a shading device in all variants, which is closed during the day (from 7 a.m. to 5 p.m.) in the summertime.

The variants Optimised 1 and Optimised 2 are used for comparison with the corresponding Status Quo variants (SQ1 and SQ2). Variant Optimised 1 is used to check whether and to what extent cooling can be dispensed simply by means of quarter optimization measures. The variants Optimised 3 and Optimised 4 represent target concepts with regard to achieving climate neutrality.

[37]Ventilation of the living/dining area in summer when the room temperature is > 24 °C and the outside temperature is < room temperature with 6 l/h (6 a.m. to 7 a.m.) 4 l/h (4 p.m. to 10 p.m.). In summer, night-time ventilation via tilted windows was assumed in the bedroom when the outside temperature was > 15 °C and the outside temperature was < room temperature.

[38]The cut-off position of external venetian blinds ensures maximum transparency with complete shading of direct sunlight.

Variant Optimised 3 is intended to check whether the situation can be achieved by improving the thermal qualities[39]. Finally, the variant Optimised 4 represents a solution in which a sustained high level of comfort can also be ensured in the critical apartments.

Table 15: Overview of the variants examined for the Cologne quarter

	SQ1 (without cooling)	**SQ2** (with cooling)	**Optimised 1** (without cooling)	**Optimised 2** (with cooling)	**Optimised 3** (without cooling)	**Optimised 4** (with cooling)
Shell quality[40]	Efficiency House 55	Efficiency House 55	Efficiency House 55	Efficiency House 55	Efficiency house 40	Efficiency house 40
Heat	Gas - condensing boiler, underfloor heating	Gas - condensing boiler, floor heating	Gas - condensing boiler, floor heating	Gas - condensing boiler, floor heating	Climate-neutral district heating, underfloor - heating	Geothermal heat pump with natural refrigerant, underfloor - heating
Cool	-	Split air conditioner - (26 °C)	-	Split air conditioner - (26 °C)	-	Underfloor - cooling via ground cold (26 °C)
Ventilation	Exhaust air system 0.4 1/h	Exhaust air system 0.4 1/h	Exhaust air system 0.4 1/h	Exhaust air system 0.4 1/h	Supply/ exhaust air system with heat recovery (80%) 0.4 1/h	Supply/ exhaust air system with heat recovery (80%) 0.4 1/h
PV system and battery storage[41]					Per apartment: PV: 3.5 kWp Battery: 3kWh	Per apartment: PV: 3.5 kWp Battery: 3kWh

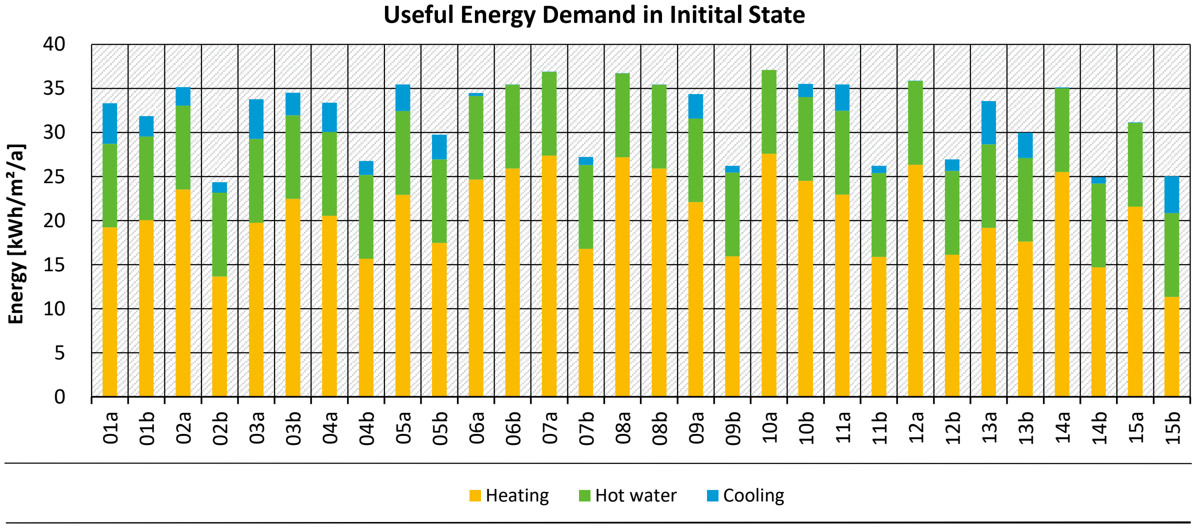
2.2.5.4.3 Results

2.2.5.4.3.1 Status quo

The figure below shows the useful energy demand of the reference apartments in the initial state (SQ2). The heating energy demand accounts for the largest share with values between 12 kWh/m^2 and 27 kWh/m^{2}a, followed by the hot water requirement with almost 10 kWh/m^{2}a. The cooling energy demand is particularly relevant in attic apartments with up to almost 5 kWh/m^{2}a. Some of the ground floor apartments have no cooling energy demands.

[39]The heat protection in summer is already optimal thanks to the measures described and can no longer be significantly improved.
[40] Specific to the German efficiency standard
[41]The size of the PV systems given in the table represents the maximum in terms of the occupancy of the roof areas.

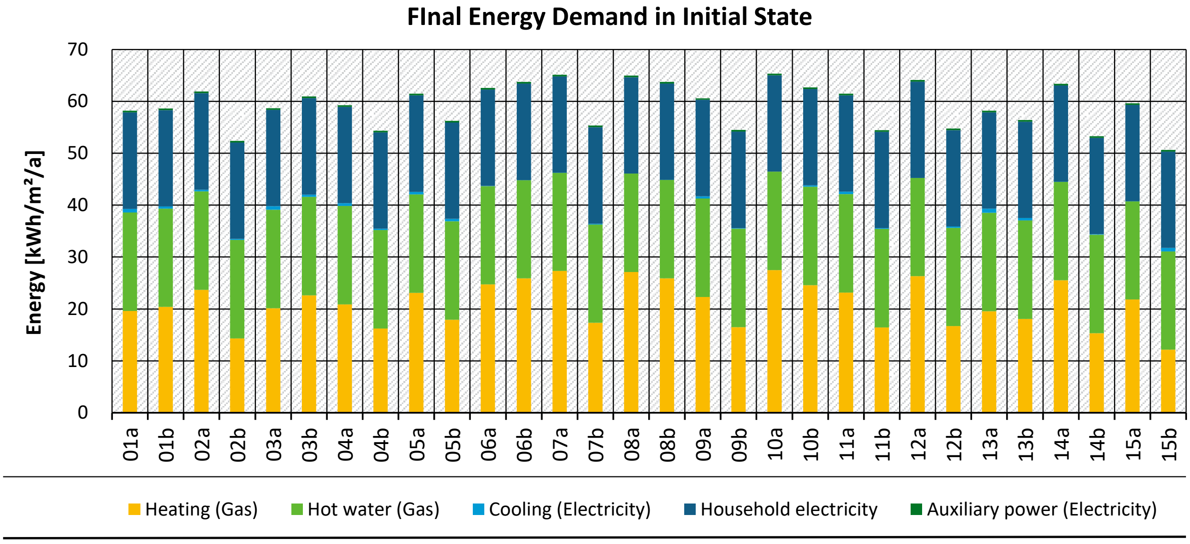
Figure 68: Useful energy demand of the reference apartments in the initial state (variant SQ2)



Source: Own illustration, Guidehouse

When considering the final energy consumption, assuming a reduced household electricity requirement of just under 19 kWh/m^{2}a [42] and the system losses [43], the picture shown in the following figure shows a very balanced distribution across the areas of heating, hot water and household electricity, each accounting for around a third of the total consumption. The final energy demand for auxiliary energy and cooling plays only a minor role.

Figure 69: Final energy consumption of the reference apartments in the initial state (variant SQ2)



Source: Own illustration, Guidehouse

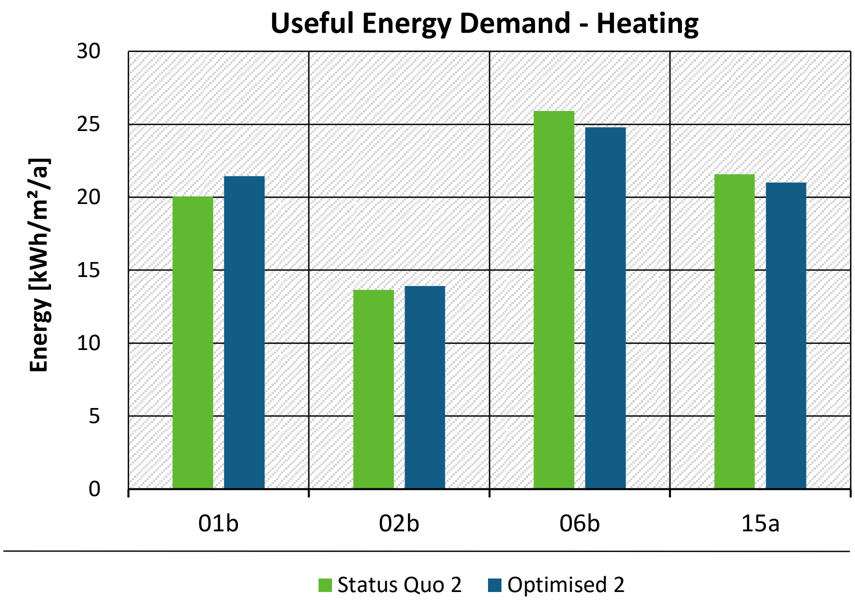
2.2.5.4.3.2 Optimised scenario

A comparison of the useful energy demand for heating the apartments that are most comparable in terms of location and geometry (01b, 02b, 06b and 15a, Figure 70) for the variants SQ2 and Optimised 2 does not show any uniform advantages for the optimised scenario. As a result, the

[42] 2,100 kWh/a were assumed per apartment. Achieving this requires low dwelling density and very efficient appliance equipment, most likely to be found in new high quality buildings.
[43] Significantly, especially for hot water, due to the required circulation systems.

optimization measures in the quarter with the same apartment location and geometry have no significant impact on the heating energy demand.

Figure 70: Comparison of the useful energy demand for heating between the initial state (SQ 2) and the optimised quarter (Optimised 2)

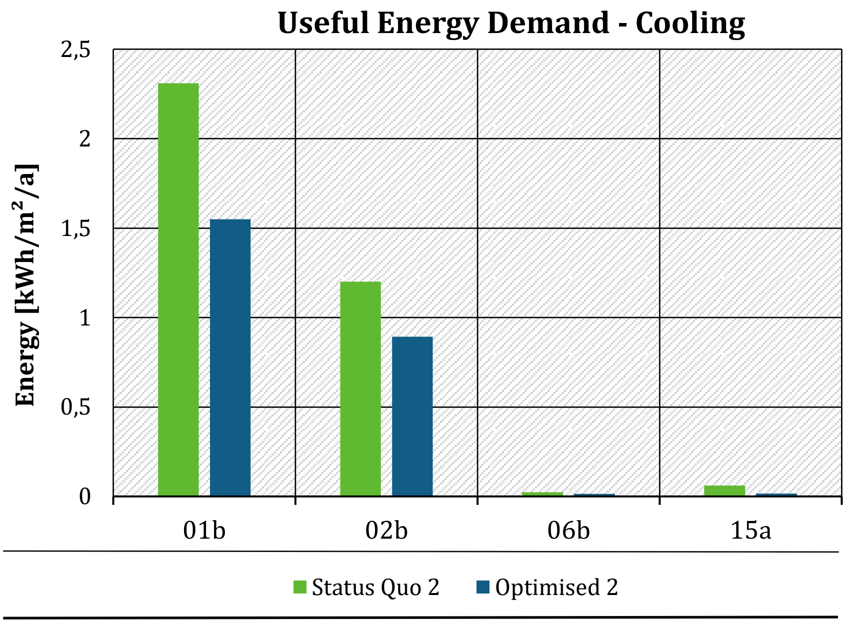


Source: Own illustration, Guidehouse

Due to the less compact construction in the optimised quarter, the corner apartments have one more exterior wall than those in the high-density status quo quarter. The heating energy demand in these apartments is therefore even slightly higher.

However, a clear difference can be seen in the useful energy demand for cooling. The already low demand can be further reduced by the quarter optimization measures, which is mainly due to the shadowing of the trees.

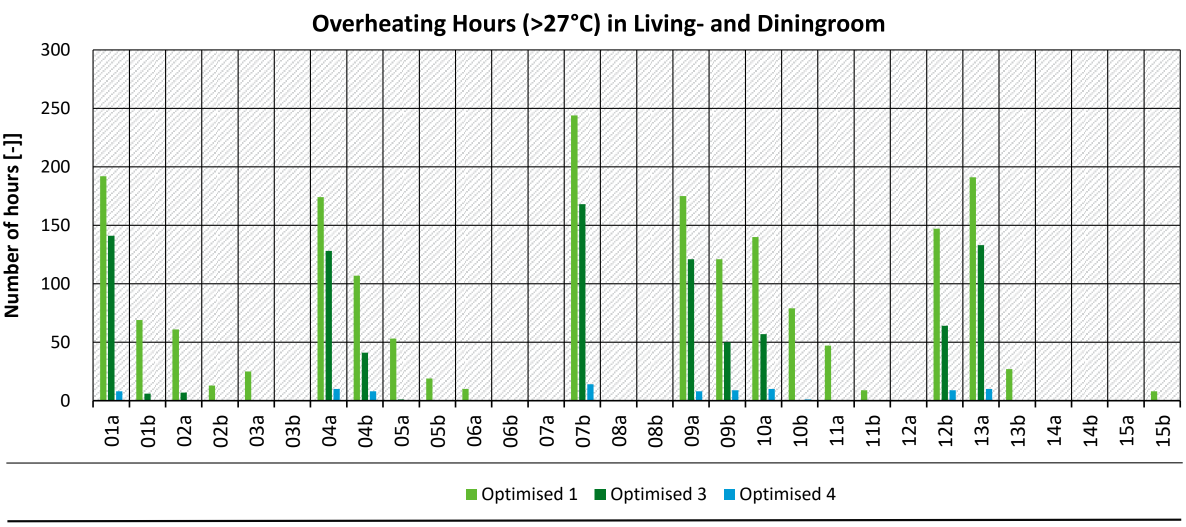
Figure 71: Comparison of the useful energy demand for cooling between the initial state (SQ 2) and the optimised quarter (Optimised 2)



Source: Own illustration, Guidehouse

The hours of overheating (>27 °C) in the zones of the reference apartments of the optimised variants during use in summertime are shown below.

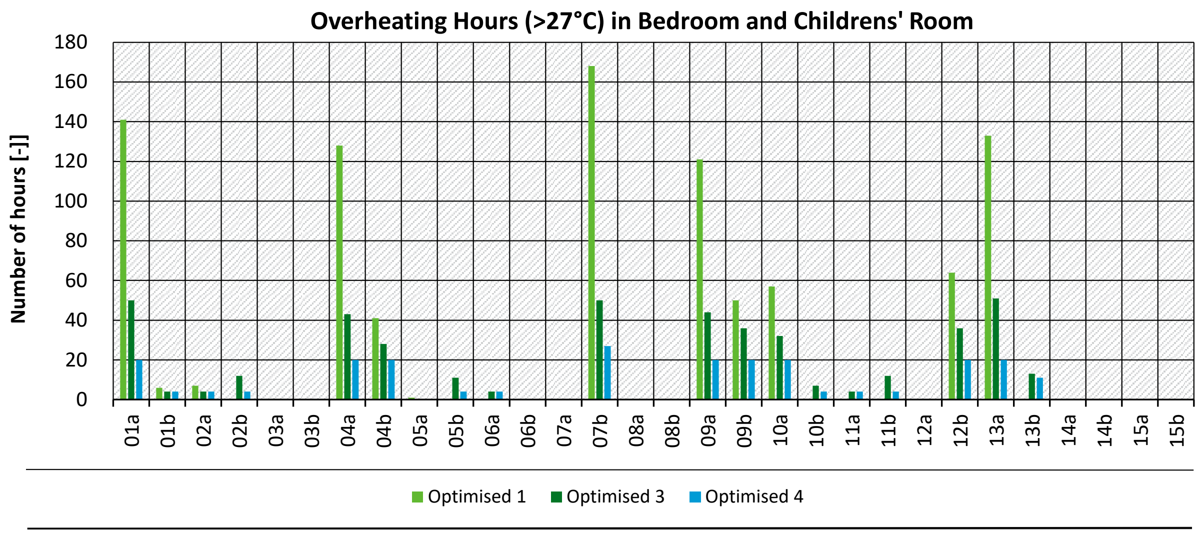
Figure 72: Comparison of overheating hours in the living/dining area of individual apartments



Quarter Optimised 1: Efficiency House 55; Optimised 3: Efficiency House 40; Optimised 4: Efficiency house 40 + passive underfloor cooling.

Source: Own illustration, Guidehouse

Figure 73: Comparison of overheating hours in bedrooms and children's rooms



Quarter Optimised 1: Efficiency House 55; Optimised 3: Efficiency House 40; Optimised 4: Efficiency house 40 + passive underfloor cooling.

Source: Own illustration, Guidehouse

The annual overheating hours in the variant Optimised 1 are sometimes well over 100 h/a in about half of the apartments[44]. An additional evaluation of the t_{imax}-exceeding hours of the maximum interior temperature of the lowest comfort category 3 according to EN 15251 shows, for example, an excess time of 156 hours for apartment 01a and 152 hours for apartment 04a. With more than 10% of the usage time in summer, these exceeding times are beyond the acceptable range, which is given as 3 to 5%. By improving thermal protection, the overheating hours can be significantly reduced, but they are still in a critical range in 1/3 of the apartments examined (exclusively attic apartments) in the 'living/dining area' zone in particular. Only cooling, here in the form of passive floor cooling using the cold (stored in the ground in winter) from the geothermal stacks (variant Optimised 4), largely eliminates the overrun hours. Only in a few apartments there still are isolated hours that are exceeded, which can be attributed to the limited performance of the floor cooling.

With regard to the desired climate neutrality, the available roof area is the limiting factor. As can be seen from the following figure, it is currently not possible for the buildings to be completely climate-neutral without an additional external supply. In the variant Optimised 3, the external supply is guaranteed by climate-neutral district heating. This makes it possible to achieve the desired climate neutrality, at least in terms of the annual balance (considering the electricity fed into the grid[45]). An increase in battery storage would not lead to a significant increase in the proportion of self-used PV electricity.

Taking the corresponding CO_2 emission factors[46] into account, the variant Optimised 1 (envelope in accordance with the German Efficiency House 55 standard and a gas condensing boiler) including household electricity results in average specific CO_2 emissions of the apartments of approx. 17 kg/m²a. In the variant Optimised 4, there are still approx. 5 kg/m²a left over the

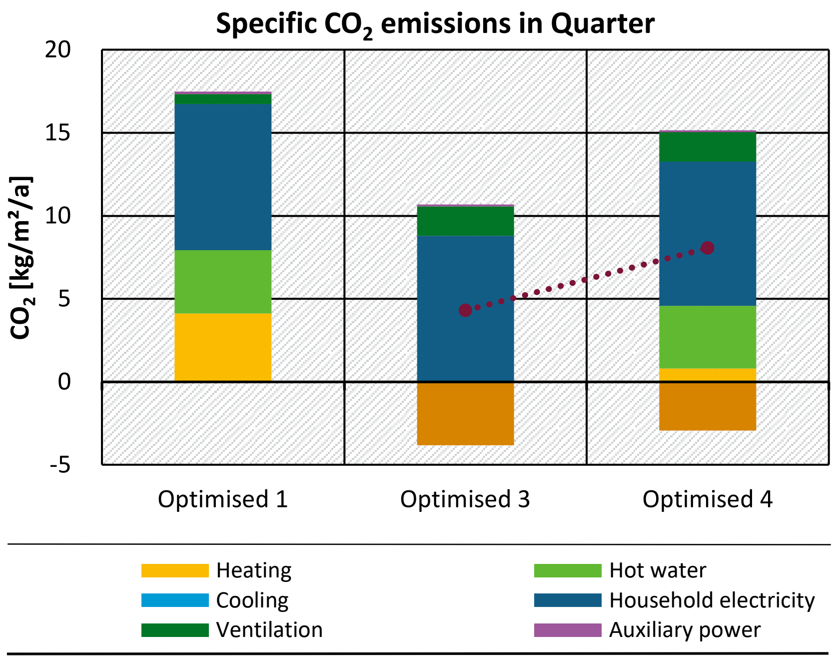
[44]In summer, the total usage time for the living/dining area is 1,071 h/a and for the bedroom and children's room 1,220 h/a

[45]In the variant examined, the electricity drawn from the grid still slightly outweighs the proportion fed into the grid.

[46]0.474 g/kWh for electricity mix, source: Umweltbundesamt 2021 (value for 2018; assumption: same values for grid procurement and feed-in); 0.201 g/kWh for natural gas, source: Juhrich 2016; 0 g/kWh for (climate-neutral) district heating.

annual balance (=> difference in grid electricity demand – PV feed-in). Although this is a reduction of more than 70% compared to Optimised 1, it requires the external provision of climate-neutral electricity to achieve climate neutrality. This will happen in the medium term through the further expansion of renewable energies in the electricity sector.

Figure 74: Comparison of CO_2 emissions of the variants for the optimised quarter



Optimised 1: Without cooling, efficiency house 55; Optimised 3: Without cooling, efficiency house 40; Optimised 4: Passive underfloor cooling, efficiency house 40. Dots indicate remaining CO_2 emissions considering the directly usable PV.

Source: Own illustration, Guidehouse

Considering differentiated electricity emission factors[47], which take into account a higher CO_2 emission factor[48] for both (the generated PV electricity and for the electricity for heat generation), the calculated climate neutrality would already be achieved for the Optimised 4 variant. For the Optimised 3, there would even be a calculated CO_2 emission sink.

Although not the focus of this research project, it should not go unmentioned at this point that the building construction also plays a decisive role in the goal of climate neutrality, especially in new buildings. Therefore, the above concepts should definitely be implemented taking into account sustainable building constructions (e.g., timber construction from sustainable forest management).

[47]The assumption of an increased emission factor for heat generation from electricity (here heat pumps and ventilation heat recovery) compared to the electricity mix can be justified as follows: Since heat generators that use other energy sources (e.g. biomass boilers) could also be used instead of heat pumps, their electricity requirements represent an avoidable, additional load for the power grid. This additional power requirement must be met by means of non-renewable power generation at times when there is no 100% supply from renewable energies. On the same basis of argument, an increased CO_2 emission factor can also be assumed for renewable PV electricity.

[48]Assumption: 860 g/kWh (displacement electricity mix (GEG 2020))

2.2.5.4.3.3 Summary assessment

The calculated cooling energy demand can be reduced through the optimisation measures in the quarter. However, since this is already comparatively low, the effects of the quarter measures on the building level are small. Significantly greater effects are achieved by improving the energetic envelope qualities. In the attic apartments in particular, however, even these measures in the optimised quarter are not sufficient to ensure good thermal comfort during the average summer considered. This can only be achieved by additional cooling measures. Adequate comfort can be ensured in all apartments by a passive floor cooling system. Since the comfort problems occur primarily in the top floor apartments, but the total cooling energy demand is low, efficient split air conditioning units with climate-friendly natural refrigerants would also be an option, provided they are available on the market. In combination with climate-neutral district heating (see variant Optimised 3) and photovoltaic systems[49] on the roofs, annually balanced climate neutrality (including household electricity) could be achieved. Depending on the calculation approach, an annually balanced climate neutrality of the buildings is also achieved for the variant Optimised 4. However, the solutions examined with a high thermal insulation standard and efficient or climate-neutral heat supply lead in any case to a considerable reduction in the remaining energy demand and thus make an important contribution to the goal of climate neutrality.

[49]Per apartment: 3.5 kWp

2.2.6 Existing Quarter Hamburg Eimsbüttel - Generalsviertel (Gründerzeit block perimeter development)

2.2.6.1 Location and description

The study area is in the Northwest of the city of Hamburg.

Figure 75: Location of the general quarters in Hamburg Eimsbüttel

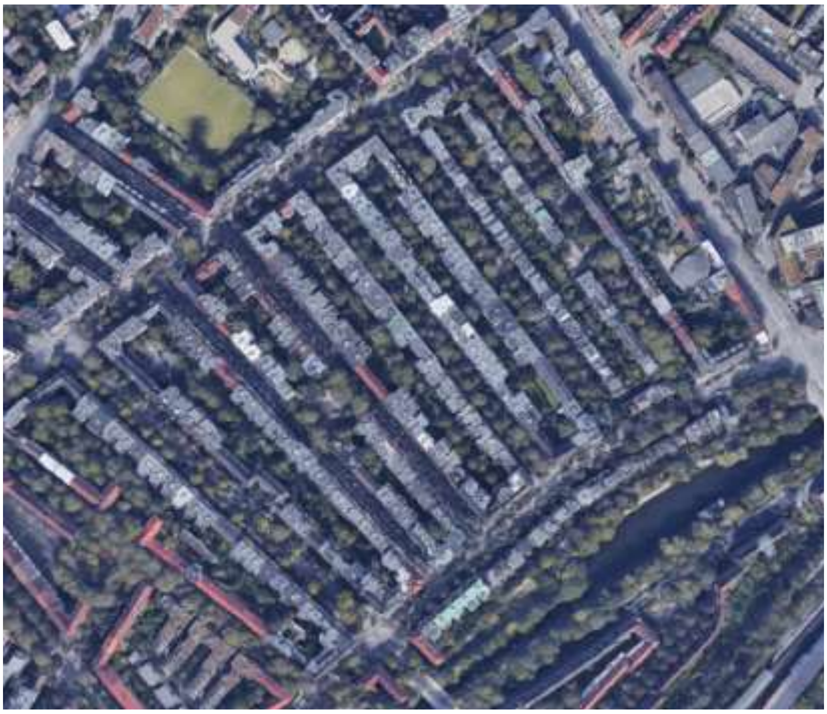
Source: Google

Figure 76: Location of the Generalsviertel in Eimsbüttel in the North of Hamburg (red circle)

Source: Own illustration, Guidehouse based on Google (background)

The predominant construction method are multi-storey buildings in slot construction on the courtyard side. The multi-family houses consisting of four to five storeys with largely light and decorated plaster facades and rich facade ornaments determine the character of the quarter. City villas are located in the Northwestern part.

Figure 77: Location of the evaluation area

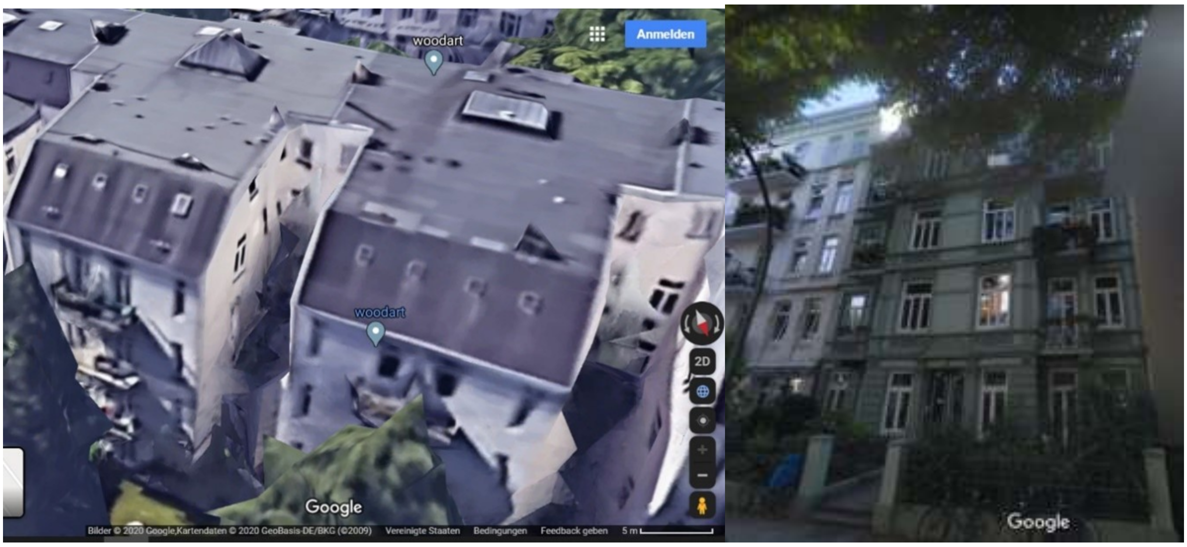


Source: Own illustration, Guidehouse based on Google (background)

Figure 78: Aerial view of the buildings in the model area

Source: Google

Figure 79: Building views



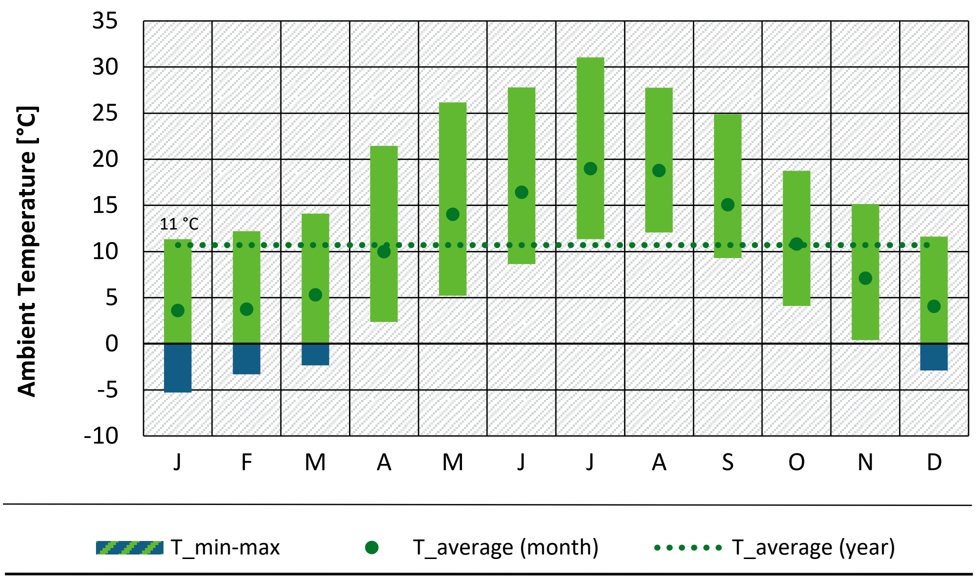
Typical backyard (left); typical street facade (right).

Source: Google

2.2.6.2 Climate

The reference climate data[50] for the Hamburg location was used as the basis for the calculations. The average annual ambient temperature is therefore 11 °C. The monthly mean values for the ambient temperature range from approx. 4 °C (January) to 19 °C (July). The summer peak values reach just over 30 °C.

Figure 80: Monthly ambient temperature in Hamburg

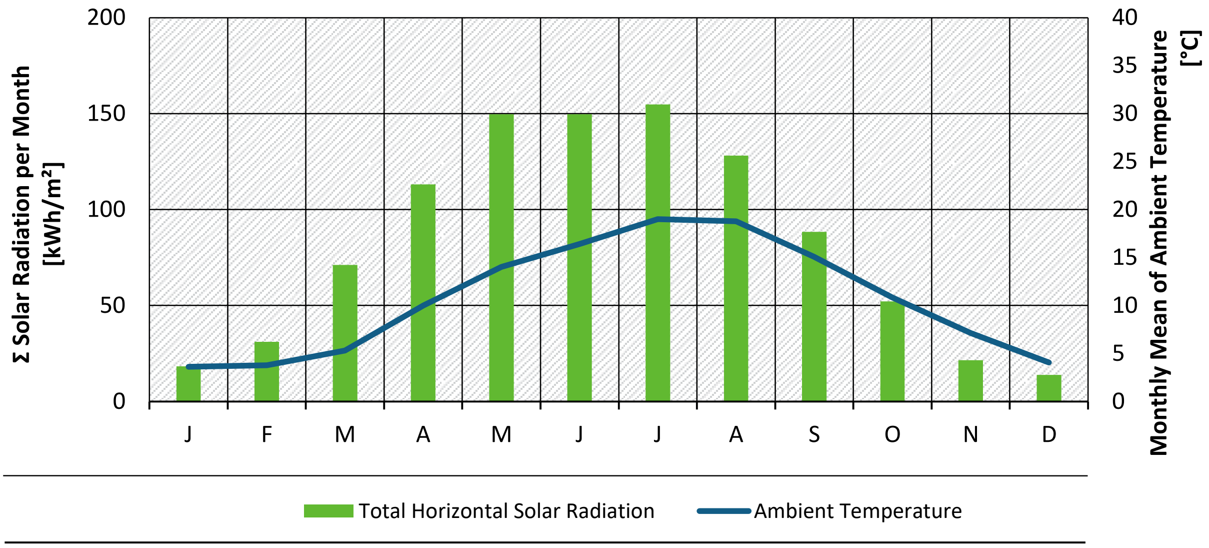


Source: Own illustration, Guidehouse

The annual global radiation is 967 kWh/m^{2}a. It is highest in July with approx. 150 kWh/m^2 and lowest in December with approx. 14 kWh/m^2.

[50] Source: Meteonorm software , version 7, most recent weather data set (period 2000-2009)

Figure 81: Monthly values for global radiation and outside temperature in Hamburg



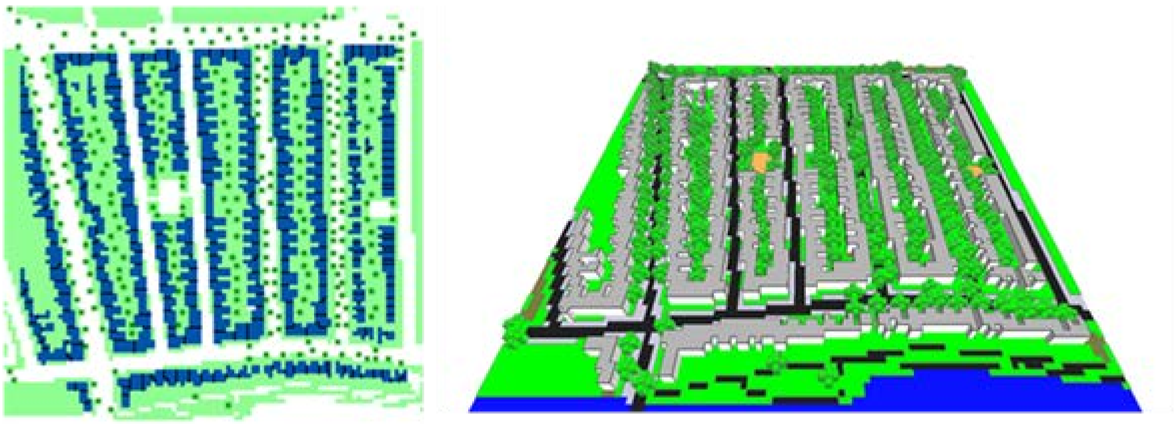
Source: Own illustration, Guidehouse

2.2.6.3 Microclimate simulation

2.2.6.3.1 Variant current state

The study area Eimsbüttel - Generalsviertel is located in the Northwest of the city of Hamburg. It is an existing quarter with apartment buildings. The area was digitized according to the current development with extensive old trees between the buildings. The building materials correspond to the construction described in Chapter 2.2.6.4.

Figure 82: Model area of the Generalsviertel (status quo) in Hamburg as a top view and 3D view.



Source: Own illustration, ENVI_MET

2.2.6.3.2 Results of current microclimate simulations

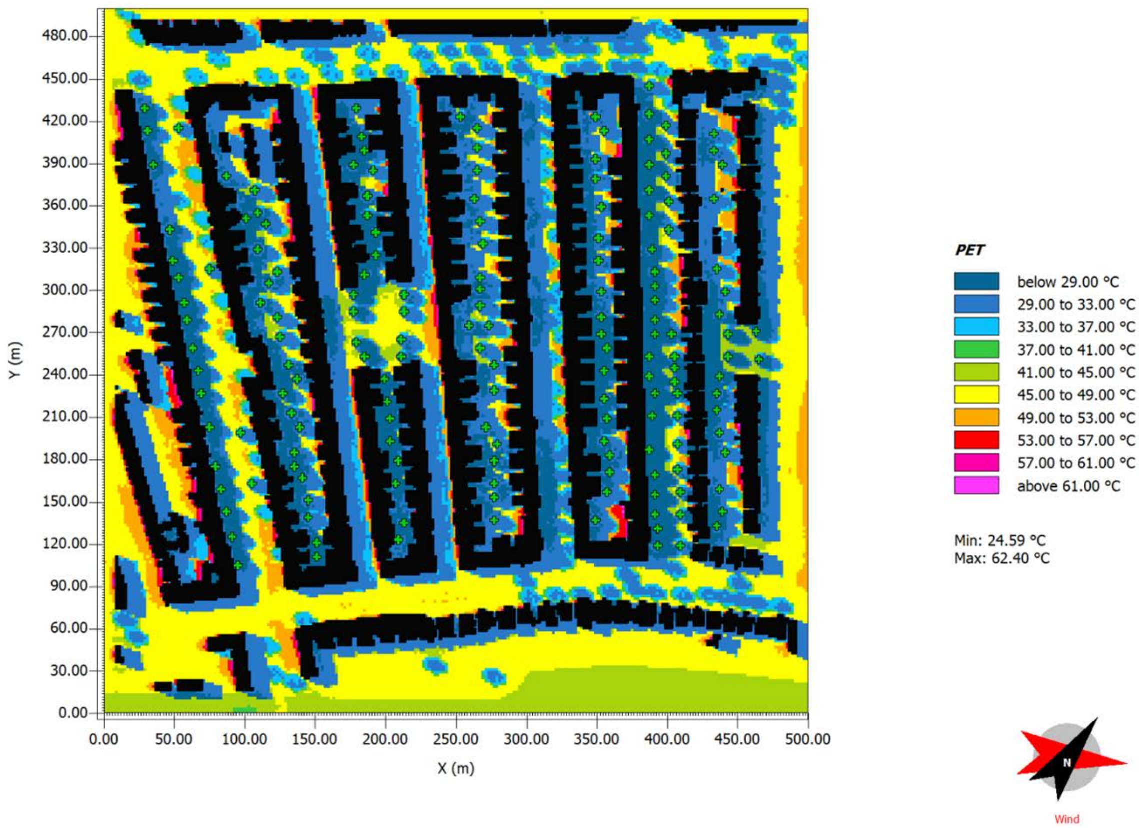
Panel_4_a_Hamburg_SQ and Panel_4_c_Hamburg_Detail in Appendix A.3 provide an overview of the distribution of air temperatures over the course of the year. The study area is dominated by the large perimeter block developments with only isolated openings and interruptions. The microclimate within the inner courtyards is correspondingly differentiated compared to the street area.

In the afternoon as well as at night, the surrounding street areas are significantly warmer than the inner courtyards. This effect is further intensified when looking at the high-resolution simulations (Annex A.3, Panel_4_c_Hamburg_Detail). In this, an additional row of buildings was included in the model area in the Northwest, resulting in a closed development on both sides. Especially in summer there is a clear contrast between the heating of the two main street axes with a southwest-northeast orientation on the one hand and the streets between the building blocks oriented Southeast-Northwest on the other.

The ventilation of the inner courtyards is poor in all wind directions due to the closed building structure. The wind speeds here are close to zero (cf. Appendix A.3 Panel_4_c_Hamburg_Detail above). However, the fact that a closed block perimeter development represents good noise protection and the inner courtyards are acoustically pleasant to stay in is also not to be neglected (Preuss et al. 2020).

In summer, the air temperatures at 4:00 p.m. in the courtyards are about 2-3 K below the air temperatures in the adjacent streets, which is mainly due to the shadows cast by the buildings and the trees in the courtyards. During the night hours in summer one can still see a temperature reduction of almost 1 K, which can mean a significant reduction in the heat load on sleeping residents. However, the lack of wind circulation can severely impair the penetration of cooler air into the building.

Figure 83: Distribution of the PET value in Hamburg on July 9 at 4:00 p.m. for the status quo



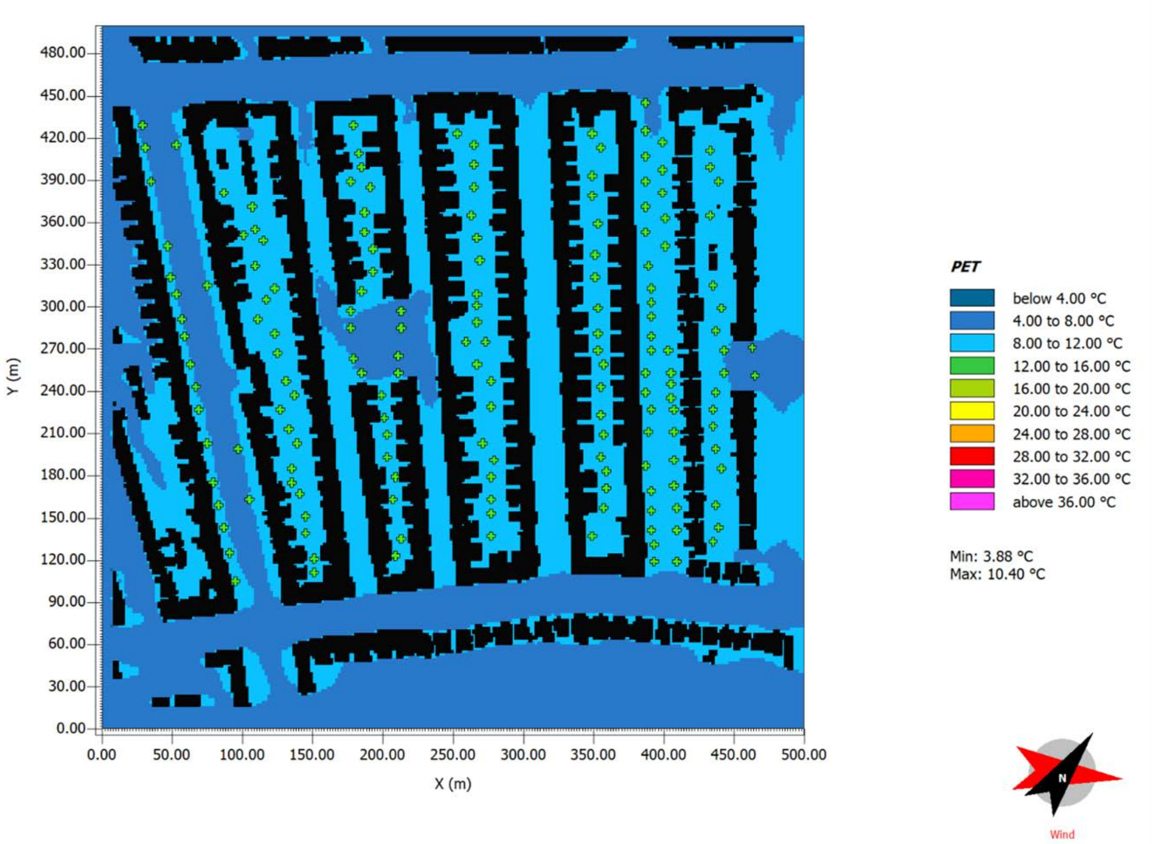
Source: Own illustration, ENVI_MET

Figure 83 shows the distribution of the PET value in the study area. As can be clearly seen, the area is divided into sunny areas with a PET around 45 °C ('hot' to 'very hot') and shaded areas with a PET around 29 °C ('comfortable' to 'slightly warm'). Due to the large differences between sunny and shaded areas, the influence of air temperature and wind speed on the PET value can only be guessed at.

Due to the generous shadowing of the inner courtyard areas both by the perimeter block development and the trees, the thermal comfort in the outdoor area there can be taken for granted. Further measures for shadowing or changes in the material properties would lead to little or no changes in the thermal perception outdoors.

Figure 84 shows the distribution of the PET value in the study area in January at 4 p.m. The thermal sensation ranges from 'cold' to 'cool' in the streets to 'slightly cool' in the wind-protected inner courtyards.

Figure 84: Distribution of the PET value in Hamburg on January 22 at 4:00 p.m. for the status quo



Source: Own illustration, ENVI_MET

2.2.6.3.3 Optimised variant

As an optimization measure, 60% of the roof areas were provided with roof greening. In addition, PV modules (inclination 10%) are provided for the building simulations, but these are not relevant for the microclimate and were therefore not considered in the simulation.

Figure 83 and the associated explanations made it clear that optimising the microclimate in the inner courtyards through additional shadowing would not produce any significant effects. Since there are also no plans to carry out massive structural changes in the existing building, the range of remaining adjustment options is limited.

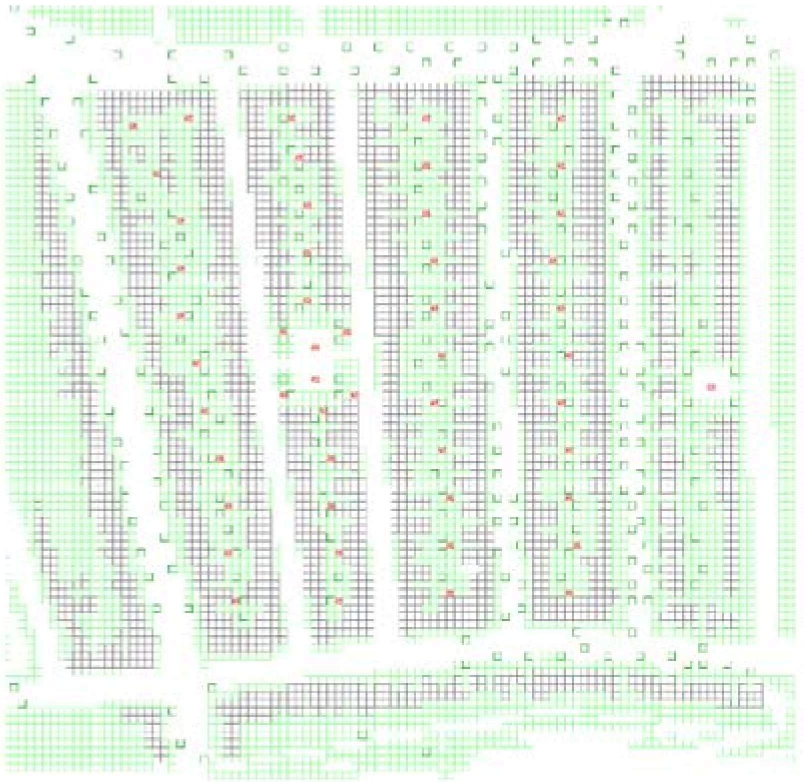
Regarding the changes in the urban climate to be expected as a result of climate change, the general increase in average air temperatures is a critical component in urban planning.

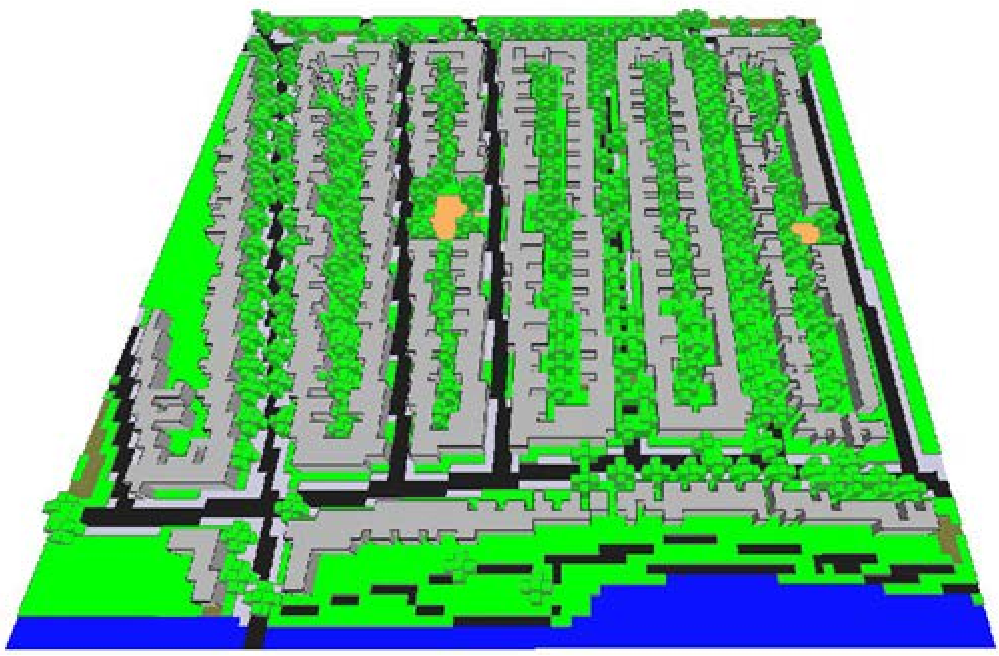
In addition to shadowing, the use of evaporative cooling (see also Sieker et al. 2019) is another way of binding thermal energy and thus reducing the temperature level. In addition to the measure of wetting surfaces and thus cooling them, spraying fine water mist is a very effective method of reducing the local air temperature, since the energy required for the evaporation of the water droplets is extracted directly from the air.

The ENVI_MET model allows the high-resolution simulation of the complex processes of such a waterspray evaporative cooling in interaction with all other urban elements and the microclimate (cf. Di Giuseppe 2021).

Since Hamburg among the cities examined is the city with probably the least water shortage, the installation of water misting systems was included in the optimization measures. The water jets eject 121 g of water per second, which is the maximum value from a water spray manufacturer. To optimise water consumption and maximise the effect, the water sprays are only activated when the air temperature at the position of the spray nozzles is 30 °C or higher and the relative humidity is lower than 80%. This means that when temperatures are high, not the entire area is cooled down, but only those parts of the area where this is necessary. Figure 85 shows the positioning of the water spray nozzles in the model area in the 3D view.

Figure 85: Model area of the optimised variant as top view and 3D view





The position of the water spray nozzles is marked with red dots in the above picture.

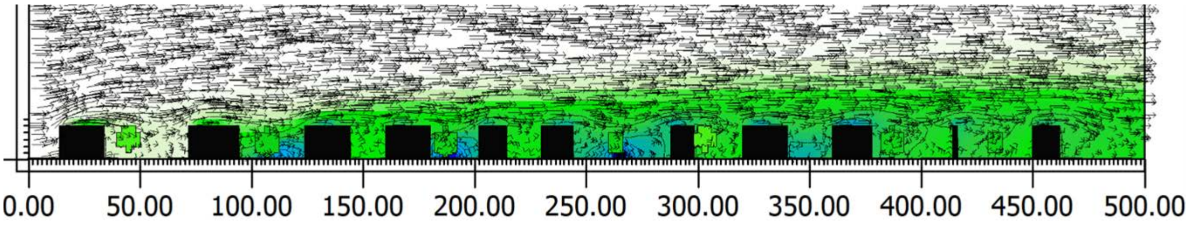
Source: Own illustration, ENVI_MET

2.2.6.3.4 Results of microclimate simulations Optimised variant

Panel_4_b_Hamburg_OPT and Panel_4_c_Hamburg_Detail in Appendix A.3 show the changes in the microclimate between the status quo design and the optimization scenario.

Looking at the months of January, March and September, it can be assumed that the water fogging was never active (air temperature < 30 °C). The observed effects can therefore be attributed to the green roofs. Although the redesign measures are above the level of 2.1 m considered here, an effect can also be seen in the lower air layers. Due to the vertical structure of the wind field with the formation of vortices behind the houses, the air influenced by the green roofs also mixes into the lower areas. Figure 86 shows this effect as an example as an XZ section at y=369 m.

Figure 86: Mixing of the air cooled on the roof surfaces into the lower air layers



Source: Own illustration, ENVI_MET

In the months of March and September, a slight increase in the air temperatures close to the ground can be observed during the day due to the green roofs. On the one hand, this effect can be explained by the reduced cooling of the green roof areas. On the other hand, green roofs also slightly increase the roughness of the buildings, which reduces the wind speed slightly. The other small changes in air temperature, both at night and during the day, can be explained by small changes in the wind field caused by the green roof and should not be overinterpreted.

For the month of July, the date for the detailed simulation was chosen so that the different water spray elements became active.

The cooling effects in the air temperature in July at 4:00 p.m. (see Appendix A.3 Panel_4_b_Hamburg_OPT and Panel_4_c_Hamburg_Detail) are very clear and, with reductions of up to -2.5 K, are well above what can usually be achieved by redesign measures.

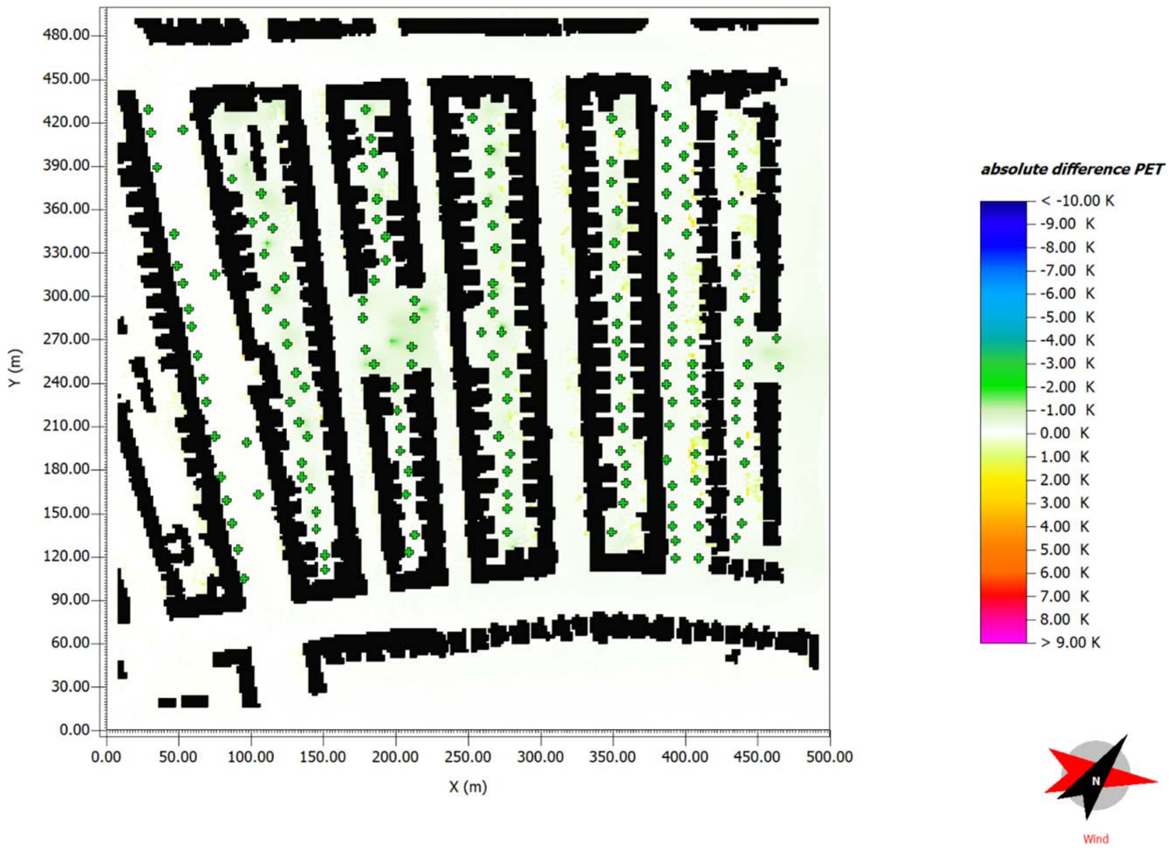
Due to the strong shielding of the inner courtyards, however, this effect is limited to the area of the inner courtyards. The surrounding areas or roads do not benefit from this change.

Figure 87 shows the difference in the PET value between the status quo and the optimization. While the water spray elements produced a noticeable change in air temperature, there was little effect on the PET distribution.

However, this was to be expected: Since there was already a high degree of shadowing and thus a comfortable PET value in the area of the inner courtyards in the initial situation, there was little potential for optimization here. When determining the PET value, the air temperature is only a third of four influencing factors after the radiation flux and the wind speed. Especially in the daytime hours, in the presence of direct sunlight, the pattern of sun and shade dominates the PET distribution. The changes in the PET value more or less correspond to the changes in the air temperature in Kelvin and are therefore rather small in the planning context.

When assessing the effectiveness of measures, however, those situations in which the most effective measures such as shadowing have already been applied must also be considered. Here, instruments such as the direct air cooling through evaporation considered can achieve a further reduction in air temperature, which initially appears to be secondary in the PET analysis.

Figure 87: Change in the PET value in Hamburg on July 9 at 4:00 p.m. due to the optimization measures



Source: Own illustration, ENVI_MET

Since no significant change in the PET could be observed in July, the representation of differences for January is not discussed separately.

2.2.6.3.5 Summary assessment

The study area in Hamburg is characterized by a very well greened perimeter block development, which allows a separate microclimate to develop within the inner courtyards of the blocks. Due to the low wind circulation and the shadowing from the buildings and trees, this is consistently cooler than the comparative situation in the surrounding street canyons. The greening of roofs was examined as optimization measures on the one hand, and the installation of water spray elements on the other.

The latter are activated when local temperatures exceed 30 °C and then lead to a very effective reduction in air temperature of up to 2.5 K.

The green roofs also cause slight changes in the air temperature at pedestrian level. These effects can be traced back to a change in the roof surface temperatures on the one hand and to a slight change in the wind field due to the changed roughness. However, they are small and can be neglected for the interpretation of the optimization measure.

In winter, protection from the wind in the study area is an option to slightly improve the thermal situation outdoors. However, due to the ability to dress appropriately, thermal comfort is generally easier to achieve in winter than in summer. Staying outside in Hamburg in January is classified as unlikely anyway.

2.2.6.4 Building simulation

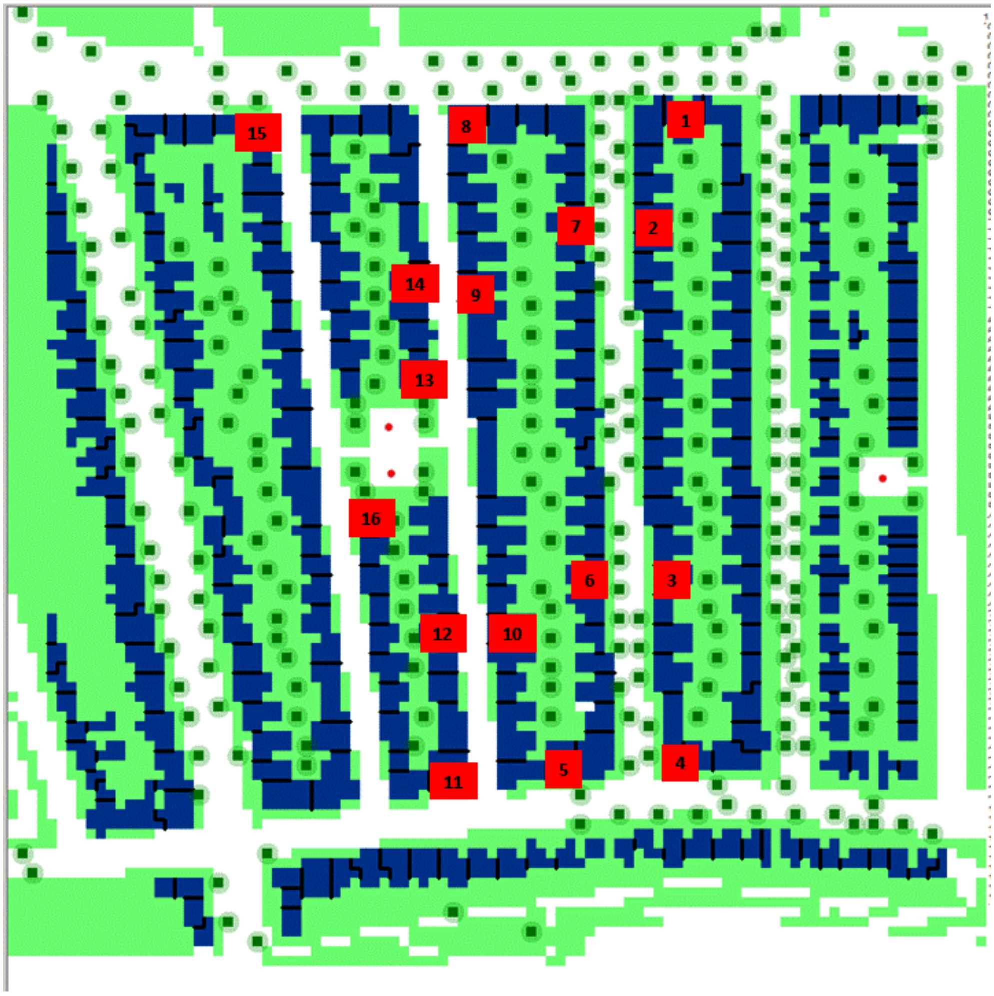
2.2.6.4.1 The simulation model

The evaluation area consists mainly of a closed perimeter block development, which can be assumed to be similar in terms of geometry and building physics. The evaluations regarding consumption and comfort were carried out at apartment level.

An apartment with 84 m^2 of floorspace was chosen as the reference geometry, which was divided into two zones ('living- and dining room' and 'bedroom and children's room') for the modelling. The living- and dining rooms were always oriented to the south as far as possible.

The location of the 48 apartments (16 locations, each with attic, middle and ground floor apartments) selected according to the qualitative criteria of "representativeness" and "diversity" for the best representation of the quarter can be seen in the following figure.

Figure 88: Location of the reference apartments in the quarter



Source: Own illustration, Guidehouse and ENVI_MET

The envelope qualities of the buildings in the study area were chosen according to the ZUB catalog of typical regional materials (Klauß et al. 2009).

Accordingly, the facades consist of plastered solid bricks and have a U-value of 1.5 W/m^{2}K with a total thickness of 38 cm.

For the roofs (mainly flat roofs), a light timber construction with 10 cm insulation was assumed (renovation compared to the initial state). The U-value of the roof is therefore 0.4 W/m²K.

For the windows, too, the original windows were not used for the simulations, but heat-insulating double glazing of the 1st or 2nd generation with a U-value of 1.6 W/m²K and a g-value of 0.6. A solid construction with a U-value of 1.1 W/m²K was assumed for the floor to the unheated basement. Other parameters e.g., with regard to the heating system, ventilation and sun protection can be found in Table 16 below.

2.2.6.4.2 Variants

The variants considered in the building simulations are summarised in the following table.

The basis is the variant Status Quo 1 (SQ1), which describes the current situation. In variant SQ2, quarter measures to improve the microclimate are considered, with the buildings themselves being assumed to be unchanged. Based on this variant, the variant Optimised 1 (Opt1) was developed, in which very good insulation[51]. The extensive insulation measures also allow the heating system temperatures to be reduced considerably, so that a switch can be made to central building monoblock air heat pumps with natural refrigerant propane for effective heat supply. To avoid legionella problems, the hot water, which is also generated by the central heat pumps, is provided for the individual residential units by means of heat transfer stations. To be able to keep the temperature as low as possible, electrical reheaters must be taken into account for the taps in the kitchens. In variant Optimised 2 an effective sun protection (see table below) was assumed to improve the indoor climate. Finally, in variant Optimised 2, additionally the roofs are covered with PV systems as far as possible (assumption of occupancy rate: 60%) and appropriate battery storage is considered to increase the proportion of PV self-use.

[51] U-values after renovation: U (roof)=0.1 W/m²K; U (window)=0.95 (g=0.5); U (garden façade)=0.2 W/m²K; street facade unchanged, as a listed building

Table 16: Overview of the variants examined for the Hamburg quarter

	SQ1	SQ2	Opt1	Opt2	Opt3
Microclimate	Status Quo	Optimised	Optimised	Optimised	Optimised
Heat protection	Partially renovated	See SQ1	Energetically renovated	See Opt1	See Opt1
Heating system	Gas condensing boiler, radiator with a design temperature of 70/ 50°C	See SQ1	Central heating with monobloc air heat pump with natural refrigerant radiator with a design temperature of 50/ 40°C	See Opt1	See Opt1
Hot water system	Central circulation system[52]	See SQ1	Central, circulation - system with apartment-wise heat transfer - station	See Opt1	See Opt1
Cooling	-	-	-	-	-
Ventilation	Window ventilation Permanent air exchange 0.4 1/h additional ventilation for cooling in summer[53]	See SQ1	Window ventilation: air change: 0.25 l/h[54] additional ventilation for cooling in summer, see SQ1	See Opt1	See Opt1

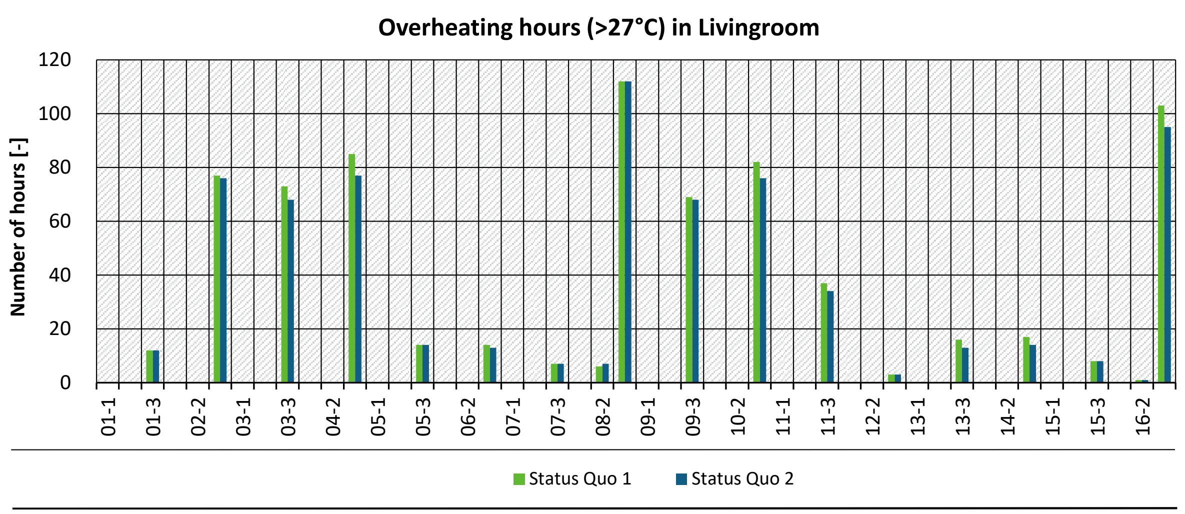
[52]For the existing buildings, it was assumed that all accessible tubes, as in the new building, are insulated in accordance with the current level of requirements.
[53]Summer (short-time intense) ventilation at room temperatures above 24 °C and cooler outside temperature as well at the presence of the residents: in the morning from 7-8 a.m. an air change of 6 1/h; afternoons/evenings from 4 p.m. to 10 p.m. with an air exchange rate of 4 1/h; night ventilation via a tilted window in the bedroom from 10 p.m. to 6 a.m. with an air exchange rate of 0.4 1/h
[54]Reduced air exchange due to improved airtightness because of the renovation

	SQ1	SQ2	Opt1	Opt2	Opt3
Sun protection	Manually operated Street side: Internal (mean fc value: 0.75); Garden side exterior (mean fc value: 0.5)	See SQ1	See SQ1	Improved and automatically operated street side: Sun protection in the space between the panes (average fc value: 0.3), garden side: outside (average fc value: 0.2)	See Opt2
Renewable energies on site	-	-	-		60% of the roofs are covered with PV modules (10% inclination), battery storage (per apartment: 2.4 kWp modules + 2 KWh battery storage)

2.2.6.4.3 Results

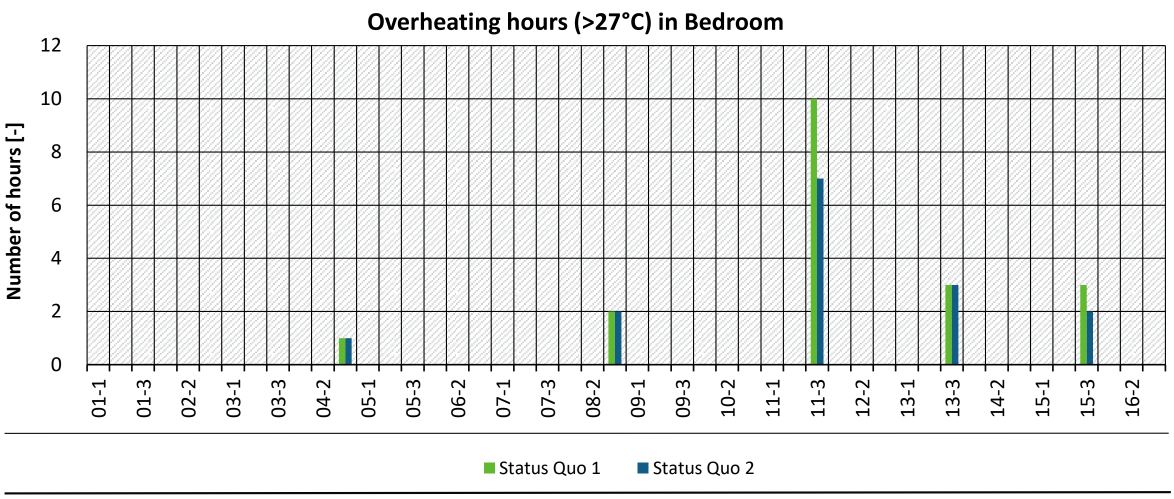
The overheating of the investigated buildings in the Hamburg quarter is already significantly lower in the initial state than in the Cologne or Frankfurt quarter and occurs almost exclusively in the attic apartments in the living area (apartments with the index number -3 in the following figure). Through the measures to optimise the microclimate in the quarter, a measurable but only small reduction in overheating hours can be achieved in some apartments.

Figure 89: Comparison of the overheating hours in the residential zone for the variants SQ1 (initial state) and SQ2 (optimised quarter)



Source: Own illustration, Guidehouse

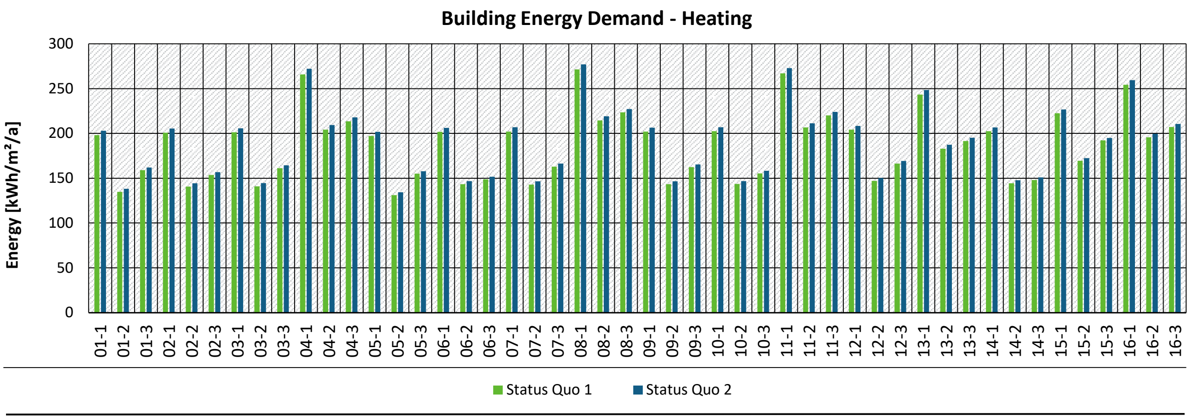
Figure 90: Comparison of the overheating hours in the sleeping area zone for variants SQ1 (initial state) and SQ2 (optimised quarter)



Source: Own illustration, Guidehouse

However, the denser stock of trees in the optimised quarter is also accompanied by a slight increase in the useful energy demand for heating, as can be seen in the following figure.

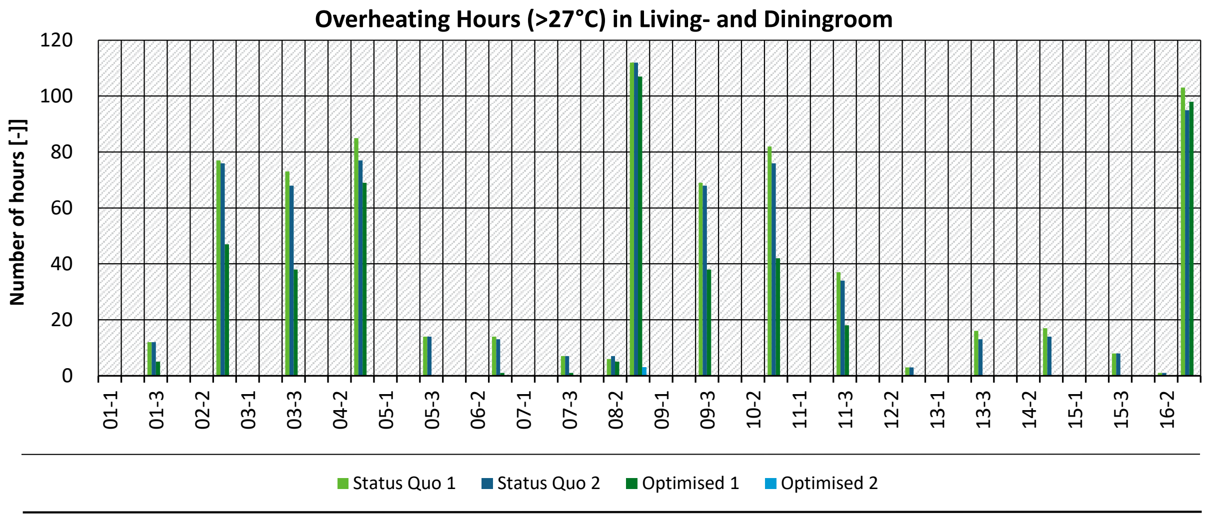
Figure 91: Comparison of the useful energy demand for heating the reference apartments of variants SQ1 (initial state) and SQ2 (optimised quarter)



Source: Own illustration, Guidehouse

The hours of overheating in the living area can already be significantly reduced or completely eliminated in many apartments through the insulation measures alone (see variant Opt1 in the following figure). By improving the sun protection (Opt2 variant), it is finally possible to keep the operative temperatures below 27 °C in almost all apartments all year round.

Figure 92: Comparison of the hours of overheating in the residential zone for variants SQ1, SQ2, Opt1 and Opt2

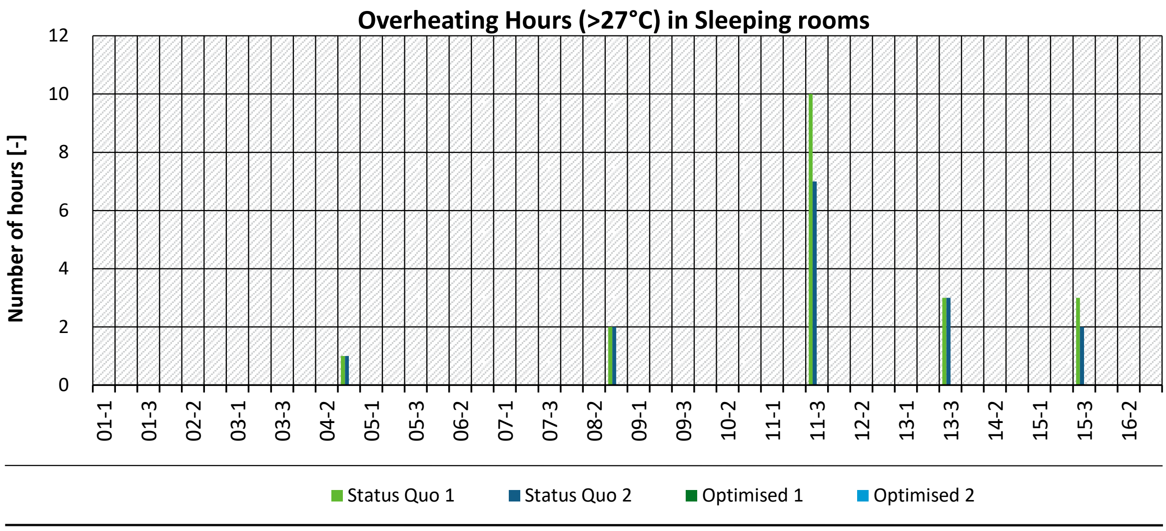


SQ1: initial state, SQ2: optimised quarter, Opt1: improved insulation and Opt2 additionally improved sun protection.

Source: Own illustration, Guidehouse

In the north-facing sleeping rooms, the insulation alone can prevent overheating, as can be seen in the following figure.

Figure 93: Comparison of the overheating hours of the sleeping area zone for variants SQ1, SQ2, Opt1 and Opt2



SQ1: initial state, SQ2: optimised quarter, Opt1: improved insulation, Opt2: additionally improved insulation

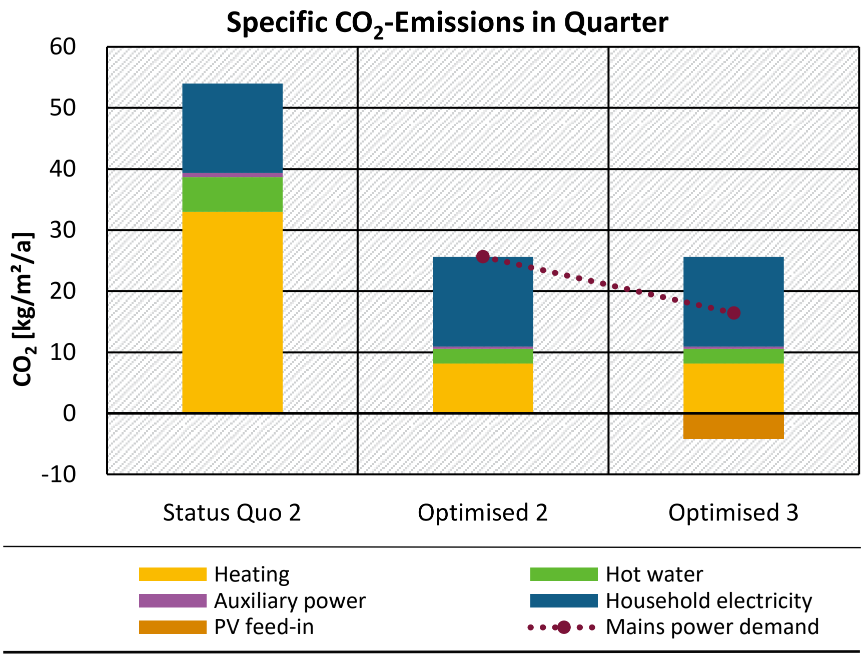
Source: Own illustration, Guidehouse

Figure 94 shows a comparison of the floorspace-specific CO_2 emissions of the different variants. While these are just under 40 kg/m^{2}a in the non-refurbished SQ2 variant without household electricity, the CO_2 emissions can be reduced by almost ¾ to approx. 11 kg/m^{2}a through the energy-related refurbishment measures described and the air heat pump[55]. Through the direct

[55] Considered CO_2 factor electricity: 0.474 g/kWh; Source: Umweltbundesamt 2021 (value for 2018; assumption: same values for grid purchase and feed-in)

use of electricity from the PV systems and battery storage according to variant Opt3, the living area-specific CO_2 emissions (including household electricity[56]) can be reduced by a further 36% from 26 kg/m² to just 16 kg/m². However, even considering the calculated credit from feeding in the excess PV electricity of 4 kg/m², a completely climate-neutral supply is not possible from renewable energies generated on site alone. However, the relatively windy location near the coast offers the possibility of further reducing operational CO_2 emissions by using electricity from nearby wind turbines.

Figure 94: Comparison of the CO_2 emissions of individual quarter variants



Status Quo 2: no building measures; Optimised 2: improved heat and sun protection; Optimised 3: additional PV and battery storage.

Source: Own illustration, Guidehouse

With consideration of differentiated emission factors (higher factors[57] for the generated PV electricity and for the electricity for heat generation), for variant Opt 3 a CO_2 emission factor for the electricity mix of 444 g/ kWh would be sufficient to achieve calculated annual climate neutrality.

2.2.6.4.3.1 Summary assessment

The overheating hours (>27°C) observed above all in the attic apartments can be slightly reduced through the optimization measures in the quarter. At the same time, however, the heating requirement of the apartments will also increase slightly. By improving the thermal envelope qualities, but above all by providing effective sun protection, sufficient comfort can be achieved in all apartments. By central building heat supply with monoblock air heat pumps with natural refrigerants and 60% coverage of the roofs with PV systems considering differentiated electricity emission factors, a negative annual CO_2 balance can be achieved if the CO_2 emission factor for the electricity mix falls below 444 g/kWh.

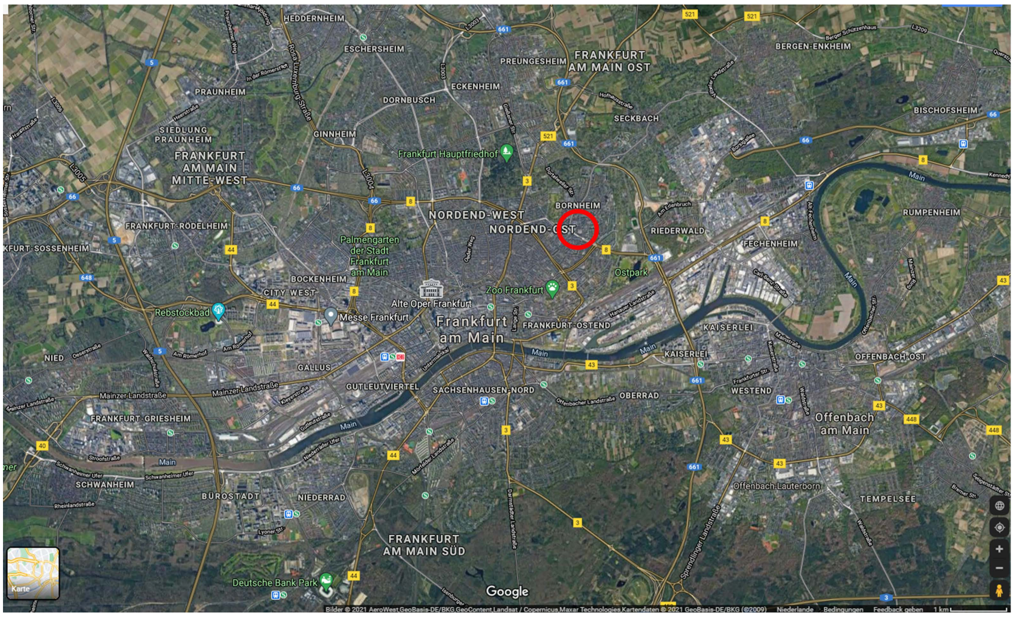
[56]A specific household electricity requirement of 31 kWh/m²a was taken into account
[57]Assumption: 860 g/kWh (displacement electricity mix (GEG 2020)); Further background information on the calculation approach: see Chapter 2.2.5.4.3.2

2.2.7 Densification quarter Campo Bornheim in Frankfurt am Main

2.2.7.1 Location and description

The densification quarter Campo Bornheim is located approx. 2 km Northeast of the centre of Frankfurt.

Figure 95: Location of the "Campo Bornheim" quarter in Frankfurt (red circle)



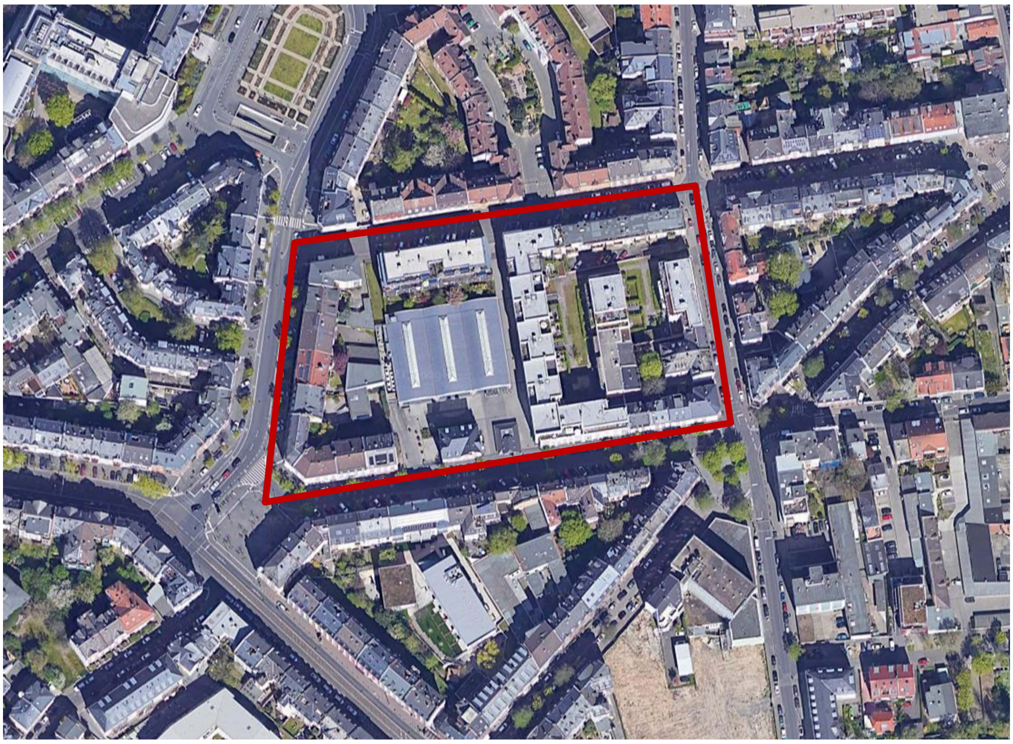
Source: Own illustration, Guidehouse based on Google (background)

The construction project implemented in 2009 involves the closure of a block perimeter development on an inner-city conversion area. Around an old tram depot, an ensemble of five to six-storey buildings with a total of 140 owner-occupied and rented apartments built to the passive house standard was created. Both the urban arrangement of the buildings and their design and height are based on the Wilhelminian block perimeter development of the neighboring blocks.

In addition, the project included both the restoration and reconstruction of a listed wagon shed and its conversion into a supermarket and the restoration of a listed residential building.

In 2013, the project received the "Green Building Award" from the city of Frankfurt am Main.

Figure 96: Location of the study area (red rectangle)



Source: Own illustration, Guidehouse based on Google (background)

The following illustrations show the western block perimeter development with five-storey existing buildings and the Northern one with mostly six-storey new buildings.

Figure 97: View of block perimeter development of existing buildings

Source: Google

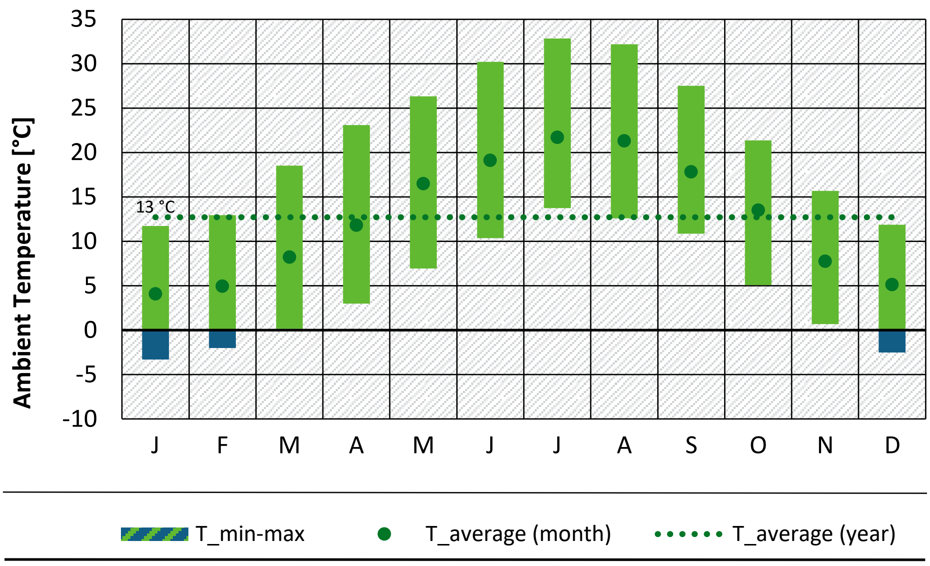
Figure 98: View of new buildings

Source: Google

2.2.7.2 Climate

In contrast to the investigations of the other quarters, the current climate[58] (meteonorm 7, 2020) was not used for this location, which is already very hot in a Germany-wide comparison. Instead, the climate expected for the Frankfurt location in 2050[59] was considered, so the effects of climate change are therefore also considered in the microclimate and building simulations at this location. The average annual ambient temperature is therefore 13 °C. The monthly mean values for the ambient temperature range from approx. 4 °C (January) to 22 °C (July). The summer peak values reach almost 33 °C.

Figure 99: Monthly ambient temperature values in Frankfurt (forecast values for 2050)

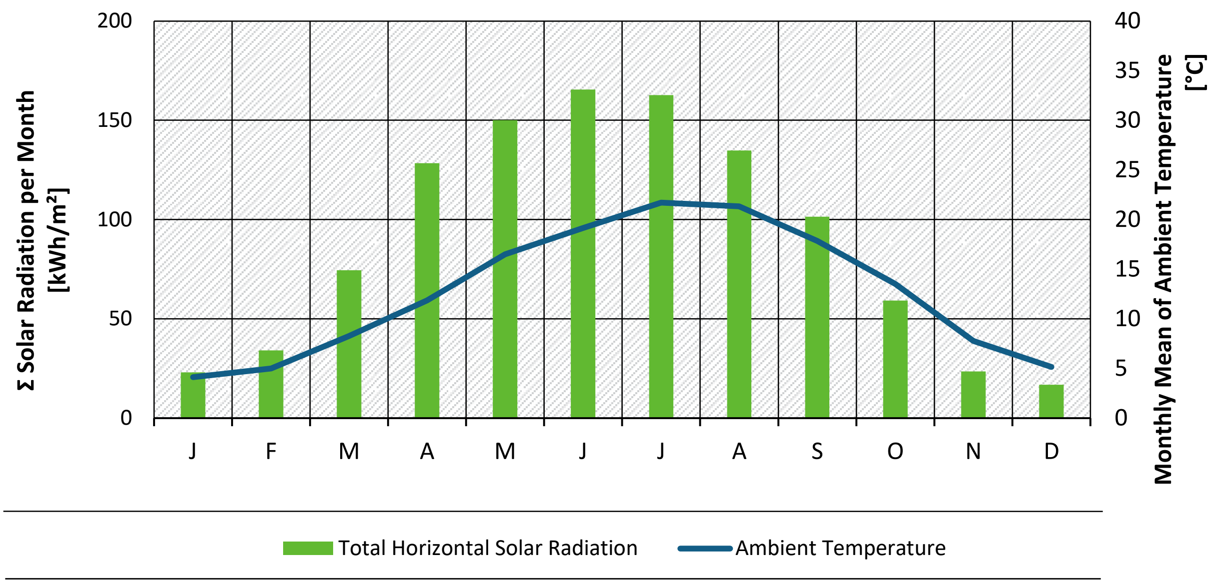


Source: Own illustration, Guidehouse

The annual global radiation is 1,074 kWh/m^{2}a. The monthly sums of global radiation reach their peak value of 166 kWh/m^{2}a in June. In the winter months from November to January not even 25 kWh/m^{2}a (i.e., less than 15% of the summer peak value) are reached.

[58]Source: Meteonorm software, version 7, most recent weather data set (period 2000-2009)
[59]IPCC scenario B1 (+2.8 °C compared to pre-industrial level)

Figure 100: Monthly values for outside temperature and radiation in Frankfurt (forecast values for 2050)



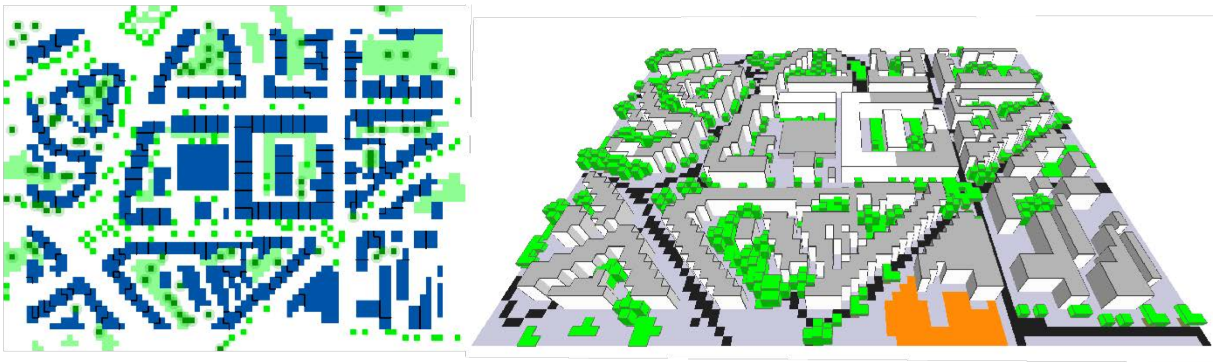
Source: Own illustration, Guidehouse

2.2.7.3 Microclimate simulation

2.2.7.3.1 Variant current state

The examined quarter Northeast of the old town of Frankfurt is a typical, highly dense inner-city area, which classifies as a critical overheating area. It consists of owner-occupied and rental apartments as well as a listed tram depot that has been converted into a supermarket.

Figure 101: Model area in Frankfurt (status quo) as top view and 3D view



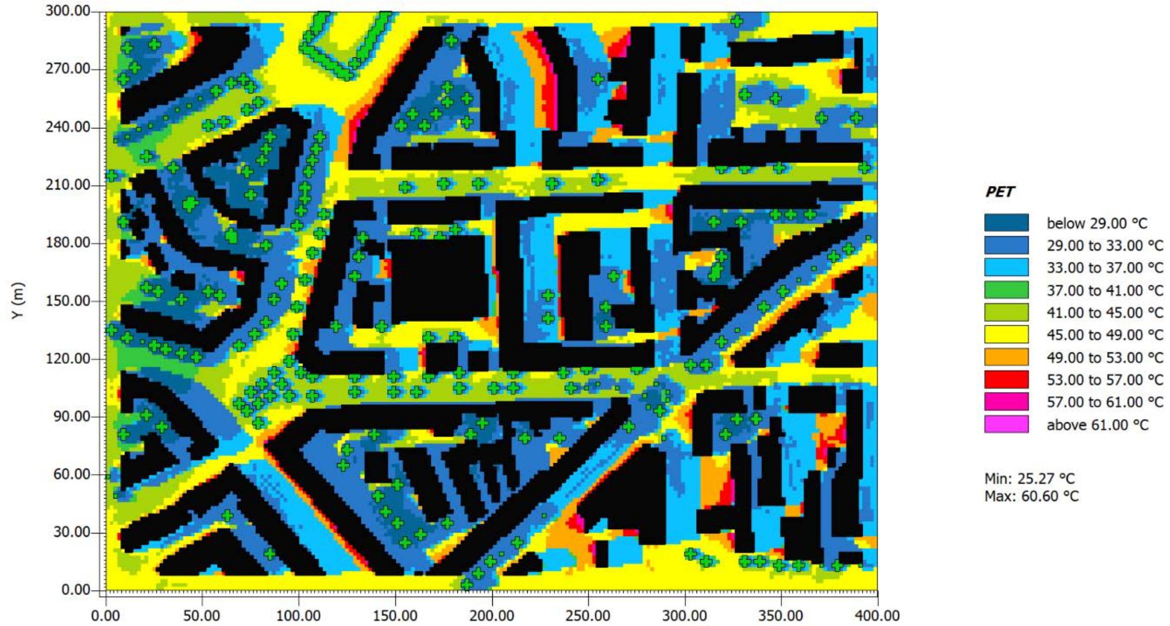
Source: Own illustration, ENVI_MET

2.2.7.3.2 Results of the microclimate simulation - current state

The microclimate in the study area shows a differentiation between the street areas and the inner courtyards, which is typical for perimeter block developments (see Appendix A.3 panels Panel_5_a_Frankfurt_SQ and Panel_5_c_Frankfurt_Detail). Due to the higher resolution of the detail simulations, the resulting structures appear somewhat more clearly than in the coarser resolution overview simulations.

During spring and summer, the courtyards are slightly cooler than the surrounding street areas, both during the day and at night. However, since the building structure is relatively inhomogeneous, no clear pattern can be identified. In summer, the range of air temperatures during the day between the warmest and the coolest areas is just under 1.5 K, at the other times of the year just under 1 K. At night, the temperature range is reduced to less than 1 K and should therefore not be overinterpreted.

Figure 102: Distribution of the PET value in Frankfurt on July 1st at 4:00 p.m. for the status quo

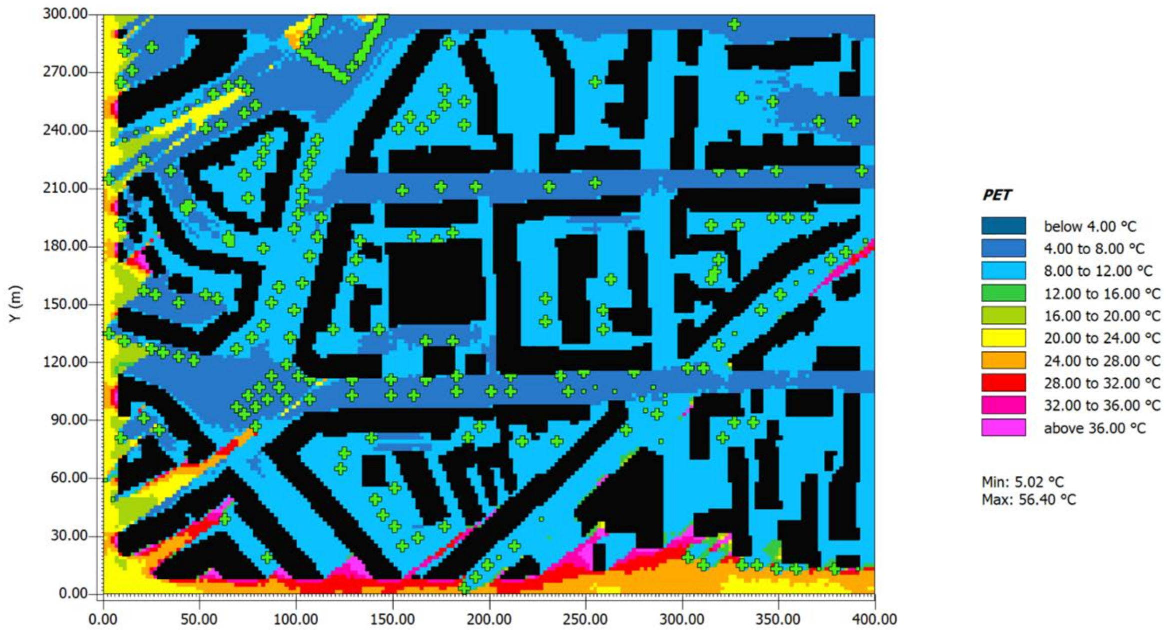


Source: Own illustration, ENVI_MET

Figure 102 shows the distribution of the PET value at 4:00 p.m. in July. Depending on the local wind speed, the PET values in the shadow areas are between 29 and 35 °C, i.e., in the 'slightly warm' to 'warm' range. Values of around 46 °C can be found in the unshaded zones, which locally increase to around 55 °C in the weak wind zones in the North and near facades. All of these areas can be assigned to a 'very hot' comfort level.

January thermal comfort at 4 p.m. (Figure 103) is characterized by almost complete shadowing of the study area. The sun's rays can only reach pedestrian level at the edges of the model and the Northwestern street. The model edges are artefacts that result from the end of the simulation area and therefore do not provide usable data. The wind-permeated street areas have a PET of almost 7 °C, so they can be assigned to a 'cool' thermal comfort. In the areas that are more sheltered from the wind, the PET is marginally higher with values around 9 °C, which would formally be assigned to be 'slightly cool' area, but makes no relevant difference in terms of quality.

Figure 103: Distribution of the PET value in Frankfurt on January 22 at 4:00 p.m. for the status quo

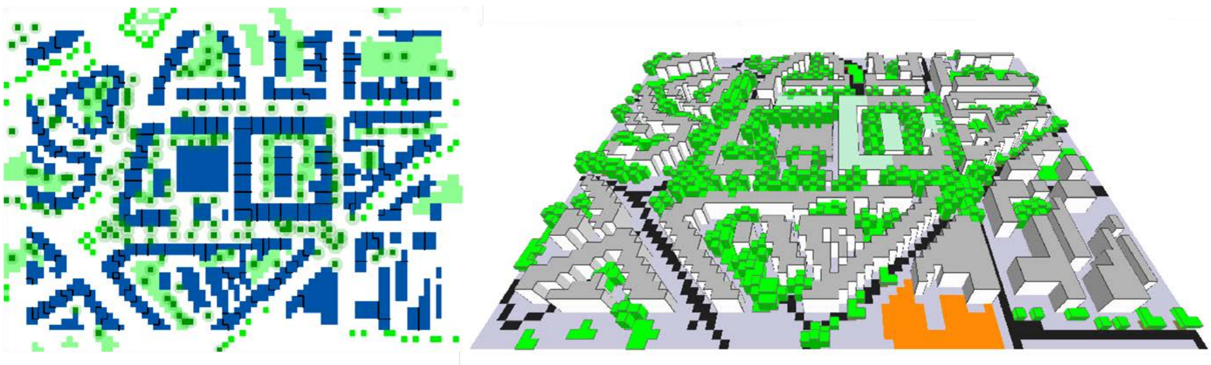


Source: Own illustration, ENVI_MET

2.2.7.3.3 Optimised variant

No changes were made to the building structure in the model for the microclimatic optimisation. Thus, the greening of large, shady trees both in the inner courtyards and in the street area was planned as an essential measure (see Figure 104). Furthermore, the existing flat roofs were greened. As with the previous microclimate simulations, the photovoltaic systems on the roofs were not considered.

Figure 104: Model area of the optimised variant as top view and 3D view



Source: Own illustration, ENVI_MET

2.2.7.3.4 Results of microclimate simulation - optimised variant

Panel_5_b_Frankfurt_OPT and Panel_5_c_Frankfurt_Detail show the air temperatures of the optimised variant compared to the status quo.

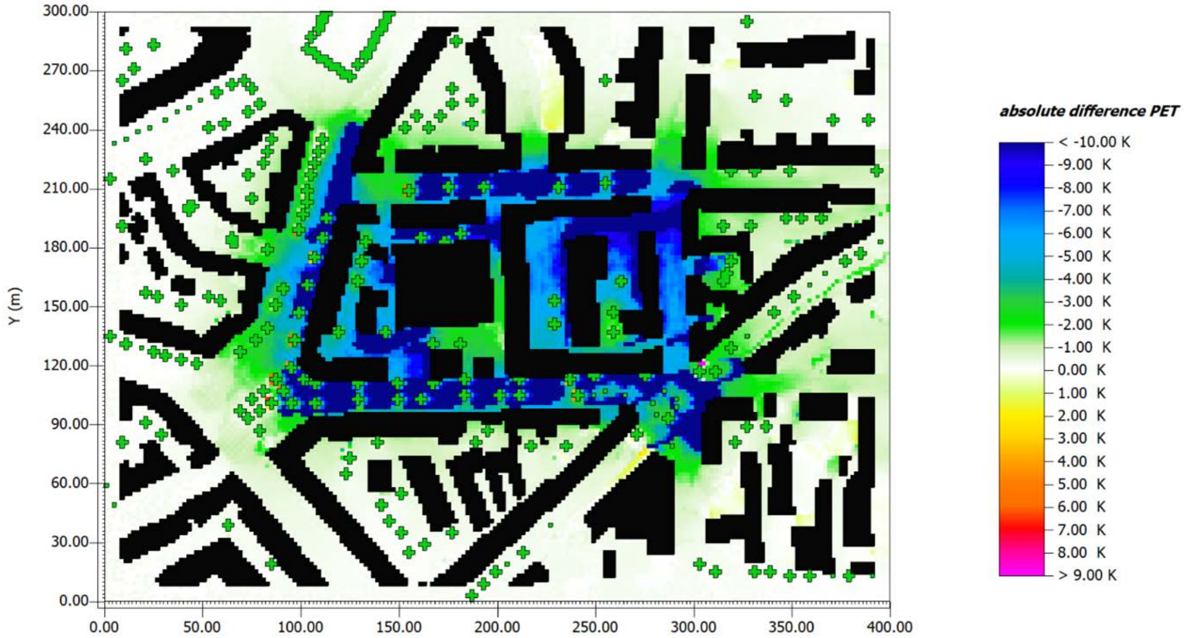
Due to the intensive use of large-crowned trees, two typical microclimatological effects can be observed: During the night hours, as well as in winter and spring at 4:00 p.m., the protective effect of the tree crowns dominates and a slight increase in air temperature can be observed. This is caused by the modification of the long-wave radiation balance, the so-called 'beer garden effect'. The thermal radiation from the ground surface is partly intercepted by the branches and leaves of the trees and scattered back to the ground. This effect also occurs in winter when the trees are leafless, but the sky is still approximately 30% obscured by the branches. The effect of the trees as wind obstacles is added to this effect.

In the summer months, the beer garden effect can potentially counteract the goal of improving the thermal situation in the study area. In fact, it can also be determined in the present example that in the early morning hours in July the air temperature in the green areas is approx. 0.5 K higher than in the status quo case (cf. Appendix A.3 Panel_5_c_Frankfurt_Detail).

During the day in summer, however, a clearly positive effect of transformation dominates, which leads to a reduction in air temperature of up to 2 K and more. However, due to the poor flow through block structure, this effect is locally limited to approximately those areas in which greening was carried out, the long-distance effect is very limited.

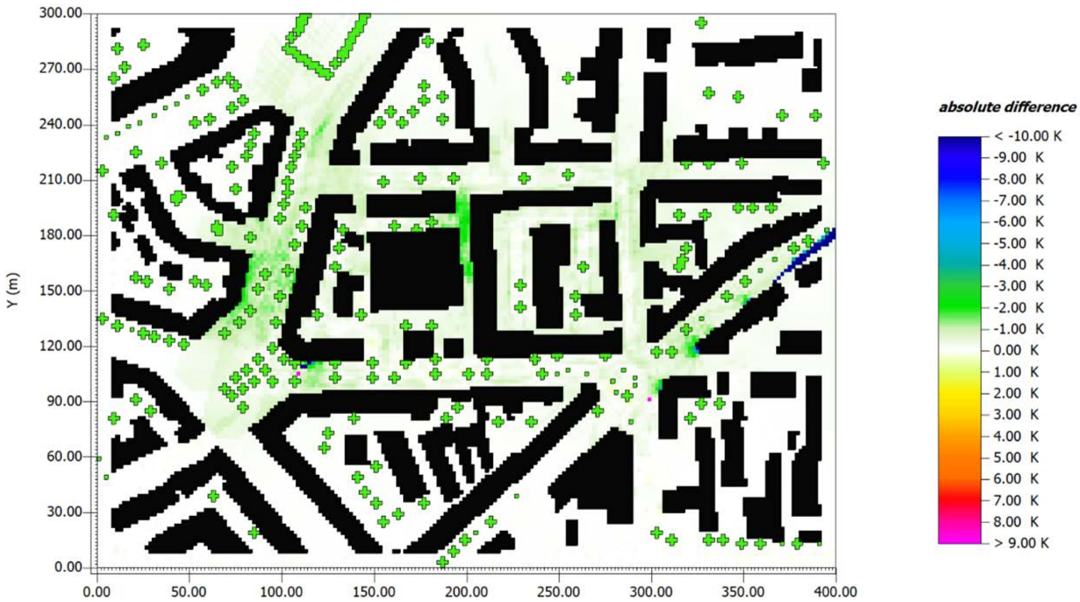
The change in the PET value in the study area (Figure 105) again underscores the previous statements. Shadows are the dominant element here, but the reduction in air temperature is also reflected in a reduction in PET by 2 to 3 K in the unshaded areas.

Figure 105: Change in the PET value in Frankfurt on July 1st at 4:00 p.m. due to the optimization measures



Source: Own illustration, ENVI_MET

Figure 106: Change in the PET value in Frankfurt on January 22 at 4:00 p.m. due to the optimization measures



Source: Own illustration, ENVI_MET

Figure 106 shows the change in the PET value on January 22 due to the optimisation measures. Since, as already explained when looking at the status quo, the entire study area is already shaded at 4:00 p.m., there is no major difference in the PET distribution between the status quo and the optimised variant. Only minimal changes can be read, which can be traced back to minor modifications of the wind field.

2.2.7.3.5 Summary assessment

In the study area in Frankfurt, the focus was on the use of large-canopy street trees and green roofs to reduce heat stress in 2050 under the assumption of IPCC scenario B1. A reduction in air temperature of up to 3 K was achieved during daylight hours in summer, which corresponds to a neutralization of the temperature increase forecast for Frankfurt by 2050. For winter, spring and the summer night hours, the use of large-crowned trees leads to a slight local increase in air temperatures due to the protective effect of the branches and leaves. In the specific planning case, it must be checked whether a possible heat build-up can be prevented by alternative arrangements of the trees.

In densely built-up areas like Frankfurt, most of the urban area is already in the shade of the houses in the afternoon hours in winter. Additionally introduced shadowing elements, such as the large-crowned trees in this case, therefore have no effect on thermal comfort in winter.

2.2.7.4 Building simulation

2.2.7.4.1 The simulation model

In the building simulation, two basic building types were distinguished regarding building physics: existing buildings and new buildings.

Based on the ZUB catalog for existing buildings (Klauß et al. 2009) , a solid construction with relatively high thermal storage masses was assumed for the existing buildings. Accordingly, the facades consist of plastered solid bricks with a U-value of 1.5 W/m²K. An insulation of 10 cm was taken into account for the roofs (mainly gable roofs in rafter roof construction) (Klauß et al. 2009)). The U-value of the upper part of the building is therefore 0.4 W/m²K. First-generation thermal insulation double glazing with a U-value of 1.6 W/m^2K and a g-value of 0.6 was assumed for the windows. A solid construction with a U-value of 1.1 W/m^2K was considered for the floor to the unheated basement.

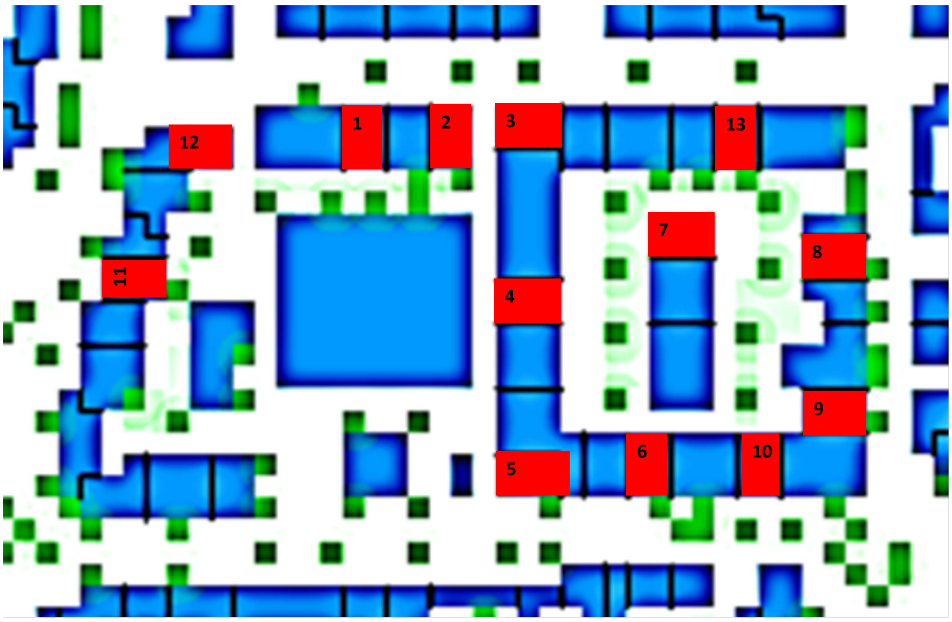
In contrast to the actual implementation, the German efficiency standard EH 55 was considered for the new buildings in the initial case. Accordingly, a monolithic construction made of lightweight aerated concrete with a U-value of 0.2 W/m^2K was assumed for the facades. A construction consisting of interior plaster, 20 cm of concrete, 24 cm of insulation and sealing with a resulting U-value of 0.14 W/m^2K was required for the flat roofs. A solid construction with a U-value of 0.25 W/m^2 was considered for the floor, and triple glazing with a U-value of 0.9 W/m^2K for the windows. Compared to the existing buildings (approx. 20%), the proportion of window surfaces on the facade of the new buildings is significantly higher at around 30%.

Other parameters e.g., regarding the heating system, ventilation and sun protection can be found in Table 17 below.

The simulations were carried out at apartment level. An apartment with 80 m^2 of floorspace was chosen as the reference geometry for both the existing building and the new building. Regarding the zoning of the apartments, the same assumptions were made as for the model building in Cologne.

The location of the 39 apartments (13 locations each with attic, middle and ground floor apartments) selected to depict the quarter can be seen in the following illustration. The apartments with the numbers 1 to 8 are new buildings. The apartments with the numbers 9 to 13 are located in existing buildings.

Figure 107: Location of the reference apartments in the quarter



Source: Own illustration, Guidehouse and ENVI_MET

2.2.7.4.2 Variants

The starting point for the investigations for the Frankfurt quarter is the Status Quo 1 (SQ1) variant, in which the envelope qualities already described were considered. All buildings are heated by central gas condensing boilers, which also take care of hot water preparation. The individual apartments are connected to the central hot water tank via circulation systems. A cooling is initially not provided. This is considered in the SQ2 variant using split air conditioning units. The Optimised 1 (Opt1) and Optimised 2 (Opt2) variants correspond to the SQ1 and SQ2 variants in terms of building physics and technology. However, the measures to optimise the microclimate (see chapter microclimate simulations) were considered. Based on the Opt2 variant, the following variants Opt3 to Opt6 were developed.

In the Opt3 variant, improved insulation and effective sun protection were taken into account to improve thermal insulation in summer and winter. An energy standard corresponding to a further improved thermal standard (German EH 40- standard) [60] with the following parameters was adopted for the new buildings:

- U-value facades: 0.15 W/m²K
- U-value roofs: 0.1 W/m²K
- U-value floor to basement: 0.15 W/m²K
- U-value window: 0.8 W/m²K (triple thermal insulation glazing with g= 0.55)

In addition, a ventilation system with 80% heat recovery was considered.

For the existing buildings, it was assumed that it would be possible to insulate the facades and roofs in such a way that the U-values mentioned above could also be achieved. The triple glazing described above was also adopted for the windows. An insulation restriction of a maximum of 4 cm was only assumed for the floor due to the limited ceiling height, so that a U-value of only 0.5 W/m²K can be achieved here. Retrofitting a ventilation system with heat recovery is considered unrealistic in the existing building and is therefore not included in the calculation.

In the variant Opt3, effective, automatically operated external sun protection is taken into account for both new buildings and existing buildings. In addition, it is assumed that the heat supply can be switched from natural gas to climate-neutral district heating in the future.

In the variant Opt4, the option of cost-effective cooling that is as sustainable as possible is to be examined by providing central air-to-water heat pumps with natural refrigerants. The extensive insulation measures and the partial retrofitting of fan-convectors in sensitive rooms such as living rooms and children's rooms can significantly reduce the system temperatures of the heating system in the old building, so that efficient heat supply via sustainable monoblock air heat pumps with the refrigerant propane is also possible here. The hot water generation is made available for the individual residential units by means of heat transfer stations [61].

In the variant Opt5, the roofs are also largely covered with PV (assumption: 50% of the roof area), which corresponds to an installed capacity of approx. 1.5 kWp per apartment [62].

Finally, variant Opt6 is used to investigate how far the PV self-use share can be increased by appropriate battery storage.

The main parameters of the variants considered in the building simulations are summarized in Table 17.

[60] With regard to the envelope qualities and the ventilation, this is probably very close to the actually realized buildings (passive house quality).
[61] See descriptions for details the corresponding solution in the Hamburg district
[62] A total of 210 kWp on the new buildings

Table 17: Overview of the variants examined for the Frankfurt quarter

	SQ1 (without cooling)	**SQ2** (with cooling)	**opt1** (without cooling)	**Opt2** (with cooling)	**Opt3** (without cooling)	**Opt4** (with cooling)	**opt5** (with cooling)	**Opt6** (with cooling)
Microclimate	Status Quo	Status Quo	Optimised	Optimised	Optimised	Optimised	Optimised	Optimised
Heat protection	New building: EH 55 Existing: partially renovated	see SQ1	see SQ1	see SQ1	New building: EH 40 Existing: refurbished	see opt3	see opt3	see opt3
Heating system	Gas condensing boiler New construction: underfloor heating Stock: radiator[63]	see SQ1	see SQ1	see SQ1	Climate-neutral district heating, New construction: underfloor heating Stock: radiator[64]	Central heating with monoblock air heat pump with natural refrigerant New construction: underfloor heating Existing: radiators, partially replaced by fan-convectors[65]	see opt4	see opt4
Water heating	Central circulation system[66]	see SQ1	see SQ1	see SQ1	see SQ1	See SQ1	See SQ1	See SQ1
Cooling	-	Split air conditioners, 26 °C set temperature	-	Split air conditioners, 26 °C set temperature	-	New construction: underfloor cooling Existing: fan-convectors	see opt4	see opt4

[63]Design temperature: 70/ 50
[64]Design temperature: 55/ 40
[65]This makes it possible to lower the design temperature to 50/40
[66]In the case of the existing building, it was assumed that all accessible lines, as in the new building, are insulated in accordance with the current level of requirements.

	SQ1 (without cooling)	**SQ2** (with cooling)	**opt1** (without cooling)	**Opt2** (with cooling)	**Opt3** (without cooling)	**Opt4** (with cooling)	**opt5** (with cooling)	**Opt6** (with cooling)
Ventilation	Permanent air exchange 0.4 1/h New building: exhaust air system Stock window ventilation and infiltration additional ventilation for cooling in summer[67]	see SQ1	see SQ1	see SQ1	New building: supply and exhaust air system with heat recovery (80%), air change rate: 0.4 1/h window ventilation: air change: 0.25 l/h[68] additional ventilation for cooling in summer, see SQ1	see opt3	see opt3	see opt3
Sun protection	Operated manually[69]	see SQ1	see SQ1	see SQ1	Automatically operated effective sun protection[70]	see opt3	see opt3	see opt3
Renewable energies on site	-	-	-	-	-	-	1.5 kWp/ apartment[71]	PV: 1.5 kWp/apartment Battery [72]2 kWh/ apartment

[67]Summer (intermittent) ventilation at room temperatures above 24 °C and cooler outside temperatures as well as the presence of the occupants; in the morning from 7-8 a.m. with an air change of 6 1/h, in the afternoon/evening from 4 p.m. to 10 p.m. with an air change of 4 1/h; Night ventilation via a tilted window in the bedroom from 10 p.m. to 6 a.m. with an air exchange rate of 0.4 1/h

[68]Reduced air exchange due to improved airtightness because of the renovation

[69]An average Fc value of 0.5 was assumed to consider the unavoidable control errors

[70]Assumption: mean Fc value of 0.2

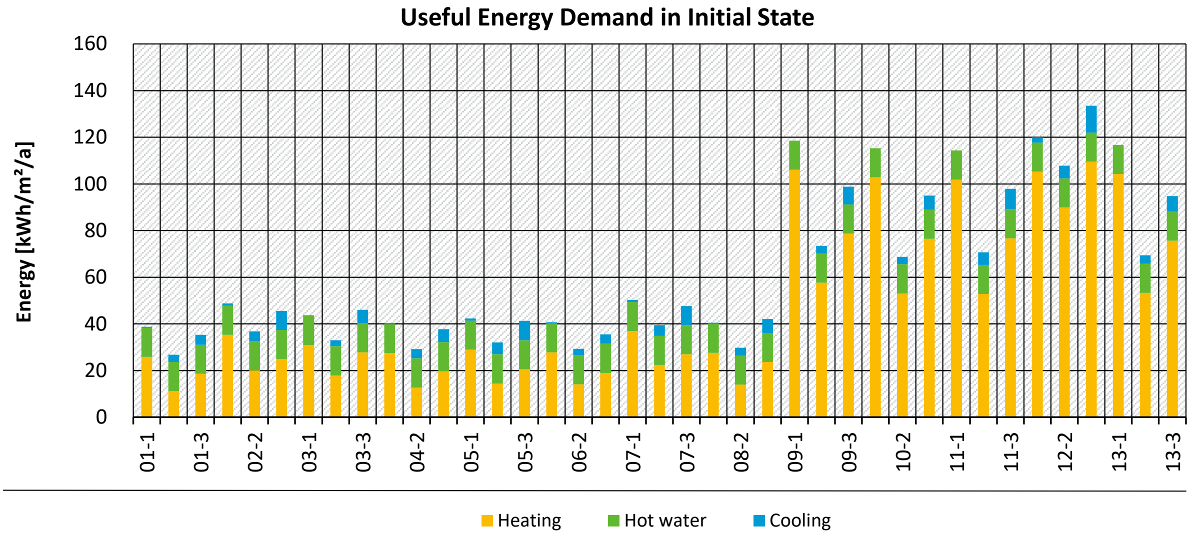
[71]Roughly corresponds to an occupancy of 50% of the roof area, assumed orientation: 30° inclination with southern orientation

[72]A purely technical consideration was assumed, i.e., that both the battery storage and the PV can be used for building technology as well as for household electricity.

2.2.7.4.3 Results

As expected, the useful energy demand for heating is highest in the partially renovated existing buildings. In the attic and ground floor apartments (apartments with the last digits -3 and -1) this is in the range between 76 kWh/m^2 and 110 kWh/m^2 (see the following figure). The useful energy demand for heating in the middle-floor apartments (apartments ending in -2) is significantly lower. A qualitatively similar behaviour can also be observed in the new buildings, with the useful energy demand for heating here being in a range between 11 kWh/m^2 and almost 40 kWh/m^{2}a. Regarding the useful energy demand for cooling, no systematic deviations can be observed between the new building and the existing building. Significant differences arise here because of the location of the apartments. While the ground floor apartments only have a negligible useful energy demand for cooling, this increases in the middle-floor apartments and reaches maximum values of up to 13 kWh/m^{2}a in the attic apartments. The useful energy demand for hot water was assumed to be the same for all apartments at 12.5 kWh/m^2 a.

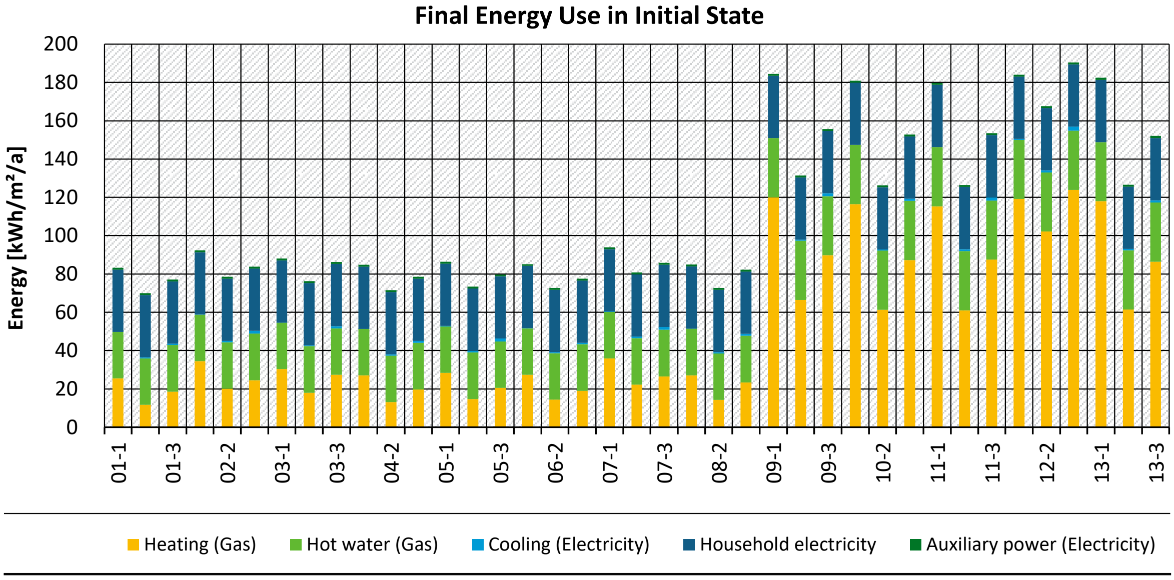
Figure 108: Useful energy demand of the apartments of variant SQ2 (with building cooling) in the Frankfurt quarter



Source: Own illustration, Guidehouse

If one considers the final energy demand, the picture shifts, as can be seen in the following figure. While the characteristic values for heating change only slightly, the final energy demand for domestic hot water increases sharply due to the distribution losses and exceeds the heating energy demand in the middle-floor apartments in the new building. Since the cooling in the considered variant SQ2 is provided via split air conditioning units, which have an assumed average seasonal performance factor (SEER) of 5, the final energy demand for cooling drops accordingly. The technical auxiliary energy demand is low, especially in comparison to the household electricity requirement, which was set to 32.5 kWh/m^{2}a, or the hot water demand, which, including losses in the new building, is 24 kWh/m^{2}a and 31 kWh/m^{2}a in the existing buildings.

Figure 109: Final energy demand of the apartments of variant SQ2 (with building cooling) in the Frankfurt quarter

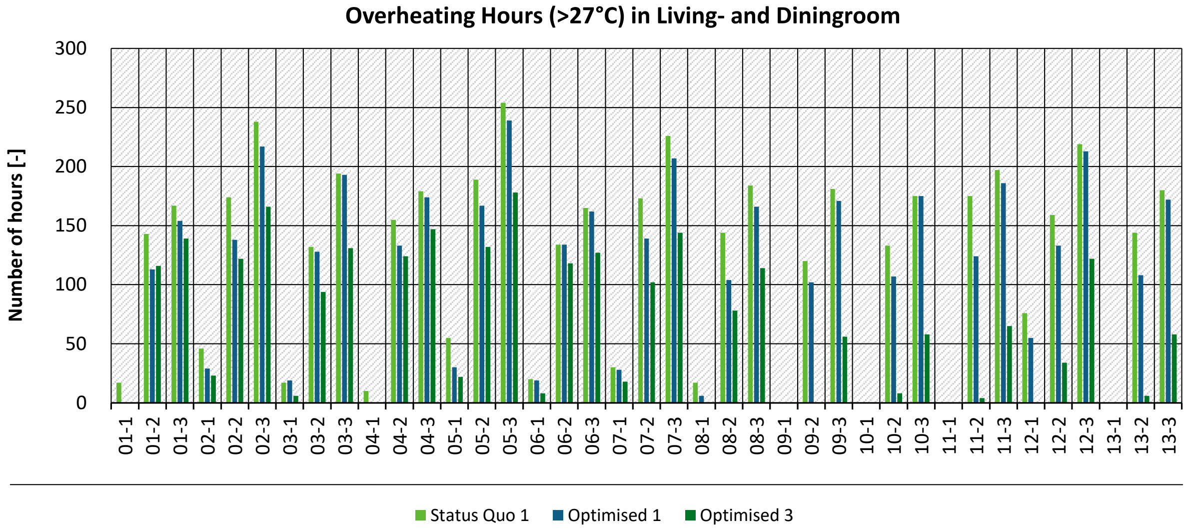


Source: Own illustration, Guidehouse

The annual overheating hours, both in the living/dining area and in the bedrooms and children's rooms in the middle and attic apartments of the variants SQ1 and Opt1, often exceed 150 h/a[73], i.e. it gets uncomfortably warm here in 15% of the usage time (cf. Figure 110 and Figure 111). The situation in the ground floor apartments is significantly less critical. With one exception, no overheating can be observed in the existing buildings. A slight improvement is achieved through the microclimatic optimization of the quarter (variant Opt1). The hours of overheating can be significantly reduced by improving the building envelope and sun protection (see variant Opt3 in Figure 110 and Figure 111). Overall, however, the overheating hours, especially in new buildings, are often still over 100 h/a in the middle and top floor apartments and thus in an unacceptable range, so that cooling is required to ensure sufficient comfort in summer. This applies to both new buildings and existing buildings.

[73]The total number of hours of presence in summer for the living/eating zone is 1,071 h/a and 1,220 h/a for the bedroom and children's room zone.

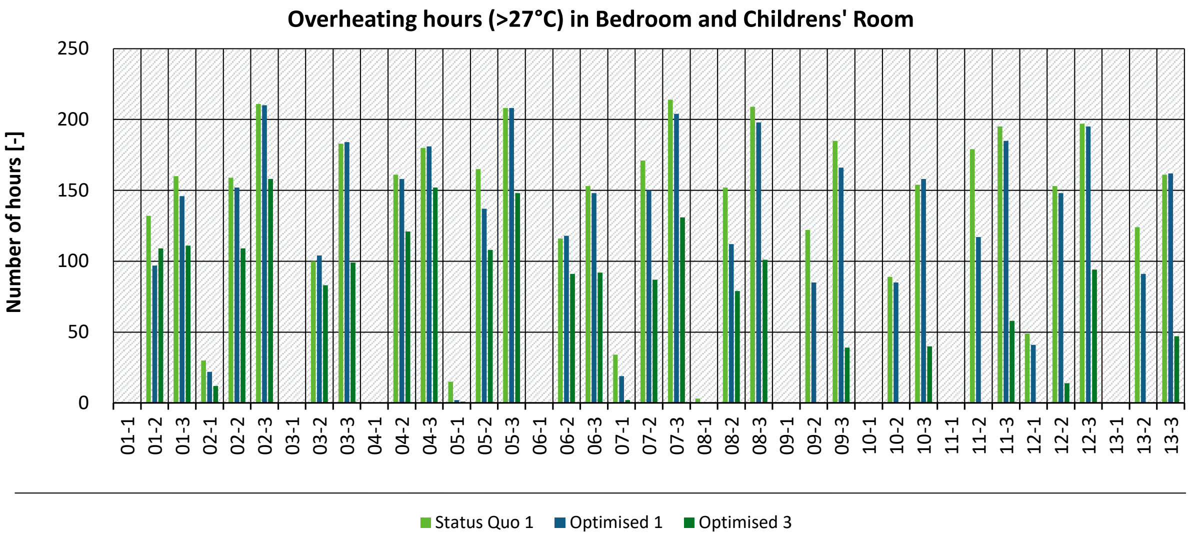
Figure 110: Comparison of the overheating hours (> 27 °C) in the living and dining areas of the apartments in the Frankfurt quarter



Quarter variants Status Quo 1 (initial state, building without cooling), Optimised 1 (optimised quarter, building without cooling) and Optimised 3 (optimised quarter and optimised building without cooling).

Source: Own illustration, Guidehouse

Figure 111: Comparison of overheating hours (> 27 °C) in the bedrooms and children's rooms of the apartments in the Frankfurt quarter



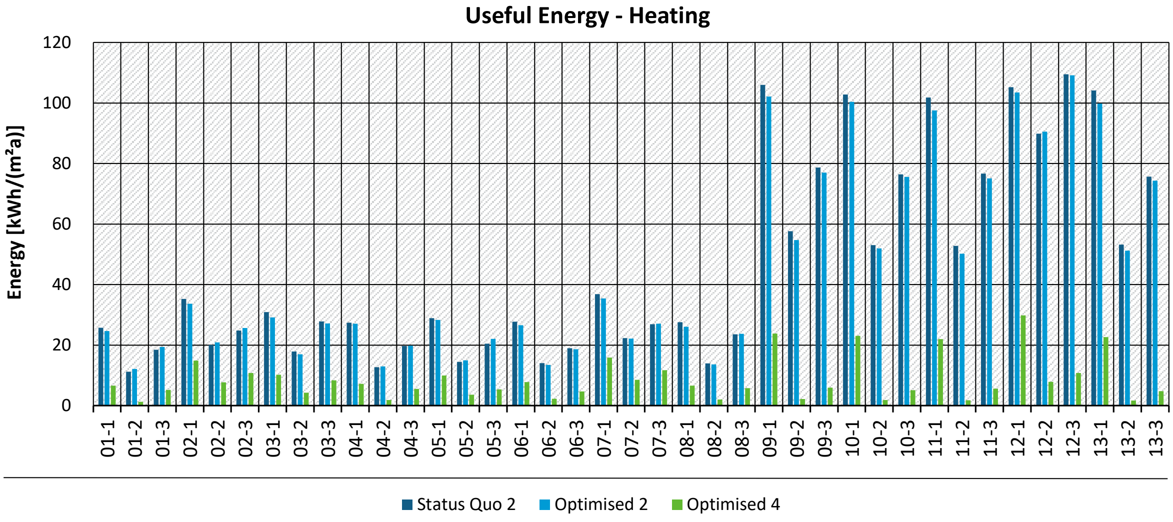
Quarter variants Status Quo 1 (initial state, building without cooling), Optimised 1 (optimised quarter, building without cooling) and Optimised 3 (optimised quarter and optimised building without cooling).

Source: Own illustration, Guidehouse

As can be seen in the following two figures, both the heating energy demand and the cooling energy demand are slightly reduced by the microclimatic optimization measures (compare variants SQ2 and Opt2). The heating energy demand of the non-optimised building variants SQ2 and Opt2 is in the range between 11 and 37 kWh/m²a for the new apartments, for existing apartments between 53 kWh/m²a and 110 kWh/m²a and is lowest in the middle-floor apartments. The cooling energy demand is significantly lower and is in the range between

0 kWh/m²a and 11 kWh/m²a in the apartments of the non-optimised building variants SQ2 and Opt2 and is lowest in the ground floor apartments. The insulation and sun protection measures (Opt4 variants) reduce both the heating and cooling energy demands. In new buildings, the heating energy demand of all apartments falls below 15 kWh/m²a (passive house standard), in existing buildings it falls even more significantly to below 30 kWh/m²a. The maximum cooling energy demand can even be limited to 3 kWh/m²a.

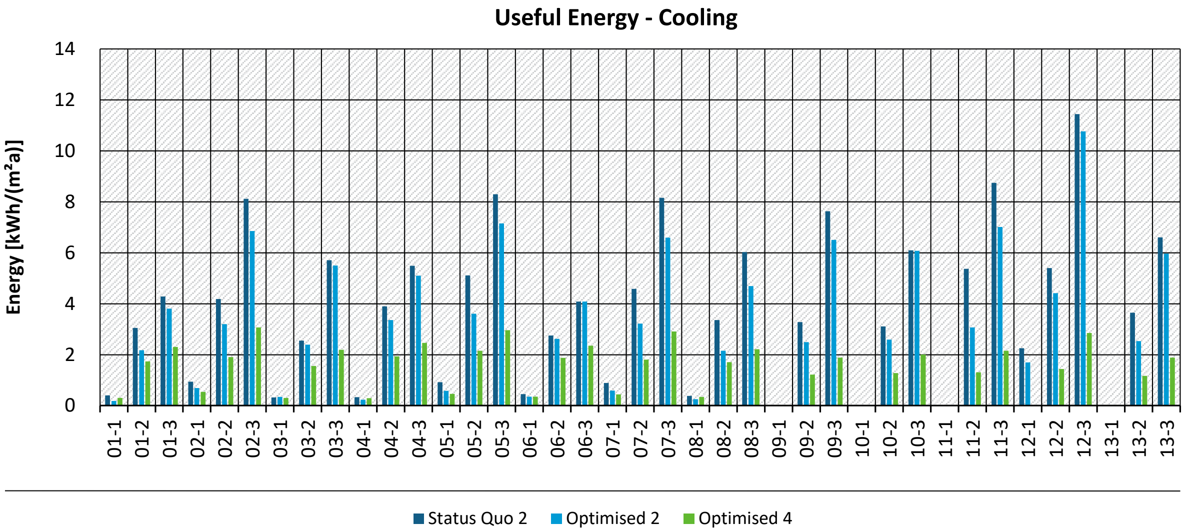
Figure 112: Comparison of the useful energy demand for heating the apartments in the Frankfurt quarter



Quarter variants SQ2 (initial case), Opt2 (optimised microclimate) and Opt4 (optimised microclimate and improved buildings).

Source: Own illustration, Guidehouse

Figure 113: Comparison of the useful energy demand for cooling the apartments in the Frankfurt quarter



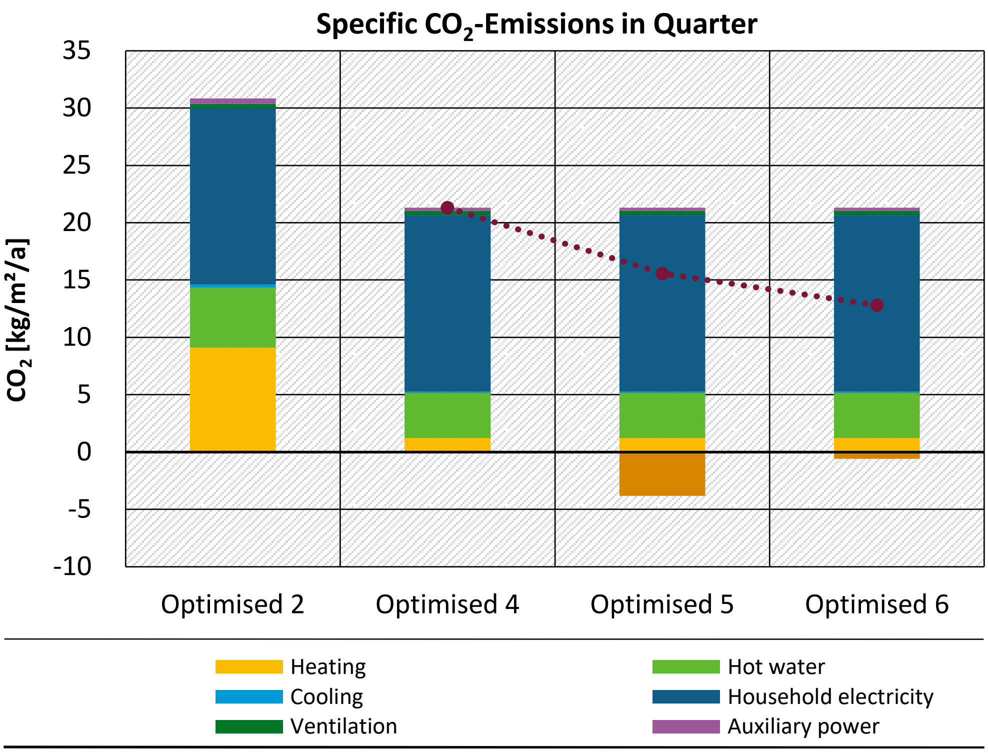
Quarter variants SQ2 (initial case), Opt2 (optimised microclimate) and Opt4 (optimised microclimate and improved buildings).

Source: Own illustration, Guidehouse

Similar to the other two German quarters, self-sufficient energy supply for the quarter cannot be achieved solely through improvement measures and renewable energy provided on site.

The building-related CO_2 emissions[74] (without household electricity) could be reduced by approx. 10 kg/m²a, i.e., approx. to a third, through the improvement measures in the building (cf. variants Opt2 and Opt4 in Figure 114). Through the direct use of the electricity generated by the PV systems on the roofs (on average 1.5 kWp per apartment, see variant Opt5), CO_2 emissions can be reduced by additional 5.7 kg/m²a. A further reduction of another 2.8 kg/m²a is possible by considering the battery storage (per apartment on average 2 kWh, cf. variant Opt6). The remaining surplus of PV power which has to be fed into the grid is minimal.

Figure 114: Comparison of the CO_2 emissions of different variants



Opt2 (no building measures), Opt4 (enhanced thermal protection and sun protection), Opt5 (additional PV) and Opt6 (additional battery storage). Dots indicate the remaining CO_2 emissions considering the directly used PV.

Source: Own illustration, Guidehouse

Overall (including household electricity, which accounts for the largest share of CO_2 emissions at approx. 15 kg/m²a), specific CO_2 emissions of approx. 13 kg/m²a remain when uniform electricity emission factors are taken into account. Although this is a reduction of almost 60% compared to the variant Opt2 t, it also means that additional renewable energies from the region must also be provided for the quarter in Frankfurt to achieve climate neutrality. If differentiated (i.e., higher emission factors for PV and electrical heat generation[75]) are considered, the CO_2 grid electricity factor would have to reach a limit of 213 kg/kWh for annual climate neutrality.

With the planned promotion of the expansion of renewable energies for the power supply in Germany, this limit should be reached in the medium term.

[74] 0.474 g/kWh for electricity; Source: Umweltbundesamt 2021 (value for 2018; assumption: same values for grid purchase and feed-in); 0.201 g/kWh for natural gas; Source: Juhrich 2016

[75] 860 g/kWh (displacement electricity mix (GEG 2020)); Further background information on the calculation approach: see Chapter 2.2.5.4.3.2

2.2.7.4.3.1 Summary assessment

The microclimatic optimisation measures in the quarter (above all through the implementation of the large-crowned trees) can measurably, but not decisively, reduce the overheating hours (>27 °C) in the interior of uncooled buildings and the useful energy demand for cooling in cooled buildings. The shielding effect also minimally reduces the total useful energy demand for heating. Even with consideration of the effective measures of very good building insulation and very effective sun protection, without cooling it is not possible to achieve sufficient summer comfort in the summer months, neither in existing buildings nor in new buildings. However, the cooling energy required for this plays a subordinate role in the overall energy balance. With the efficiency measures described, the building-related energy demand can be significantly reduced to around a third. With regard to the CO_2 emissions of the apartments in the quarter, however, household electricity dominates. With PV systems on the roofs, the electricity requirement can be significantly reduced. However, it is not possible to have a neutral annual electricity balance (production = consumption). However, a numerical annual climate-neutral energy supply is possible if differentiated emission factors for electricity are taken into account. For this, the CO_2 emission factor for the electricity grid would have to be 213 g/kWh.

2.2.8 Summary of the results from the simulations

2.2.8.1 Microclimate simulations

The application of high-resolution microclimate models enables the numerical prediction of the impact of structural changes in urban planning areas on the urban climate.

Two different possible applications of high-resolution city climate data were used in the present study: on the one hand, the possibility of adapting regional climate data to the special conditions of the building location in the urban context and, on the other hand, the analysis of the spatial-temporal distribution of thermal comfort in the outdoor area.

The first application was implemented in practice to adapt the climatological input data of the thermal building simulation to the local conditions for each plot. The analysis horizon of the ENVI_MET model, which actually only covers a short period of time, was extended to a complete year. By dividing the arithmetic tasks into different time layers, which were simulated on different computers and reassembled into a season series, this approach was chronologically feasible in the context of this project. For a practical application, however, it will be necessary to draw conclusions by analogy e.g., using AI methods, so that a complete year does not have to be simulated.

The second application does not aim to generate complete season series, but to understand the interactions between the built environment and the microclimate and to derive tips for optimal planning from this.

These analyses thus focus on typical situations, such as a hot summer's day, which make it possible to understand the complex processes in the urban quarter.

The thermal comfort index PET was used to analyse the data. The PET describes the thermal sensation of a person under the influence of radiation flows (especially solar radiation), wind, air temperature and humidity. Here, the influence of solar radiation is the dominant factor. For this reason, shadowing measures are particularly effective in improving thermal comfort. However, in already shaded areas or in the absence of solar radiation, the local wind speed and air temperature have a significant impact on thermal comfort.

In contrast to local shadowing elements, the distribution of wind and air temperature depends on the overall dynamics of the microclimate in the study area and can only be optimised through an overall concept.

The assessment of the effectiveness of measures and the selection of suitable measures depends very much on the thermal situation found in the status quo and must be assessed for each individual case.

The most efficient measure is to reduce direct sunlight by using shadowing elements. Technical solutions such as sun sails or green structures such as trees can be considered here. Technical solutions are limited to the pure shadowing of the sun's rays and can themselves heat up considerably and thus contribute to indirect heating of the environment. Vegetation, on the other hand, does not warm up much due to the transpiration of the leaves and has a cooling effect on the environment even in the shade and at night. A prerequisite for this, however, is an adequate water supply to ensure the survival of the plants. This can prove to be a limiting factor in dry climates, so structural solutions are more likely to be considered here than in areas with an adequate water supply.

The cooling by water misting (water spray) presented for Hamburg is also a very efficient method to significantly reduce the air temperature, which can achieve the maximum cooling effect in connection with shadowing measures. However, here, too, the availability of clean water and a corresponding technical infrastructure for water misting is a basic requirement that cannot be met in many hot climates.

A special challenge is the reduction of the heat load during the night hours. Although the outdoor area is generally little frequented at night, the provision of cool or cooler air is also an important prerequisite for passive ventilation of the interior rooms for a healthy sleep.

The thermal load during the night hours is defined on the one hand by the heating and subsequent release of thermal energy from the different urban structures. A reduction in the energy input during the daytime hours has a long-lasting effect here and can reduce the heat load. Further cooling at night can only be achieved by evaporative cooling, with open green areas with a sufficient view of the sky playing an important role. Tree stocks, on the other hand, can also appear as warming factors within built-up areas due to the shielding effect (so-called 'beer garden effect') and the deceleration of the wind. The assessment of the effects of local transformations during the night hours is therefore even more sensitive to the respective urban structure, so that the individual case must be examined.

2.2.8.2 Building simulations

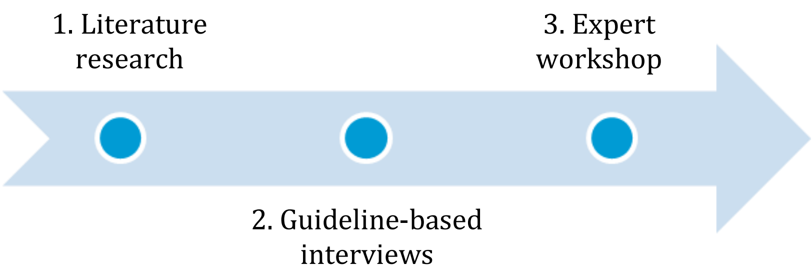
The optimisation measures taken into account to reduce the heat island effect at quarter level have a measurable, but usually relatively small, positive influence on indoor comfort in summer. Regarding energy aspects, the slight reduction in the cooling energy demand is often almost completely offset by the slight increase in the heating energy demand. Apart from the buildings in Hamburg, cooling is necessary in all cases to ensure good summer comfort, despite extensive preventive measures (ventilation cooling, sun protection and improvement of the building envelope). Above all, the attic and middle-floor apartments prove to be critical regarding the overheating problem. The cooling energy demand of the building is largely independent of the year of construction and, apart from the ventilation behaviour, is rather influenced by the quality of the envelope and sun protection. Compared to other energy demands, such as household electricity, domestic hot water or heating energy demand, the final energy demand for cooling in the German quarters is comparatively low. This is not least due to that highly efficient cooling systems (e.g. floor cooling) that were taken into account. This all makes it more important not to use fluorinated refrigerants, which cause unavoidable direct greenhouse gas emissions or, in the case of unsaturated HFCs (also known as hydrofluoroolefins (HFO)) or their decomposition products further environmental damage. Regarding the desired climate neutrality through renewable energies on site, the ratio of the available roof area to the living space is the limiting factor. While for the quarter in Tunis, due to the high level of solar radiation and the predominantly low number of storeys, PV systems on the roofs can generate as much electricity as is required in the optimised quarter. This is not possible even in Madrid, which is also very sunny. Due to the geometry of the eight-storey building, there was only 1 kWp of installed PV capacity possible per apartment. Even in the German quarters examined, the available roof area is not sufficient for an annual climate-neutral electricity balance, despite the lower number of storeys and the extensive improvement measures on the buildings. This is mainly due to the remaining household electricity demand. Its minimization is therefore a key component in making (residential) quarters climate-neutral. Arithmetical annual climate neutrality is possible if differentiated CO_2 factors (i.e. higher emission factors for PV and electrical heat generation[76]) are taken into account. In large city quarters with a high residential density (cf. Campo Bornheim quarter in Frankfurt), however, a further improvement in the CO_2 electricity mix factor in the German electricity grid is necessary.

[76] 860 g/kWh (displacement electricity mix (GEG 2020)); Further background information on the calculation approach: see Chapter 2.2.5.4.3.2

3 Stakeholder analysis and workshops

To ensure the transfer of the project results into practice, the research project included a comprehensive exchange with practitioners. This is based on the work steps shown in Figure 115, which are described in more detail in the following sections.

Figure 115: Overview of the procedure for exchanging information with practitioners.



Source: Own illustration, Öko-Institut

3.1 Literature research

3.1.1 Stakeholder analysis and responsibilities

Based on a literature analysis, the responsibilities for the various measures to avoid urban heat islands considered in Section 1.3 were first examined. These are regulated differently depending on the municipality. Table 18 shows examples of typical responsibilities of the various offices. In addition to the various responsibilities for the individual measures, in many municipalities the responsibility for coordinating the topic is located in one of the offices (e.g., environmental office).

Table 18: Responsibilities for implementing measures to avoid urban heat islands

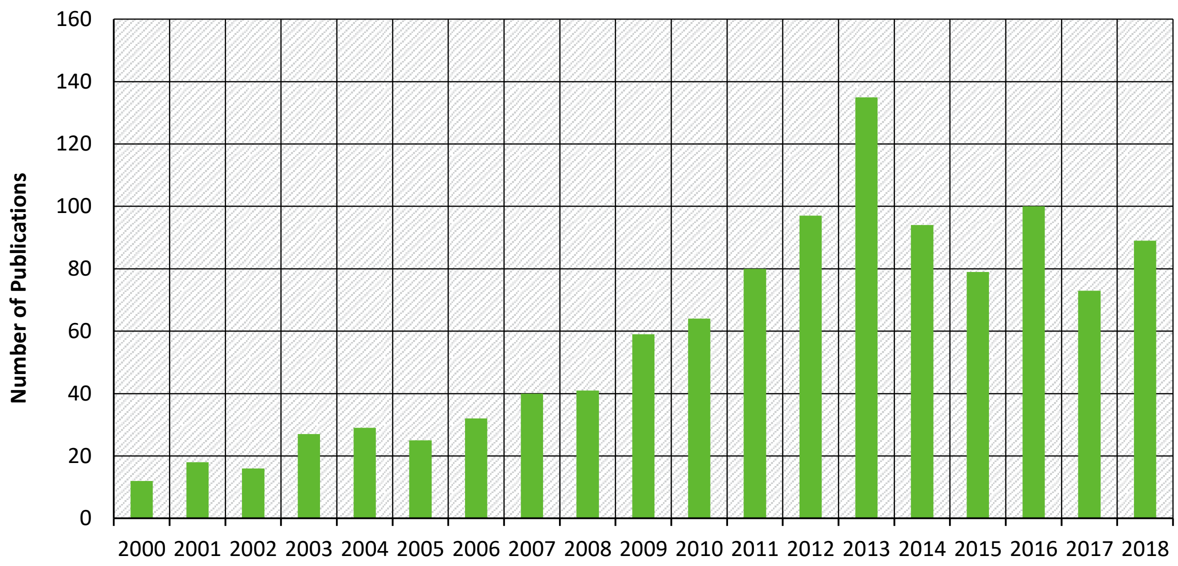
No.	Designation	Responsibility of the city administration	Examples of responsible offices
1	Brightening of coverings and surfaces in open spaces	For urban areas: direct responsibility of the city administration	Civil engineering office
2	Securing and expanding the tree population	Trees on public land: direct responsibility of the city administration. Trees on private land: municipal options for action via tree statutes, tree protection regulations or development plans	Office for Green Spaces, Environment Office, Regulatory Office
3	Securing existing and creating additional forest areas	Direct responsibility of the city administration	Forest office
4	Unsealing of open space surfaces/ avoidance of sealing	On urban areas: direct responsibility of the city administration e.g., about land use plan	City planning office
5	Securing and expanding green and open spaces	Direct responsibility of the city administration e.g., about land use plan	City planning office

No.	Designation	Responsibility of the city administration	Examples of responsible offices
6	Preservation of urban air circulation and networking of open spaces	Direct responsibility of the city administration e.g., about land use plan	City planning office
7	Roof and facade greening	No direct responsibility of the city administration; in new buildings: options for action via development plans	Building authority, city planning authority
8	Increasing the proportion of water in the quarter	Direct responsibility of the city administration	City planning office
9	Shadowing of open spaces and paths	Direct responsibility of the city administration	City planning office

3.1.2 Importance of the topic

In general, the literature analysis shows that the importance of the topic has increased significantly in recent years. Figure 116 shows the annual number of German-language publications over time and underlines the clearly increasing relevance of the topic. The analysis makes it clear that the number of publications in the last 10 years is many times higher than in the previous period.

Figure 116: Number of German-language publications on urban heat islands.

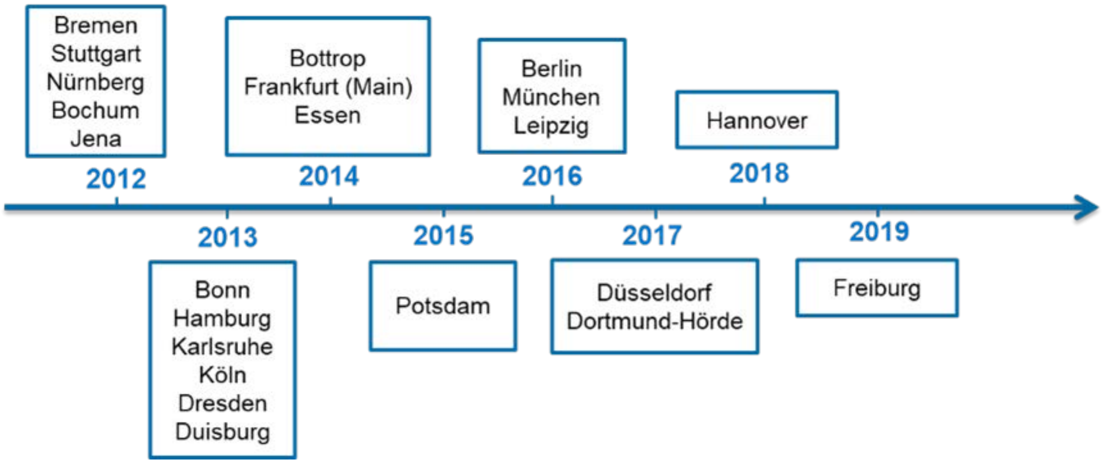


Source: Own representation based on data from google scholar[77], Öko-Institut

In addition to the increasing relevance of the topic in scientific publications, the topic is also becoming increasingly important in municipal planning. This is reflected in the numerous climate adaptation concepts that have been developed in various municipalities in recent years (see Figure 117).

[77]The analysis includes publications with the keywords "heat island" and "heat island".

Figure 117: Overview of publication dates of climate adaptation plans in cities.



Source: Own illustration, Öko-Institut

3.1.3 Data basis and planning tools

Temporally and spatially resolved temperature data represent an important planning basis for concepts to avoid urban heat islands and are typically a central component of municipal concepts. This also requires software tools to develop such a database based on the values from measuring stations.

The comparison of climate adaptation concepts from different municipalities shows that the concepts differ in terms of the data basis and the tools used. Since the role of data availability and planning tools is only insufficiently examined in the literature, this was further discussed in the expert interviews.

3.2 Guide-based interviews

As part of the research project, a total of 16 interviews with municipal actors were carried out between February and July 2019. Actors from Berlin, Bonn, Dresden, Düsseldorf, Erfurt, Freiburg, Hamburg, Hanover, Cologne and Ludwigsburg were interviewed. The following topics were examined in the interviews (see Appendix A.2 for a detailed description of the questions):

- Experiences with goals and measures that have already been implemented
- Actors and responsibilities in the implementation of measures
- Importance of the topic compared to other concerns
- Data availability
- Barriers and supporting policies

The evaluation of the interviews is divided into the presentation of the measures implemented in the municipalities (Section 3.2.1), the obstacles discussed in the interviews (Section 3.2.2) and the suggested potential for improvement and options for action (Section 3.2.3).

3.2.1 Measures taken

The measures of the respective municipalities mentioned in the interviews are listed below. They are divided into measures at the planning level and practice and sorted according to frequency and relevance.

Table 19: Measures at the planning level

Measures at the planning level	Examples/ notes
Climate adaptation concepts	Many municipalities have developed climate adaptation concepts in the last 10 years.
Urban climate analysis	Many municipalities have carried out urban climate analyses, some of which exhibit very high resolution, thus showing urban heat hotspots. However, these climate analyses are associated with a high-cost factor.
Heat action plans	Some municipalities have prepared action plans for heat situations.
Progress reports	Regular reporting is practiced in many municipalities to pass on information and to check the implementation of measures.
Urban development plans with planning reference cards	Many municipalities take climate adaptation into account in the current land use plans. However, the planning information cards usually only contain recommendations, not mandatory specifications. There is a problem with commitments to climate adaptation in existing buildings.
Additional assessments in critical zones	For construction projects in zones that have been assessed as critical in the city climate analyses, some municipalities require additional expert opinions on their climate compatibility.
Anchoring in the urban concept	Incorporation of the topic in the mission statement of the municipality/department/the mayor emphasizes the relevance of urban heat islands and increases the scope of the adaptation measures.
Greening statute	Some municipalities have a greening statute that obliges new buildings to have green roofs.
Positive interpretation of the term climate adaptation	Municipalities are attempting to make the topic more attractive and accessible by reinterpreting the term climate adaptation (preservation of quality of life instead of the term catastrophe).

Table 20: Measures in practice

Measures in practice	Examples/ notes
Subsidy programs for roof and facade greening in existing buildings	Many municipalities create incentives for green roofs and facades in existing buildings through subsidy programs. In some interviews it was mentioned that the implementation of facade greening is often more difficult than that of roof greening.
Increasing the proportion of urban greenery	Many municipalities want to plant more city trees, but encounter many obstacles in the implementation (e.g., insufficient space for roots, insufficient budget for maintenance).
Climate-adapted city green	Adaptation of the species composition of the city forest to the future climate to ensure the continued existence of the city green under changed climatic conditions.
Connection and keeping clear of cold air aisles	Some municipalities are investigating how they can maintain or improve the supply of cold air in the municipality through building restrictions.
Better drinking water supply	Many municipalities are increasing the number of drinking fountains in public spaces to improve access to drinking water during heat events.
Climate adaptation of municipal buildings	Due to the climate adaptation of existing municipal buildings and the climate-friendly construction of municipal new buildings, some municipalities serve as role models and pioneers for climate-adapted construction for their citizens.
Citizen Awareness	Some municipalities are using relevant and tangible examples to sensitize their citizens: e.g., description of the heat development in popular places in the city or comparison of the heat effect of different garden materials.
Combination of green and water areas	Many municipalities consider the development of green and water areas to be integrated to use the synergetic cooling effect of urban greenery and water areas.
Increase of infiltration areas	Some municipalities named the increase of infiltration areas as a measure against flooding during heavy rain events. This is implemented, among other things, via subsidy programs or guidelines for new buildings.
Minimise new surface sealing	Some municipalities cited minimising new land sealing by preferring the construction of residential and commercial space on derelict and vacant land in the city rather than on vacant land on the outskirts.
Training of professionals	Some municipalities specifically rely on training programs for professionals to close gaps in knowledge or to counteract misconceptions, e.g., Training programs for architects on the combination of PV and green roofs.
Mobile shading devices	Mobile shading devices, as a complement to other shading devices, can reduce heat exposure in critical public places.

3.2.2 Obstacles

The obstacles to the implementation of measures by the respective municipalities mentioned in the interviews are listed below. They are sorted by frequency and relevance.

Table 21: Obstacles

Obstacles	Examples/ Notes
Climate adaptation is not legally binding: Climate adaptation is not yet a mandatory task	• The lack of legal anchoring of climate adaptation is seen by all municipalities as a major obstacle to the implementation of measures to avoid urban heat islands. • Lack of prioritization in the event of conflicting goals: All municipalities complain that climate adaptation is not able to assert itself when there are conflicting goals in relation to other, legally binding municipal interests (e.g., noise protection, monument protection, housing shortages, etc.). • Many local authorities consider the 2011 amendment to the Climate Protection Act of the Building Code to be too vague. • Most municipalities are demanding legally binding guidelines for avoiding urban heat islands.

Missing budget	• Almost all municipalities have difficulties in financing the following areas:
	  ○ Staff,
	  ○ Subsidy programs (e.g., green roofs and facades) in existing buildings,
	  ○ Maintenance of climate adaptation measures, e.g., maintenance of city trees and facade greening,
	  ○ Own funds (applies to municipalities or private individuals).
	• All municipalities criticize the lack of a budget for climate adaptation. Project-related financing complicates long-term personnel planning and project management. A municipal funding pool for climate adaptation is desired.

Staff shortage	• Climate adaptation as an additional task for all municipalities. • Time limits due to project-related financing are a major problem in all municipalities. • In smaller municipalities in particular, there is often a lack of specialist staff.

Lack of information on the consequences of urban heat islands and the effectiveness of measures against urban heat islands	• Almost all municipalities complain about a lack of information about the consequences of urban heat islands:
	  ○ Lack of data on morbidity or mortality rates due to heat,
	  ○ Lack of dissemination of key data on heat development (hot days, tropical nights, etc.) at municipal level that can be used by politicians,
	  ○ Partly missing data on potential risks in the city (e.g., vulnerable population),
	  ○ Uncertainties in climate forecasts,
	  ○ Without data on impacts, there is little evidence to support action against urban heat islands.
	• All municipalities criticize a lack of information about <u>the effectiveness of measures</u> against urban heat islands:
	  ○ Difficult to quantify the effect of measures against urban heat islands,
	  ○ Spatial differentiation is important, but expensive.

Obstacles	Examples/ Notes
Difficulty of mandatory climate adaptation in stock	• Land use plans only affect new buildings, which only make up a very small part of the development. • Many municipalities criticize that the stock, which makes up the main part of the built-up city, is very difficult to reach by law and that subsequent changes to the land use plans are not socially feasible. • Many municipalities complain about the lack of information among the target groups, e.g., private homeowners or homeowner associations, about urban heat islands and options for action against urban heat islands. • Voluntary measures for the building stock require a lot of public relations and persuasion work and are not used across the board in many municipalities by the population. • Small proportion of buildings in public hands.
Lack of impetus at federal and state level	• All municipalities would like politicians at the federal and state level to play a strong pioneering role, which prioritizes climate adaptation. • Laws at the federal level are needed so that they can be transferred to the state and local levels.
Obstacles in cross-departmental cooperation	• Unclear responsibilities, lack of cross-departmental coordination and lack of coordination of tasks in many municipalities. • Climate adaptation is a cross-cutting issue involving a variety of actors, all with different backgrounds and goals. This leads to multidimensional conflicts of interest and goals. • Awareness of climate-adapted urban development is already high in most municipalities, but awareness and implementation often diverge.
Lack of penetration of climate adaptation in urban planning and urban redevelopment	• Some municipalities criticize the lack of awareness of climate change adaptation among city planners and builders. • Some municipal representatives criticize the lack of cooperation between the responsible bodies for climate adaptation on the one hand and construction on the other hand in the city administration.
Complexity of the problem area of urban heat islands	• Urban heat islands are much more difficult to grasp and combat than other urban problems such as housing shortages. • Since no quick successes can be achieved, it is often not an attractive topic for politicians in most municipalities.
Partly missing integrated consideration of climate adaptation	• Some municipalities complain that climate protection and climate adaptation are not always viewed in an integrated manner. • Many municipalities complain that climate change adaptation is not always thought of across sectors.
Little support for municipalities	• Assistance is particularly needed in financially weak municipalities. • Many local authorities hope to avoid duplication of work by having assistance provided.
Partial lack of networking and cooperation between municipalities	• Many municipalities would like better networking at state, federal and EU level. • Inexperienced municipalities can learn from experienced municipalities. • Avoidance of duplication.
Difficulty implementing facade greening (compared to roof greening)	• In many municipalities, facade greening is more difficult to implement than green roofs. Reasons for this include: o More prejudices against facade greening in the population,

Obstacles	Examples/ Notes
	○ Increased maintenance effort for the green facade.
Lack of space for measures against urban heat islands	• Due to too narrow urban infrastructure (e.g., cables, sewers), some municipalities cannot find space for new urban trees. • In all municipalities there is a conflict of objectives with the need for housing.
Uncertainty about liability issues	• Some municipalities cited a lack of information and legal certainty on liability issues when implementing measures to combat urban heat islands.
Rigid funding structure	• Some municipalities wish to rethink the funding structure to ensure effective funding that reflects the needs of the municipality, e.g., promote greening of both public and private buildings in one programme.

3.2.3 Suggestions and options for action

The suggestions made in the interviews for improving the options for action by municipalities in adapting to climate change and avoiding urban heat islands are listed below. They are sorted by frequency and relevance. The list also includes particularly positive practical examples that were mentioned by the interviewees.

Table 22: Suggestions for improving the options for action mentioned in the interviews

Suggestions	Examples/ Notes
Climate adaptation as a mandatory task due to a strong legal framework	• Legally mandated climate adaptation and heat action planning that assign mandatory responsibilities. • Mandatory climate impact assessment (similar to the environmental impact assessment). • Mandatory action rather than voluntary action. • Concrete guidelines or limit values for climate or heat-adapted urban development (comparable to noise protection). ○ Good example: Paris: by 2020, every Parisian should not need more than 7 minutes to walk to the nearest green space or water feature (Ville de PAris 2021) . • Improved legal position in the following laws: ○ Construction Code (German BauGB): ▪ Climate adaptation as a duty, not just a balancing task. ▪ Densification in the district should be climate-adapted, regardless of the energy status of the district (§34 BauGB). ○ Urban development funding: ▪ Measures to adapt to climate change as a prerequisite for urban development funding. ▪ Good example: Hesse - Guideline of the State of Hesse to promote sustainable urban development (RiLiSe) 2017: Urban development funding primarily for sustainable urban development (Hessian Ministry for Social Affairs and Integration 2017) . ○ Land use plans: ▪ Stricter building restrictions or building bans in cold air channels or other sensitive areas (climatopes) instead of just

Suggestions	Examples/ Notes
	recommendations in the planning information map of the land use plans and subsequent consideration. ▪ Subsequent changes to the development plans for existing buildings. o Strong climate laws at state level: ▪ good example Thuringian climate law - ThürKlimaG (2018): Climate adaptation anchored in § 10-13 (Thuringian state parliament 2018a) o Integrate mandatory measures into other existing municipal statutes, e.g., in parking space statutes or front yard statutes. Problem of verification. o Other laws that interviewees would like to see improved: ▪ State building code ▪ State water laws ▪ Road building code
More budget for climate adaptation	• Separate, special budget for climate adaptation in municipalities, e.g. through a climate adaptation title. • Increased budget enables long-term staff retention and better support programs.
Improvement of the data basis in municipalities	• Climate Analysis: o Mandatory for municipalities, with submission from the legislature. o Better financial support for climate analysis, especially for smaller municipalities. o Regular update. • Impact of urban heat islands: o Calculate heat-related mortality and morbidity rates in communities. Mandatory guidelines for data collection from the federal government. ▪ Good examples: Berlin: Specialist article: an average of 5% of deaths from 2001 to 2010 can be statistically attributed to elevated temperatures (Scherer et al. 2013) . Berlin & Hesse: Estimates of heat-related deaths in the hot summer of 2018: 490 (Berlin), 740 (Hesse) (Robert Koch Institute 2019) . o Better processing and dissemination of key data on heat at community level (e.g. number of tropical nights). • Objective data on the effectiveness of measures against urban heat islands. o e.g., temperature reduction potential of the various measures under different climatic conditions (roof and facade greening, water management, shadowing, brightening of surfaces, tree populations, etc.). o Key data on the climatic behaviour of different surface types. o Cost-benefit analysis to demonstrate cost-effectiveness. ▪ Good example: UBA study on the costs and benefits of 28 adaptation measures to climate change in Germany (Tröltzsch et al. 2012).

Suggestions	Examples/ Notes
	○ Processing of the existing scientific knowledge about the effectiveness of measures in a language that is easy to understand.
Federal and state governments as active pioneers	• Actions at federal and state level need actual broadcasting at local level. ○ Good example: Thuringia: Climate Adaptation Strategy (IMPAKT 2) and climate law (ThürKlimaG, (Thüringer Landtag 2018b)).
Better networking	• Within the municipalities: ○ Urban development and climate adaptation in one department. ○ Regular exchange on climate adaptation between all participating offices, e.g. through long-term working groups. • Between the municipalities: ○ Inter-municipal workshops or project meetings that promote the transfer of knowledge and exchange of experience between climate adaptation actors from different municipalities. ➔ Example: Expert workshop in spring 2020 as part of this project.
Expand and better publicize assistance for municipalities	• Disseminate existing assistance and make it accessible to municipalities. ○ Good example: Climate precaution portal (KliVo, (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) 2020)) of the German Adaptation Strategy (DAS): bundles data and information on climate change and climate change adaptation for municipalities. • Expand support for the implementation of measures to adapt to the consequences of climate change, especially for smaller municipalities that are financially weaker and have less experience on the subject than larger municipalities.
Make information better known to the general public	• Spread existing aids and make them more accessible to the population. ○ Good example: practical guidebook climate-friendly building by Difu (Jolk et al. 2017a) : informs citizens about measures for new construction and existing buildings and names other sources of information and advice centres.
Increasing the ability to act and legal certainty	• Identification of concrete, implementable key measures instead of abstract goals. • Increased legal security in liability issues.
Reduction of administrative hurdles in funding programs	• The high administrative effort involved in acquiring funding is a major obstacle for municipalities and ties up a lot of staff.

3.3 Expert workshop

On March 31, 2020, a technical discussion took place as part of the research project, in which the results were discussed with experts from science and practice. The representatives of various municipalities made up the largest share of the participants with about half, followed by scientists and experts from planning of measures to avoid heat islands. The workshop was held in online format due to the Corona pandemic.

As part of the technical discussion, the results of the microclimate simulation for the quarters in Tunis and Cologne were presented and discussed with the participants. In the open discussion that followed, further suggestions for the implementation of measures to avoid heat islands were made. In particular, the use of green space factors, the use of windows of opportunity for redesign measures that are pending anyway, and the greater consideration of evaporation to avoid heat islands were emphasized. The suggestions were included in further project processing.

4 Proposals for adapting the legal framework and other instruments

In the following, suggestions for improving various aspects relating to the topics of urban climate, summer heat protection and sustainable building cooling are developed. Some of the suggestions are derived from the results of the investigations carried out as part of this research project, but also some additional relevant aspects are taken up. The proposals were selected based on a previously made selection, which was reduced to the 10 most important points from the point of view of the client and the authors during a project meeting. Identified opportunities for improvement in German municipal, state-specific and national as well as transnational (EU) legislation and regulations are addressed thematically. Funding programs were also considered.

4.1 Overcoming the barriers to natural refrigerants

As a result of the European F-gas regulation (European Commission, 2014) , the previously common fluorinated refrigerants with a higher global warming potential for refrigeration/air conditioning systems and heat pumps will become even more scarce and expensive. The use of natural, i.e. fluorine-free, refrigerants as an alternative can significantly reduce both the emission of fluorinated greenhouse gases (F-gases), new fluorinated gases and the input of persistent (i.e. very stable) and groundwater-penetrating atmospheric degradation products of all fluorinated refrigerants (Behringer et al. 2021) .

In devices with low cooling capacity such as refrigerators, natural refrigerants, today mostly the hydrocarbon isobutane, have long been standard (Vogelsammer 2021) . Systems with natural refrigerants such as the hydrocarbon propane are also available for heat pumps in tumble dryers (Jendrischik 2020) or for house heating (e.g. Fraunhofer 2019, HAUTEC heat pumps , Energie-Experten.org 2021).

Although systems using natural refrigerants have been developed and tested for a long time, the number of systems using natural refrigerants for cooling and heating rooms is increasing only slowly. One reason for this is the flammability of some natural refrigerants. Hydrocarbons such as propane, butane and isobutane are specified in the ISO 817 standard for refrigerant classification in safety class A3 (low toxicity, higher flammability), ammonia in class B2L (higher toxicity, lower flammability). If there is damage or a leak in the refrigerant-carrying components or lines, there is a risk of fire and explosion due to escaping refrigerant. For the safe use of flammable refrigerants, the components and the system design must therefore be adapted and risk analyses must be drawn up.

Different values apply to the maximum permissible filling quantities for flammable refrigerants, which differ depending on the refrigerant, the standard used and the installation situation.

There are no restrictions on filling quantities for outdoor use, since dangerous concentrations are unlikely to form. However, there are requirements for ensuring safety and enclosure. For devices in rooms/buildings, various maximum permissible filling quantities for the use of flammable refrigerants are specified, depending on the room location, room size, accessibility and refrigerant.

Although the maximum permissible filling quantity of 150 g of flammable refrigerant (regardless of the room size) from the standard IEC 60335-2-24 only applied to household refrigerators, it was transferred to other standards in the series (Colbourne 2020). In many cases, important factors such as the size of the room, the position in the room and additional possible safety precautions were not taken into account, which has made it difficult to use natural refrigerants in cooling and air conditioning devices and heat pumps with higher performance (Colbourne 2020).

In recent years, these maximum values have been intensively discussed in the European standardization committees and some adjustments to the relevant standards have been made or suggested. The valid draft now includes the product standards (IEC 60335-2-40/A11) for electrically operated heat pumps, air conditioners and room air dehumidifiers and (IEC 60335-2-89) for commercial refrigerators/freezers. The EN 378 series (EN 378-1 EN 378-2:2018-04; EN 378-4:2019-12; EN 378-4:2020-12;) also contains filling quantity specifications for refrigeration systems and heat pumps depending on the room size, adjustments are discussed further. In contrast to the also flammable fluorinated A2L refrigerants, which also form toxic fluorine compounds in the event of a fire, the filling quantities possible today for systems with natural flammable refrigerants (except outdoors) are still comparatively low.

A standardization mandate from the EU Mandate M/555 (European Commission (EC) July 14, 2021) resulted in two additional technical specifications for refrigeration, air conditioning and heat pump systems with flammable refrigerants: for installation (CEN/TS 17606:2021) and for operation, maintenance, servicing, repair and decommissioning (CEN/TS 17607:2021) . CEN/TS 17606 deals with advice on alternative risk analysis. On this basis, the safe use of flammable natural refrigerants in systems with higher filling quantities can be expanded and thus enable more environmentally friendly heating and cooling.

Some companies already offer system concepts with natural refrigerants. For the successful use of flammable refrigerants, it is advisable to involve specialist companies for air conditioning and heating technology who have experience with systems with natural refrigerants as early as the planning of the building or the conversion. This is necessary in order to include sensible system concepts and the requirements for installation space, ventilation, noise protection and any regional building regulations etc. from the start.

The following measures can support the broader introduction of refrigeration/air conditioning technology with natural refrigerants:

- Approval of the previous draft standards.
- Further examination and revision of the relevant refrigeration standards to improve the conditions of use for A3 refrigerants, adjustment and, if necessary, increase of the maximum permissible charge quantities for A3 refrigerants in relation to the improvements already made for fluorinated combustible A2L refrigerants.
- Inclusion of the expertise of companies that offer natural refrigerants in the development of standards, promote participation in the standards committees.
- Promotion of specialist training specifically on the standards and their application for natural (halogen-free) refrigerants for the refrigeration industry, in order to both Getting to know regulations and new possibilities as well as showing ways to use natural refrigerants.
- Promotion of planners for halogen-free refrigeration/air conditioning technology.
- No funding for systems with halogenated refrigerants in public funding programs (as is already practiced in the refrigeration and air conditioning directive (Federal Office for Economic Affairs and Export Control (BAfA)) in an exemplary manner).
- Use the exemplary effect of the federal and state governments by procuring new refrigeration/air conditioning technology only with natural (halogen-free) refrigerants.

- In the refrigeration/air conditioning trade: Further training specifically for expertise when handling A3 refrigerants, to convey safety aspects and, if necessary, to eliminate prejudices and fears of contact.
- Independent advisory platform for natural refrigerants.
- Raising the awareness of architects, planners and builders for halogen-free cooling concepts, e.g. promotion of good practices in building and architects' magazines, on relevant platforms, in training courses and at conferences.
- Creation of a directory with relevant companies and good practice examples (both online).

4.2 Efficiency requirement and summer heat protection in the GEG

4.2.1 Initial position

The thermal protection of buildings in summer can make an important contribution to keeping the temperatures in the interior at a tolerable level in summer. In addition, measures to protect against heat in summer in buildings with active cooling can help to reduce the energy required for cooling.

In the German Building Energy Act (GEG), summer heat protection in newly constructed buildings is addressed in section 14. § 14 (1)-(3) stipulate that the buildings must be provided with structural measures to limit solar radiation and specify the requirements with reference to the German standard DIN 4108-2.

In § 14 (4), the requirements for summer heat protection are subject to economic efficiency, provided the building has cooling systems.

4.2.2 Judgement

Due to the reservation of economic efficiency in § 14 (4), stricter requirements apply in buildings without active cooling than in those in which cooling systems are available. This could therefore be an incentive to plan cooling systems in buildings.

Since the requirements for summer heat protection according to § 14 (1)-(3) for uncooled buildings are obviously independent of the savings to be achieved, a restriction of the requirements in § 14 (4) for cooled buildings is not justifiable beyond the principle of economic efficiency.

4.2.3 Suggestion for improvement

Against the background of the increasing use of active cooling, the requirements for summer heat protection should also apply without restrictions if the building has cooling systems. Section 14 (4) of the German GEG should therefore be deleted without replacement.

4.3 Tightening of regulatory requirements to limit the cooling energy requirements of buildings

Improvement proposal for the implementation of the German Building Energy Act (GEG).

4.3.1 Initial position

Due to climate change and the formation of urban heat islands, many buildings are increasingly experiencing overheating problems in summer. As a result, more and more active cooling systems are being used, especially in new buildings. In new residential buildings with underfloor heating, the cooling is often implemented using air-to-water heat pumps that can be switched to cooling mode.

4.3.1.1 Current consideration GEG

According to § 14 of the GEG, buildings are to be erected in such a way that the sun's entry is limited by adequate structural summer heat protection according to the recognized rules of technology. Compliance with the requirements of German standard DIN 4108-2: 2013-02 is decisive for this.

According to GEG § 15 and § 18, the calculated annual total primary energy demand of new buildings must not exceed 0.75 times the corresponding reference building specified in Appendix 1 (residential buildings) or Appendix 2 (non-residential buildings).

4.3.1.1.1 Residential building

Neither sun protection nor cooling is currently considered for the reference residential building.

Provided cooling systems must be considered when determining the annual primary energy demand. The calculation method according to German standard DIN V 18599: 2018-09, which is still unusual for residential buildings, must be used.

4.3.1.1.2 Non-residential building

The reference non-residential building is to be assumed to have the same sun protection device as that of the building to be erected. For room cooling, a distinction is made between air-only air conditioning systems and room cooling. Specific parameters and characteristic values are specified for each of the two types of room cooling. The primary energy demand for the cooling system and the cooling function of the ventilation and air conditioning system regarding usage zones 1 to 3 (offices), 8 (classrooms), 10 (bedrooms), 16 (toilets), 18 to 20 (ancillary and circulation areas and storage) and 31 (gymnasiums) are only counted for 50%.

4.3.2 Judgement

4.3.2.1 Residential buildings

In principle, the current normative specifications ensure that the primary energy demand for cooling in residential buildings to be constructed must be completely compensated for by energy-related measures from other areas. However, the fact that no sun protection is specified in the reference building is considered unfortunate. This judgement is based on the assessment that, as a rule, comparatively little importance is attached to summer heat protection when planning residential buildings and that official inspections of summer heat protection obviously take place very rarely.

In addition, with the current practice of cooling using reversible air-to-water heat pumps, which is certainly not unusual, it is to be feared that these are often not considered in the calculation. On the one hand, this would usually mean a change in the usual calculation method (according to DIN 4108/4701) for the specialist planner and, on the other hand, would also have a negative impact on the calculated primary energy demand, so that further measures might be required to achieve the desired level of thermal insulation. At the same time, it can be assumed that an unconsidered presence of a cooling function of the heat pump will not be checked.

4.3.2.2 Non-residential buildings

In the case of uses for which only 50% of the cooling energy demand can be credited (including offices and classrooms), the current normative specifications ensure that when cooling is provided, this must be either highly efficient or compensated for by energy-related measures from other areas. However, the fact that only the sun protection of the planned building has to be taken into account in the case of the reference building must be assessed critically. In addition, even when complying with the minimum requirements of DIN 4108-2: 2013-02, considerable potential for reducing energy demands through possible more efficient sun protection measures often remain unconsidered.

4.3.3 Suggestions for improvement

4.3.3.1 Residential buildings

The calculations made as part of this research project have shown that in many cases mechanical cooling can be dispensed with effective sun protection in cool summer climate regions. Even in the event that cooling cannot be avoided to ensure the desired minimum requirements for comfort, effective sun protection is an important basic requirement in order to limit the cooling energy demand.

It is therefore proposed in the reference building as sun protection *for all south-facing windows* the characteristics of a *to use manually operated white external blinds (45° position)*. For all *East- or West-facing windows*, it is proposed to use the parameters for *manually operated dark gray roller shutters (3/4 closed).*

To avoid the presumably frequent non-consideration of the cooling function of air-to-water heat pumps, it is proposed to request an explicit declaration of the intended function (only heating or heating and cooling) in the proof of energy demands when they are planned to be used. If necessary, this should also be checked during the final inspection of the building.

4.3.3.2 Non-residential buildings

Instead of the previous simple adoption of the sun protection parameters from the planned building, it is proposed to use the parameters of a *white external blind (45 ° position) that is automatically operated depending on the irradiation as a reference sun protection for all non-north-facing windows in non-residential buildings*.

4.4 Practical help for audit authorities

Suggestions for improving the implementation of the requirements for summer heat protection according to German standard DIN 4108-2: 2013-02.

4.4.1 Initial position

To ensure summer heat protection for new buildings, section 14 of the German GEG provides for an audit based on DIN 4108-2: 2013-02. Evidence of compliance with the requirements for heat protection in summer must therefore be provided at least for the room that leads to the highest requirements for heat protection in summer (critical room). Despite the existence of this requirement, many new buildings apparently overheat in summer, which often results in the retrofitting of an air conditioning system. This can be attributed both to insufficient requirements of the standard (Schlitzberger 2013) and to widespread disregard of legal requirements.

Last but not least, due to the relatively large audit effort required by the responsible authorities, it can be assumed that many building applications are currently being inadequately checked for compliance with the minimum requirements of DIN 4108-2: 2013-02 .

4.4.2 Goal

A simple and clear checklist could provide the testing authorities with a means of improving the scope and quality of the necessary audits and thus making an important contribution to meeting the legal requirements and ultimately improving the indoor climate in summer and reducing the cooling energy demand in new buildings.

4.4.3 Suggested checklist

To minimise the audit effort for the authorities, the audit items on the checklist should be arranged hierarchically so that the effort required to identify gross violations is minimal. The following table is intended as a first suggestion of a possible checklist, which should be further developed in cooperation with the audit authorities and based on practical experience. A software implementation would also be conceivable, which, depending on the result, could also generate automatic texts for the feedback letters on the building application.

Table 23: Draft checklist for examining summer heat protection in building applications

Test question	Annotation	Result-dependent recommendation for action
1. Do the building application documents contain information on proof of summer heat protection?		Yes => Continue to audit question 2 No => Request to submit the documents later
2. Has the putative critical room been selected for testing?	This requires a localization of the selected room in the floor plans. The key parameter for an initial assessment is the ratio of the (non-north-facing) window area to the floor area. Roof windows are particularly critical.	Yes => go to audit question 3 No => Request for improvement
3. What type of verification was chosen?		a) Exception according to DIN 4108-2, section 8.2.2. - Residential buildings with a window area share of [78]≤ 35% in the critical room => go to audit question 4 - Window area share to floor area of the critical rooms < 10% => Continue to audit question 5 b) Proceed with mathematical proof according to the solar - input parameter or through building simulations => Continue to audit question 6 c) None => Request to submit the documents later

[78]area-related

Test question	Annotation	Result-dependent recommendation for action
4. Is adequate external sun protection provided for all windows that are not predominantly north-facing?	Sufficient external sun protection includes roller shutters, venetian blinds, venetian blinds.[79]	Yes => Check successful No => Request for improvement
5. Is the proportion of window area in the critical room lower than the limit values for the exception?	For most building types, it is unlikely that the critical space will have such a small proportion of window areas.	Yes => Check successful No => Request for improvement
6. Were the calculations done correctly?	The depth of the audit is at the discretion of the auditor. A list (to be optimised) should list the most common sources of error in the calculations, e.g.: - Reduction factors for the sun protection devices: With conventional sun protection, Fc must be ≥ 0.25. - Reduction factors Fc for skylights: For reasons of cost, only internal sun protection is often provided - if at all (=>reduction factor Fc ≥ 0.65). - Type of construction: In the case of houses that are built in wood (often prefabricated houses), a light construction type is generally to be used. A massive construction is rare. - Nighttime ventilation: The practical feasibility of a possibly scheduled high nighttime ventilation (n > 5 1/h) must be critically questioned. Since this requires large openings, there are usually further problems such as burglary protection, protection from outside noise and weather, which require a separate solution.	Yes => Check successful No => Request for improvement

4.5 BEG: Proposal to consider natural refrigerants (bonus rule)

4.5.1 Initial position

The German Federal Funding Program for Efficient Buildings (BEG)[80] is a key cornerstone for achieving climate protection goals in the building sector. The BEG is divided into three sections

- Residential building (BEG WG)
- Non-residential building (BEG NWG)

[79]and awnings parallel to glazing with a low transparency of < 15%
[80] Federal Office of Economics and Export Control (BAfA)

- Individual measures (BEG EM)

The funding is granted either as a low-interest loan or as an investment cost subsidy. The amount of funding depends on the quality of the measures.

As part of the BEG, various bonuses are granted in addition to the basic subsidy (e.g., for the use of renewable energies, proven sustainability or a biomass innovation bonus for low-emission biomass plants).

Efficient refrigeration technology for room cooling in existing non-residential buildings is funded as part of the BEG's individual funding measures[81]. In accordance with the minimum technical requirements[82], compression refrigeration systems must have capacity control and achieve a type-dependent minimum annual efficiency [83]. The funding rate is 20% of the eligible expenses. Both the material costs and the costs for professional installation and adjustment by the respective specialist company are eligible for funding.

In practice, compression refrigeration systems with climate-damaging partially fluorinated hydrocarbons (HFCs) are predominantly used for room cooling.

The use of hydrofluorocarbons is limited at EU level by regulation (EU) No. 517/2014. The CO_2-equivalent global warming potential of the partially fluorinated hydrocarbons placed on the market is to be reduced to a fifth of the initial amount (183.1 million t CO_2 equivalent in 2015) by 2030.

The proportion of the overall climate impact that caused by direct emissions of refrigerants through leaks during operation, maintenance/repair and disposal of refrigeration machines dependent on many factors. It is in the range between 3-17% per year (Offermann et al. 2016) . With a decreasing CO_2 emission factor for electricity, this increases accordingly.

There are currently no plans to exclude heat pumps with fluorinated refrigerants from the subsidy, but this should be reviewed by January 1, 2025. At a minimum, however, the use of natural refrigerants or synthetic refrigerants with a low global warming potential (GWP) is recommended.

4.5.2 Suggestion for improvement

As an immediate climate-effective measure, analogous to the innovation bonus for low-emission biomass systems, it is proposed to grant an innovation bonus of 5% for refrigeration systems and heat pumps until the time of a possible exclusion of the subsidy for systems with fluorinated refrigerants, if these do not use fluorinated refrigerants (but natural refrigerants such as propane).

Even with the BEG funding for new buildings would be e.g., in the form of an addition to the sustainability class, an appropriate bonus scheme for the use of heat pumps or air conditioning systems without fluorinated refrigerants is also conceivable.

Finally, these incentives could also strengthen the currently apparently lacking awareness of the use of these climate-friendly technologies and thus take another important step towards climate neutrality.

[81] Federal Ministry for Economic Affairs and Energy (BMWi) December 17, 2020
[82] Federal Ministry for Economic Affairs and Energy (BMWi) 2020
[83]according to the manufacturer's documentation for the product-specific characteristics

4.6 Definition of renewable cooling within the framework of the EU Renewable Energy Directive

4.6.1 Initial position

The EU directive on the promotion of the use of energy from renewable sources (Renewable Energy Directive (RED)[84] and its new version RED II[85]) set the framework for the expansion of renewable energies in the EU. As part of the National Energy and Climate Plans (NECPs), the EU member states report on progress towards the targets for the expansion of renewable energies under the RED, with the reported figures broken down into the areas of electricity (RES-E), heating and cooling (RES-H&C) and transport (RES-T).

While the RED provides the methodology for calculating the renewable energy shares for electricity, heating and transport, it does not provide guidance on how to calculate the renewable cooling share. Due to the lack of methodological guidelines, the member states are currently unable to identify renewable cooling. Cooling therefore currently plays no role in achieving the goal.

According to the 2018 recast of the EU Renewable Energy Directive (RED II), the Commission must present a Delegated Act establishing a methodology for calculating the amount of renewable energy used for cooling and district cooling by December 2021. A similar approach was taken for heat pumps. Guidance for member states on how to calculate the renewable energy from heat pumps according to Article 5 of the RES Directive was published in 2013.

Determining the calculation methodology can potentially have an important impact on which technologies are classified as 'renewable' and thus contribute to the achievement of the RED targets. The methodology is currently being developed on behalf of the EC[86] and was evaluated in a stakeholder consultation in autumn 2020. As of April 2021, there is no final proposal for the definition.

4.6.2 Options for defining renewable cold

The definition of renewable cooling within the framework of RED II can basically contain two components: Requirements for the electricity used for cooling[87]and direct or indirect requirements for the heat sink used. Since power consumption is recorded separately in the RED and RED II, the definition of renewable cooling focuses primarily on the proportion of ambient energy.

A similar approach is taken in the RED/RED II for heat pumps, where the ambient energy used is classified as renewable if the efficiency of the heat pump exceeds a specified threshold. The efficiency of the heat pump is defined as the seasonal performance factor (SFP[88]). While heat pumps make use of the ambient energy for heating, conventional refrigeration technology only uses the ambient energy to 'dispose of' the waste heat from the refrigeration process.

In principle, the minimum requirements to be specified for the definition of renewable cold serve to limit the amount of heat given off by the heat pump in cooling mode to the environment

[84]Directive 2009/28/EC (Official Journal of the European Union 2009)
[85]Directive (EU) 2018/2001 (Official Journal of the European Union 2018)
[86]See Tender N° ENER/C1/2018-493: Renewable Cooling under the Revised Renewable Energy Directive (European Commission (DG Energy) 2018)
[87]In the case of ad/absorption refrigeration, requirements could also be placed on the heat used for refrigeration generation, due to the far greater importance of electricity-based systems, the consideration is concentrated on this area.
[88]See Annex VII of the Directive

in a reasonable way, which can be counted as renewable cold. The range of possible definitions is limited at the lower end by the situation where no ambient energy is recognized as renewable cooling (i.e., no credit for conventional refrigeration in the RED II) and at the upper end by the situation where all ambient energy (i.e. independent of the cooling application, the efficiency of the system or the type of cold source used).

In Braungardt et al. (2019) the following options for considering renewable cooling in the EU Renewable Energy Directive are considered:

4.6.2.1 Option 1: Minimum energy efficiency requirements

Option 1 follows the same approach as for heat pumps in heating mode and defines the minimum requirements via the efficiency of the cooling production. In addition to being consistent with the methodology for heat pumps, the advantage of this approach is that it only includes techniques that meet minimum standards for energy efficiency and thus contribute to a reduction in CO_2 emissions. However, defining the minimum standards poses a greater challenge compared to the approach for heat pumps: for heating, the minimum SPF requirements are chosen in such a way that the fossil fuel input required to generate electricity is lower than that required to provide heat based on the combustion of fossil fuels. This means that the useful heat provided by heat pumps directly replaces fossil fuels. In contrast, combustion processes are not replaced in refrigeration, so that the determination of the minimum standards has no clear scientific and technical basis. Despite the lack of scientific basis with regard to the definition of renewable cooling, ambitious minimum standards are generally to be welcomed from an environmental point of view, since conventional air conditioning systems are prevented from contributing to the achievement of the goals. There is also the challenge that, depending on the level of ambition of the minimum standards in some member states, the inclusion of refrigeration can lead to a significant increase in the share of renewable energy and thus the ambition of the targets is reduced. Another challenge can be the availability of data, since data on cooling is not included in the annual Eurostat questionnaires. Insufficient data is therefore to be expected, particularly for the inventory of devices and systems for refrigeration. An advantage of the minimum energy efficiency standards approach is that the approach has synergies with the minimum standards based on the Ecodesign Directive.

4.6.2.2 Option 2: Minimum heat sink temperature requirements

As a second option, minimum requirements can be set for the temperature of the heat sink (e.g. 10 K below the ambient air temperature). The benefit of this approach is that it favours natural heat sink techniques. As a rule, these do not require any power-driven cooling circuits and therefore typically have lower energy consumption. A challenge to the approach is that member states would need to provide estimates of the installed capacity of the relevant refrigeration systems. This data is not usually available in energy statistics.

4.6.2.3 Option 3: Heat sink type requirement

As a third option, the minimum requirements can be defined via the type of heat sink. For example, the outside air can be excluded as a heat sink. Thus, with this approach, all conventional air conditioning and reversible heat pumps would not contribute to the share of renewable cooling. The ground (geothermal energy), water or snow, for example, could be permitted as possible heat sources. Similar to option 2, an advantage is that natural heat sink techniques are typically preferred and that the distinction between renewable and non-renewable cooling reflects the direction of heat flows according to the second law of thermodynamics. Here, too, one challenge is the availability of reliable statistical data.

4.6.3 Conclusions

The definition and methodology for calculating renewable cold should be designed in such a way that conventional systems and devices for generating cold cannot be counted as renewable cold.

While the use of refrigerants does not currently play an explicit role in the evaluation of the options and the development of the methodology, there are synergies with the ambitious design of the efficiency requirements: If the requirements are set in such a way that conventional air conditioning systems are excluded from the credit and the creditability is based on systems for free cooling, this has a beneficial effect on the spread of cooling systems without the use of refrigerants.

4.7 Elaborations on the demand for proof of urban climate neutrality in environmental impact assessments for new districts

4.7.1 Initial position

When planning and building new city districts or similarly dimensioned redesign projects, a large number of rules, ordinances and limit values currently regulate the construction project. Most of these regulations concern the structures themselves, but the interaction between structures (distances, daylight access, hours of sunshine) are also considered in guidelines and regulations. For the pure outdoor area, which is often planned independently of the buildings due to the property developer, there are essentially specifications for noise protection (e.g., DIN 18005 Part 1) and for air pollution control (e.g. TA Luft, EU Directive 1999/ 30/EG). Even for the relatively easy to determine variable such as ventilation and wind comfort, there are no binding legal requirements, but only different dimensions for comfort consideration, the selection and use of which is voluntary. The German Society for Sustainable Building (DGNB), for example, defines various evaluation criteria for sustainability in its "Criteria Catalog for Quarters", including for the aspect of urban climate (ENV 1.5), but remains very general here.

4.7.2 Suggestion for improvement

Both the microclimate within the planning or development area and the effects of structural changes on the immediate surroundings should be considered in the form of comprehensible and clearly defined rules and limit values.

A possible extension of the environmental impact assessment to the area of urban climatology would initially aim at the interactions of planning with the immediate environment. The aim here must be that, as a minimum requirement, the climatological conditions in the other areas of the city should not deteriorate as a result of the new district planning or structural change. These include in particular

- Ensuring the ventilation of the adjacent areas, in particular the continuation of fresh air and cold air channels and
- as a minimum requirement, the avoidance of the airflow being heated by the buildings. Ideally, a cooling effect should be achieved in which the air flowing out of the quarter is cooler on average than the air flowing in.

Locally unfavourable microclimatological conditions cannot always be avoided within the district. Planning should therefore be examined regarding the intended use with regard to the following criteria:

- Is there sufficient wind comfort in all areas relevant for pedestrians for all relevant wind directions at the locally usual wind speeds and wind peaks?
- Does the intended use of different areas (passage, stay, etc.) correspond to the microclimate offered? Not only the general distribution has to be considered, but also the temporal dynamics of use and the microclimate.
- Due to climate change, an increase in the frequency and intensity of summer heat waves can be expected in the future. The planning of the quarters should be reviewed to ensure that the local microclimate still exhibits sufficient cooling dynamics even assuming such hot periods. When planning greening measures in particular, it must be ensured that they are also sufficiently watered, as otherwise the cooling effects can be reduced or even reversed.

As the examples presented in this report make clear, estimating the effects of structural changes on the microclimate is a highly complex issue. The use of numerical simulation methods is therefore essential for taking the above aspects into account and for proving that the planning has been adapted accordingly. A purely verbal or graphic description of the suspected interactions and effects is not sufficient.

4.8 Proposals for action to specify the effects of the microclimate on urban planning

4.8.1 Initial position

As already shown in Section 4.7, the analysis and evaluation of the effects of planning measures on the microclimate and thus on the urban climate of the surrounding area is a complex issue that can only be examined using numerical methods with the necessary accuracy and neutrality.

The use of these methods in the planning process is currently neither standardized nor established. The following factors can be identified as obstacles:

a) High effort/costs in creating the model due to heterogeneous, incompatible and outdated or non-digital databases

b) High effort/costs due to complex simulation processes

c) Lack of standardization of analysis results and their evaluation

d) Missing mandatory limits

4.8.2 Suggestions for improvement

In order to improve the initial situation and to establish urban climatological concerns in the planning, the points mentioned above will be briefly addressed below.

Regarding a) Time-consuming model creation

The creation of consistent and up-to-date digital models for further analysis in numerical methods is still a major cost factor and thus an obstacle to the use of these same methods in the planning process. The current trend towards creating 'digital twins' of cities, countries or the earth is an important step towards improving the starting position. In contrast to 'normal' digital geodata, one of the core approaches of the digital twins is that all data levels are compatible with each other, and the information stored in them is made available in a standardized way via interfaces and can therefore be called up automatically by models, for example.

b) Costs of the simulation process

The costs of the simulation methods consist on the one hand of the expert costs for operating the respective simulation models and on the other hand of the costs of the calculation process itself. As already mentioned in (a), the concept of digital twins not only requires consistent data provision via interfaces, but also standardized embedding the desired simulation models. To become part of such a digital twin and thus also part of future planning processes, the expert models must also be subject to the standardization concept. As a result, special expert knowledge is no longer required, so that the entry threshold for the application of these models is lowered.

The costs for the simulation process itself will increasingly recede into the background in the future due to ever more powerful computers and cloud applications.

On c) standardization of analysis results and their evaluation

The analysis of simulation results is another costly factor in the use of microclimate models in planning. The viewing and evaluation of the simulation data by the appropriate specialist staff is essential, but the form of presentation and the scope of the analysis often depends very much on personal preferences and local customs. A standardization of the basic elements of corresponding expert reports regarding the content, the type of presentation and the concise summary of the core results would not only significantly reduce the workload and thus the costs. It would also avoid that through a skillful selection of data and findings, the results of the studies can be moved in a desired direction.

On d) Binding limit values

The determination of limit values in the form of specific threshold values is not without controversy, as it often leads to all measures being geared towards the goal of falling below the limit value. In addition, it can make sense to locally exceed limit values in non-sensitive areas if this means that other, more sensitive uses are significantly spared.

In terms of standardizing microclimate studies, it would therefore make more sense to describe the complex spatial-temporal structure of the microclimate using a number of performance indicators and, for example, to use a point scale to demonstrate that these indicators have been achieved. In contrast to the binary limit value consideration, balancing considerations across different areas or aspects of planning would also be possible.

The matrix of points achieved by a plan would, if applied in a standardized way, present the effects on the urban climate in a clear and comparable way.

4.9 Application of a green area factor

4.9.1 Initial position

Urban green spaces fulfill important climate-related functions and contribute to improving the urban climate. Urban green makes a significant contribution to reducing the effects of climate change in urban areas and represents an important municipal adaptation measure to climate change. There are numerous instruments to support the development and maintenance of urban green spaces in urban development and urban planning. The approach of the green area or biotope area factor is presented here, which some cities have already introduced to ensure the preservation of urban green areas, such as Berlin and Malmö. The following sections describe the concepts implemented in Berlin, Malmö and Vienna and discuss a possible strengthening of the instrument through its inclusion in the Ordinance on the Structural Use of Land (BauNVO).

4.9.2 Implementation examples

4.9.2.1 Berlin

In order to reduce environmental pollution in the city centre and to ensure the preservation of green spaces, the biotope area factor (BAF) was introduced in Berlin in 1990 to counteract the high degree of soil sealing in urban areas (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin 2021; Jakob 2010).

The BFF is an ecological planning parameter that can be specified in Berlin as a statutory ordinance in a landscape plan. For developed properties, this specifies the ratio of areas of a property that have a positive effect on the ecosystem to the total area of the property. This sets minimum ecological standards that apply to new construction and structural changes in the urban forms of residential, commercial and infrastructure use (Kopetzki and HafenCity Universität Hamburg (HCU) 2017) .

To calculate the factor, individual sub-areas of the entire property are first evaluated and assigned a fixed weighting factor (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin 2021). The areas are assessed with regard to the potential takeover of vegetation-based ecosystem services. Based on the ratings, a weighting factor between 0 and 1 is set for each area type. A factor of 0 means that the area has no positive effect on the ecosystem, whereas a factor of 1 is assigned to those areas that have a high value.

The individual area types of a property are added up in order to achieve the targeted BAF value on the property area. The BAF is calculated as follows:

BAF = area with an impact on the natural balance/land area

Depending on the type of development and type of use, different BAF target values apply, as the following table shows. In the case of structural changes to apartments, public facilities and daycare centres, the BAF target value depends on the degree of development and is graded into different target values.

Table 24: Target values for the BAF in Berlin

BAF target values according to development type and degree of development (ÜBG)	Structural changes		New building
	ÜBG	BAF	
Apartments	up to 0.37 0.38 to 0.49 from 0.5	0.6 0.45 0.3	0.6
Commercial Uses	up to 1	0.3	0.3
Uses typical of the core area	up to 1	0.3	0.3
Public facilities	up to 0.37 0.38 to 0.49 from 0.5	0.6 0.45 0.3	0.6
Schools	up to 1	0.3	0.4
Day care centres	up to 0.29 0.3 to 0.49 from 0.5	0.6 0.45 0.3	0.6

BAF target values according to development type and degree of development (ÜBG)	Structural changes		New building
Technical infrastructure	up to 1	0.3	0.3

Source: Own representation based on Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin 2021, modified

In the meantime, binding BAF targets have been set as statutory ordinances in 15 landscape plans covering almost 5% of Berlin's area (as of 2020).

The charter for Berlin's urban green areas and the action plan for Berlin's urban green areas 2030 envisage a further development and review of the legal anchoring of the BAF (Abgeordnetenhaus Berlin 2020).

4.9.2.2 Malmö

In the Southern Swedish city of Malmö, a green space factor (Grönyte Factor, GF) is also used as a planning tool to ensure the preservation of green spaces in urban areas. Malmö is thus adapting a concept similar to that of the BAF in Berlin.

The instrument was introduced in 2001 as part of the housing exhibition and was used for the first time in a large new building project in a district. In the meantime, the GF has been applied to all building areas in the city and is used not only in new buildings, but also in extensive renovations. The GF is recorded in the development plans in a legally binding manner. In Malmö, in contrast to Berlin, responsibility lies at the municipal level and is subject to the city planning office (Thérèse Hliwa 2015) .

As in Berlin, there are different target values for the GF for different types of use. The calculation differs from that of the BFF in that vegetation features such as B. the size of trees, are included (Miljöbyggprogram SYD) . In addition, surface coverings of roofs and facades are relevant, with which a higher GF can be assigned (ibid.). In addition, 'green points' were introduced in Malmö, which include further environmental measures (ibid.).

4.9.2.3 Vienna

The City of Vienna is intensively involved with urban green spaces, so that in the city's Urban Development Plan 2025 (STEP 2025), the technical concept of green and open space is a central component and trend-setting for Viennese green and open space planning (Stadt Wien 2014) . The technical concept adopted in 2014 includes, among other things, the creation of new recreation areas and a "local green plan".

With the "Local Green Plan" included in the technical concept, a new and standardized planning tool based on old planning tools was created in 2015 (Stadt Wien 2021) . This method can be created on a sub-space and event-related basis, especially in urban development areas where structural changes are occurring.

Various types of open space are clarified, located and evaluated with regard to their effectiveness in supplying the residents. A distinction is made between 12 types of open space, which form the basis of the concept. This classification is based on city-wide specifications (Vienna open space network) and thus documents the green and open space supply for the respective area. The breakdown of the types is based on their form (linear and flat open spaces) as well as their design character (urban or landscape characteristics), as the following table shows.

Table 25: Overview of open space types in Vienna's green and open space planning

	Surrounding	Types
Linear free spaces	Urban	Type 01: Busy street spaces and zones for pedestrians
		Type 02: Green street spaces
		Type 03: Street spaces with adjoining green spaces
	Rural	Type 04: Green axes
		Type 05: Green belts
		Type 06: Green corridors
Flat free spaces	Urban	Type 07: Open spaces not accessible to the public
		Type 08: Partially public green
		Type 09: Parks
	Rural c	Type 10: Useful areas
		Type 11: Building block green space
		Type 12: Protected Areas

Source: Own representation based on the Stadt Wien 2021

For each of the individual types, goals are set until 2025 and concrete fields of action are defined.

As part of the "green.resilient.city" research project, a green space factor was developed for the city of Vienna as a basis for future legal anchoring in planning instruments (Reinwald et al. 2020) . The project also provides a set of simulation tools that can be used to simulate the microclimatic impact of existing green infrastructure and its changes at the parcel and quarter level (ibid.).

4.9.3 Judgement

As becomes clear from the examples given, there are various ways in which cities and municipalities can create and maintain sufficient green spaces/areas in the long term. The importance of green space compared to other goals in urban development can be emphasized through defined characteristic values of a green space factor. Due to their climate-relevant functions, urban green spaces play an important role in municipal climate adaptation in the long term, so that other cities are considering introducing a green space factor. For example, as part of the City of Nuremberg's "Open Space Master Plan", there is a proposal to apply a mandatory green space factor in urban development. The structural use should not be restricted, but ecological standards for the use of building areas should be set. The green area factor can make an important contribution to improving the microclimate, particularly in the case of a high building density, i.e. in the inner city area of Nuremberg, and the high climatic stresses that prevail there.

To achieve a comprehensive application of green space factors in municipalities, the green space factor should be specified in the land use planning. To this end, an amendment to the Ordinance on the Structural Use of Land (BauNVO) should be sought in order to include the BAF in addition to the dimensions of structural use such as the number of floor areas and number of floors as a measure of free space.

4.10 Good practice examples for the implementation of climate adaptation measures at municipal level

Since the amendment of the building code in 2011, climate adaptation has been defined as a planning principle in land use planning and must be taken into account. For example, the requirements for healthy living and working conditions, which also include the adaptation to overheating of buildings and urban areas on hot summer days, are recorded in the building code. However, climate adaptation must be balanced with other concerns. Since some of the requirements are vague, climate adaptation often only plays a subordinate role in comparison to other topics.

Municipalities play a central role in climate adaptation and have various options for taking climate adaptation measures. The following three examples from Mannheim, Bochum and Hanover (Germany) are examples of the successful implementation of municipal climate adaptation measures - especially in the area of heat islands - and the integration of adaptation measures during the planning process is discussed in particular.

4.10.1 Conversion area Spinelli Barracks in Mannheim

The Spinelli Barracks conversion area in Mannheim can be cited as an example of the successful implementation of climate adaptation measures in municipalities. Mannheim is located in the upper Rhine valley, one of the warmest regions in Germany, and with an average temperature of 11.9 °C in 2019 (Wetter Kontor 2021), it is particularly affected by heat stress in summer.

The area of the pilot project includes around 80 hectares of a former barracks and is - in terms of its climate-ecological balancing and relief effect - in Mannheim's most important green area. The area is not to be developed or only to a small extent, so that the central part is integrated into the existing green area as an open space. On the one hand, this is intended to expand the area where cold air originates and, on the other hand, to support the penetration of fresh air from the surrounding areas. The primary aim of the adaptation is to promote nocturnal cooling in order to reduce the heat stress on residents.

At the beginning of the planning process, a feasibility study and a referendum were carried out before additional citizen planning groups and citizen forums were founded to promote acceptance of the project through participation. A two-stage competition followed. In stage 1, climate-ecological specifications such as shadowing measures and facade greening were discussed, in stage 2 the overriding guiding ideas for the area were specified. The competitions were checked for compliance with the climate-ecological specifications. For the creation of the framework plan, thematic workshops were held for the relevant stakeholders in the planning areas of urban development and green corridors, in which scientific support groups and external experts provided specialist input.

The KomKlim research project (Vogt et al. 2018) also began with the phase of urban planning and concrete concepts for climate adaptation measures were developed. The participation of the citizens was also essential in this phase, who were involved in several events and the topic of climate adaptation thus became publicly accessible.

4.10.2 Ostpark Bochum

New, sustainable settlement areas are to be created in Ostpark Bochum. The area comprises around 13 hectares of residential land, on which around 1,300 residential units of different building types are to be built by 2025, as well as 12 hectares of green space. Due to its location in the Ruhr metropolitan area, which is characterized by high population and building densities, some areas of Bochum are exposed to high levels of thermal stress. The planning area itself lies in a designated fresh air corridor.

Climate adaptation was integrated into the process early on in the framework planning and was reflected in all phases of the process. For the creation of planning bases, there was early coordination with the specialist planners; the draft plans were discussed continuously. Reports were carried out which examined features in the planning area and thus formed the basis for climate-adapted planning ideas. In addition to a drainage concept, the main focus of the framework planning was to reduce heat stress. The drafts of the measures taken were each checked using climatological modelling, so that there are no restrictions on the fresh air corridor and the supply of cold and fresh air in the area is guaranteed. The framework plan was further specified by the specialist planners, taking climate adaptation measures into account, before the development plan was drawn up. In the development plan, measures such as the greening of roofs and the surface drainage made binding. Other measures such as climate-adapted planting of private open spaces were only identified as recommendations in the design manual. For the design planning, specialist workshops on the subject of climate adaptation were held before design specifications were defined, taking into account the corresponding adaptation measures.

For more information see Jolk et al. (2017b).

4.10.3 Quarter Herzkamp Hanover

As part of the pilot project "KlimaWohl" (Landeskapital Hannover et al. 2019) in Hanover, it should be tested how climate adaptation can be systematically taken into account in the development of a new residential area right from the start. The project area is located in a climate-sensitive outskirt of Hanover, through which a cold air corridor runs. By 2021, around 300 residential units are to be built on an area of 9,200 square meters, as well as further infrastructure such as a daycare centre, a football pitch and a quarter square.

A special feature of the project was the early cooperation between public and private actors, who included the topic of climate adaptation in their planning from the start. Nine work packages were formed for the project, which were processed in parallel to the planning and implementation process. The regular exchange between the network partners of these work packages, which was promoted by bi-weekly project meetings, was essential. The various work packages dealt with different topics and time phases of the project. In order to bring the results together across phases and organizations at the end, several closed meetings took place in this project phase.

Cooperation with other relevant stakeholder groups took place within the framework of various workshops and a citizens' workshop. Likewise, not only did an internal exchange take place, but also networking meetings with other research projects.

In the work packages, 20 measures for climate adaptation such as street trees, facade greening or an arrangement of the buildings adapted to the cold air corridor were developed, which are implemented in the selected project area.

On the basis of the project, a model (“Hanover model”) was developed that can be transferred to other municipal climate adaptation projects.

4.10.4 Conclusion

The selected sample projects show that early integration of climate adaptation into the planning process is essential for successful implementation in quarter projects. Climate adaptation should be addressed and taken into account in all phases of the process. Equally important is the interdisciplinary exchange between the planning teams and external experts in order to achieve the climate adaptation goals. The participation of the citizens should not be neglected either, so that they were included in the planning phases.

The projects listed show how climate adaptation has been successfully implemented by municipalities and can serve as a model for further municipal implementation measures.

A Appendix

A.1 Measures to avoid urban heat islands

1. Brightening of coverings on buildings and in open spaces

Short description

- The strong heat absorption on hot days can be reduced (albedo) by using bright and reflective surface materials with low heat storage capacity.
- The lighter the buildings and surfaces in a city, the lower the heating, because short-wave radiation is reflected and the material cannot heat up.
- The measure is particularly effective in densely built-up areas, as there are large roof areas. The urban heat island effect (UHIE) caused by the heating of surfaces is particularly pronounced in quarters with tall buildings.
- Maximum reduction of asphalt and metal surfaces in favour of light-coloured concrete surfaces, slab or pavement coverings (concrete, natural stone) or gravel-bound ceilings.
- Combination of lighter colours, rough surfaces and porous materials when choosing coverings to reduce surface temperature and the amount of stored thermal energy.
- Surfaces can also be brightened later by applying a light coat of paint.

Limitations

- Surface materials such as paving are more expensive to produce than asphalt.
- Bright, reflective surfaces can lead to heating of adjacent - especially dark - surfaces due to increased reflection and increase the radiation stress for people who are in these areas.
- Light-coloured surfaces such as gravel or paving do not always meet the accessibility criteria.

Applicability by climate zones

- Is already used in other climates or even has a tradition (e.g. in the Arabian region, Mediterranean region, see practical examples below)

Legal framework

- Building Code (BauGB), land use plans.

Practical examples

- Redesign of the Willi-Graf-Ufer on the Saar in Saarbrücken
  - Use of bright surface materials in the open space design.
  - Cooling of up to 10 °C on hot summer days.
- Santorini, Greece
  - White houses as traditional strategy against urban heating in the Mediterranean.
- Post-painting of streets with white paint in Los Angeles.

Sources: Brandenburg et al. 2015; Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) 2016; Arboristik.de 2018; Dirk Hessel et al. 2017; Dambeck 2010

2. Securing and expanding the tree population

Brief description:

- Avoidance of UHIE and stabilization or positive influence on the urban climate
  - Shadowing from leaves and tree crowns (15 meters crown diameter of a deciduous tree shades an area of about 160 m²).
  - Evaporation through release of water vapor through leaf pores (transpiration). Evaporation of up to 400 liters/day depending on tree species, temperature and much more water supply.
- Cooling of the ambient air by up to 2°C, cooling of asphalt under the crown by up to 20°C
- Environment affects cooling potential of trees
  - In high heat, trees close the pores of their leaves to protect themselves from drying out and there is no cooling effect for the environment.
  - Open spaces with air circulation and low humidity promote perspiration, so the cooling effect is increased when there are more open spaces and squares.
  - Do not plant the trees directly in recesses in the pavement, but in green strips, as they are more resistant there and may perspire more.
  - Heat and drought stress as well as dense soil in the city shorten the lifespan of urban trees.
- Increasing water retention, delaying water runoff.
- Most common tree species in German cities: linden, maple, oak, plane tree. Due to the longevity of trees, species that are adapted to future (more extreme) climatic conditions are particularly recommended.
  - When planting non-native tree species (neophytes), in addition to adapting to climates, it is also important to consider whether native insect species will accept the trees (biodiversity).
  - Tulip trees, ginkgo, tree hazel and ornamental cherries are considered to be suitable[89].

Limitations

- Any construction activity and inner-city densification measures that result in a loss of urban trees.
- Competition for space with other functions and facilities in public space
  - Minimum distance from trees to facades, buildings and other trees,
  - Traffic safety obligation (dead branches).
- Other restrictions can be pollution or allergies caused by pollen.
- Cost of care. The maintenance intervals for the trees increase as the plants get older (costs around €60/year[90]).

Applicability by climate zones

- In climates with high humidity, cooling from transpiration may be less because the air is already saturated with water vapor.
- Watering urban trees in very dry climates may be a problem.
- Filter and shadowing effects as well as other synergies remain.

Legal Aspects

- Forest law, nature conservation law, building code, land use plans.

Practical examples

- Berlin: 433,000 urban trees
  - 80 trees/ km city street (one tree every 13 m city street).

[89] Current information on suitable street trees can be found in the information portal of the German Conference of Garden Authorities (GALK): https://galk.de/arbeitskreise/stadtbaeume/themenuebersicht/strassenbaumliste

[90] Broken ash 2012

2. Securing and expanding the tree population

- City tree register Duisburg
  - Committed replanting of 500 trees per year,
  - Cadastre can be used to understand how many trees are in which street and where there are treeless streets, which are then successively planted.
- MillionTreesNYC
  - Planted 1 million new urban trees in the city of New York in 7 years.

More positive effects

- Fine dust filtering
- Canopy of leaves dampens city noise
- Attractive landscape element
- Positive effect on biodiversity

Sources: Brandenburg et al. 2015; Bavarian State Institute for Viticulture and Horticulture (LWG); Wolter and Nolte 2018; Senate Department for the Environment, Transport and Climate Protection Berlin 2020; Rahman 2016

3. Securing existing and creating additional forest areas

Brief description:

- Avoidance of the UHIE through evaporation and release of water vapor through leaf pores (evapotranspiration)
- Cold air production in a forest 0.6 m³/ (m² h) to well over 20 m³/ (m² h) depending on tree species and water availability
- Temperature difference between cool forest and heated city cause air circulation
  - Cool forest air flows in downtown,
  - Forest air is up to 8 °C cooler in summer.
- Actual cooling effect depends on
  - Macrospatial and microspatial meteorological conditions,
  - Topography,
  - Air channels.
- Minimum size for cooling effect: 1 to 2.5 ha.
- Extreme overheating events rarely occur within forest areas due to the large-scale shadowing effect.
- General improvement of city air through CO_2 binding and oxygen production.

Limitations

- Potential conflicts with property owners who want to sell at building land prices.
- Competition for space with urban planning goals of a growing city.

Applicability by climate zones

- In high humidity climates, cooling from evapotranspiration may be less because the air is already saturated with water vapor.
- Filter and shadowing effects as well as other synergies remain.

Legal aspects

- Forestry Act, Nature Conservation Act, Building Code, Land Use Plans

Practical examples

- The Aachen forest (2,357 ha) produces around 30% of the cold air volume in the city of Aachen (16,085 ha).

3. Securing existing and creating additional forest areas

Other positive effects
- Forests are natural carbon sinks
  o 1 ha of forest fixes around 10 t of CO_2 per year.
- 'Filter' of urban air (especially aerosols, dust and water-soluble gases)
  o 1 hectare of forest filters up to 50 tons of soot and dust per year.
- Represent an attractive landscape element.
- Recreation space for city dwellers.
- Habitat of many plants and animals.

Sources: Brandenburg et al. 2015; Wolter and Nolte 2018; Jay et al. 2015

4. Unsealing of surfaces in open space/ Avoidance of sealing

Short description
- The unsealing of surfaces (see Pannicke-Prochnow et al. 2021) helps to avoid UHIE:
  o Evaporate unsealed surfaces. If enough rainwater can seep away, the groundwater level rises. Well-drained soil releases moisture into the air and cools it.
  o On unsealed areas, the runoff of rainwater into the sewage system is lower. If the rainwater cannot seep away, it evaporates (phase transition from liquid to gaseous), whereby energy in the form of heat is extracted from the environment and the microclimate cools down.
- Unsealing to increase evaporation and seepage of precipitation can be used on a variety of surfaces, such as parking lots, courtyards, driveways, etc. Unsealing can e.g. by using the following materials:
  o Porous asphalt or porous paving,
  o Plaster with wide joints,
  o Gravel covers,
  o Gravel lawn,
  o Grass pavers.

Limitations - Many surface materials, such as paving, are more expensive to produce than asphalt. - Water-permeable coverings do not always meet the accessibility criteria. - Water-permeable coverings often do not have the high mechanical suitability for traffic areas as asphalt. They are therefore particularly interesting as a replacement for parking spaces.
Applicability by climate zones - Potentially applicable in other climates as well.
Legal framework - Building Code (BauGB), Regional Planning Act, Soil Protection Act.

Practical examples
- Green life, Baindt
  o Conversion of former federal highway into green space.
- Brenzpark, Heidenheim
  o Large-scale creation of a park on a former industrial wasteland.
- Redevelopment area Albert-Schweitzer-Strasse/Fröbelstrasse, Lahr
  o Conversion of former barracks into passive house district,
  o Unsealing of 1,400 m^2,
  o Seeding of 2,800 square meters of lawn for parking lots.

4. Unsealing of surfaces in open space/ Avoidance of sealing

- Schutter renaturation, Lahr
  o Renaturation of the Schutterufer,
  o Set back of bank development by 13 m.

Other positive effects
- Unsealed soil is a natural asset, a habitat for animals and plants and a pollutant filter. - Precipitation water, which can seep away, feeds the groundwater, while rainwater on sealed surfaces has to be drained into the sewage system, where it mixes with wastewater in mixed sewage systems. This drives up the cost of wastewater disposal. Heavy rains can also overload sewers, meaning that sewage enters streams and rivers untreated. - Too fast and too much runoff of rainwater from settlement areas increases the risk of flooding. - Unsealing may increase the visual attractiveness of public open spaces.

Sources: UMG Environmental Office Grabher 2008; Federal Association of Garden, Landscape and Sports Field Construction e. V. 2006; Baukultur Baden-Württemberg 2016

5. Securing and expanding green and open spaces
Short description

- Green infrastructures such as roadside greenery, green inner courtyards and brownfield sites are important parts of the city and contribute to reducing the urban heat island effect. The positive effect of the plants is based, among other things, on the shadowing of horizontal earth surfaces and vertical building surfaces and evapotranspiration. Irrigated plants have a higher evaporation rate.
- In the summer months, green areas are on average 3 to 4 °C cooler than brick or concrete areas, which heat up considerably during the day and give off the heat to the environment at night. Green areas in the vicinity contribute in particular to nighttime cooling.
- The following are particularly suitable for avoiding UHIE:
  o Avenues,
  o Single trees and rows of shrubs,
  o Lawns and meadows,
  o Creation of small-scale green areas such as courtyard greening,
  o Allowing spontaneous green.
- Benefits of avenues: see measures sheet city trees (p. 201).
- Rows of shrubs are particularly suitable as roadside greenery where there is no space for trees. Shrubs have the same positive effects as urban trees, only these are less pronounced. Shrubs are cheaper and quicker to plant than trees but require more care.
- Lawn or meadow strips along roads should be at least approx. 2 m or wider to create climatic effects. The greening of track bodies is another possibility and can be carried out in several designs.
- Green inner courtyards have a positive influence on the microclimate and thus on the quality of life of the residents.

Limitations
- Street space is an extreme location for plants (e.g. lack of water, pollutants), plant selection is important - also because of the predicted warming. - Ensuring road safety (dead branches). - Lack of space (awareness raising and sensitization of planners necessary). - Competition with stationary traffic. - Green areas have to be maintained and watered in order to maintain their climatic function in summer, even during dry periods.

5. Securing and expanding green and open spaces

- Removing rubbish from green spaces may be more complex than from sealed surfaces.

Applicability by climate zones

- Potentially applicable in other climates as well.
- The evaporation capacity and thus cooling through green areas depends heavily on the water supply, which is why this measure may be unsuitable for regions with very little water.

Legal framework

- Building Code (BauGB), land use plans, spatial planning law, soil protection law.

Practical examples

- The 10,000 m^2 Alaunpark in Dresden is proven to be up to 1.5 °C cooler than its non-green surroundings.

Other positive effects

- Water retention,
- Binding of carbon dioxide and dust
  - For Barcelona it was calculated that 166 tons of fine dust and thus 22% of the dust emissions caused within the city are bound by urban nature every year,
- Increasing biodiversity in the city,
- Common and playroom.

Sources: Brandenburg et al. 2015; Natural Capital Germany - TEEB DE 2017; Monteiro et al. 2016; Stiftung DIE GRÜNE STADT 2010

6. Preservation of urban air circulation and networking of open spaces

Brief description:

- By creating and keeping undeveloped, axial aisles connected to the surrounding area, urban air circulation can be promoted and the supply of cold and fresh air guaranteed. In particular, large, contiguous agricultural and forestry areas are cold air production sites. In this context, particular attention should be paid to the topography of the surrounding area
  - Slopes promote air movement,
  - Flat, wooded and unwooded green areas promote the formation of cold air.
- Cold air corridors should have a low level of roughness so as not to slow down the exchange of air
  - e.g. meadows, bodies of water, railway systems, wide streets.
- The recommended minimum width for cold air corridors is 10 times the height of the adjacent buildings (at least 50 m).
- Cold air aisles should not be 'built over'; slopes in particular should be kept free of parallel building blocks.
- Networking should occur along the main wind direction.

Limitations

- Competing urban planning goals (e.g. density, urban structure, population growth) as well as existing building structures in air corridors and traffic axes.

Applicability by climate zones

- Potentially applicable to other climates as well.

Legal Aspects

- Forestry Act, Nature Conservation Act, Building Code, Land Use Plans

Practical examples

- Frankfurt is located in the basin of the Rhine-Main plain, surrounded by low mountain ranges and has numerous high-rise buildings, which disrupts the city's even ventilation. However, the 5,000-

6. Preservation of urban air circulation and networking of open spaces

hectare Frankfurt city forest is located along the main wind direction in the southwest of the city and can thus contribute to urban air circulation.

- Mainzer Strasse in Wiesbaden is a wide aisle of fresh air that transports cooler air from the Rhine to the inner city, which is located in a basin.

More positive effects

- Increased leisure and recreational value through the networking of inner-city open spaces with the surrounding area.

Sources: Brandenburg et al. 2015; Stiftung DIE GRÜNE STADT 2010

7. Roof and facade greening

Brief description:

- Green roofs and facades can reduce the summer heating of the building surfaces without using any energy. They also have a positive effect on ambient temperatures due to their evaporation capacity.
    - In the case of extensive green roofs, the substrate layer is approx. 15 cm thick, and the planting is usually done with undemanding, low-growing plants (e.g. Sedum species). They usually have a low weight and are therefore suitable for many roofs - often no additional static work is necessary. Extensive green roofs require little maintenance, but are not suitable for walking and use.
    - Intensive green roofs are characterized by a thicker substrate layer and the use of grass, shrubs and trees as plants. However, this results in an additional static load. Intensive green roofs are usually accessible and usable for people.
- Retention of rainwater creates evaporation coolness due to evapotranspiration. Due to the reduced surface heating, the nocturnal heat radiation is also reduced.
- A slight improvement in the microclimate can be achieved with an extensive green roof, while intensive green roofs improve the microclimate. Both intensive and extensive green roofs achieve a slight improvement in the mesoclimate if all suitable roof areas of a block are green.

Limitations

- Conflict of goals: areas suitable for intensive/extensive roof greening are often also suitable for photovoltaic systems; to avoid problems, integrative planning is recommended,
- Partly high costs during construction,
- Maintenance costs depending on the installation of the green roof,
- Monument protection.

Applicability by climate zones

- Potentially applicable in other climates as well.

Legal aspects

- Building code, land use plans

Practical examples

- Bosco Verticale, Milan
    - Completely landscaped high-rise complex with 900 trees and 2,000 other plants,
    - Greening corresponds to around 7,000 m^2 of forest area.
- Green roof mapping Düsseldorf
    - Düsseldorf promotes green roofs and is the only German city that maps green roofs,
    - Over 1,300 buildings now have green roofs, which corresponds to an area of 730,000 m^2 equivalent to the size of 100 soccer fields.
- Pocket Park on shopping mall, Pforzheim
    - 7,000 m^2 continuous lawn area on the roof of a shopping centre.

7. Roof and facade greening

More positive effects

- Green roofs and facades contribute to increasing urban biodiversity and improving air quality.
- Protecting and extending the life of the roof waterproofing by providing mechanical protection and absorbing UV radiation.
- The evaporation of the stored rainwater can improve the indoor climate of the rooms directly below in summer.
- Relief of urban drainage and sewage treatment plants through rainwater retention.
- Improving air quality by binding fine dust.
- Cityscape design.
- Creation of additional free spaces for city dwellers.

Sources: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) 2017; Stiftung DIE GRÜNE STADT 2010; Environmental Planning Bullermann Schneble GmbH 2015

8. Increasing the proportion of water in the district

Brief description:

- The cooling effect of water surfaces is based on the energy required for evaporation being withdrawn from the water surface and the surrounding air. This energy expenditure is compensated by supplying warm air from the environment. Moving water (e.g. in fountains) generally contributes more to evaporative cooling than standing water surfaces. In the case of radiation weather conditions, a temperature reduction of 1 °C for a range of 400 m could be demonstrated for flowing water. Flowing waters can also be important air channels, depending on their position in relation to the main wind direction.
- Possibilities to increase the proportion of water in cities
  - The creation of / the enlargement of existing water areas,
  - The uncovering of piped bodies of water,
  - The creation of water installations.
- The increase in the proportion of water areas can be brought about by the construction of ponds, artificial watercourses or the creation of dam areas.
- The microclimate can be improved by opening up and renaturing piped sections of the stream.
- More water installations in public spaces, e.g. by hydrants with spray attachments, spray mist, splash pads, fountains, etc. help to cool down. The drainage of drinking fountains can be designed in such a way that the water runs off above ground and only seeps away later. Another possibility is the creation of more (children's) outdoor pools and water playgrounds.

Limitations

- The construction costs for standing water are high. For flowing waters and the disclosure of piped waters, the construction costs are even higher. In addition, artificial water surfaces require intensive maintenance.
- Artificial bodies of water can burst their banks during heavy rainfall and flood the surrounding area.
- Revitalization measures for piped bodies of water are often only possible to a limited extent due to the existing infrastructure or due to ownership of the land required for this.
- Compliance with hygiene regulations.

Applicability by climate zones

- Potentially applicable to other climates as well.

Legal aspects

- Nature Conservation Act, Building Code, Land Use Plans

Practical examples

8. Increasing the proportion of water in the district
- Renaturation of the Rosengartenbach in the district of Siegen-Niederschleden o Partial disclosure of 130 m of stream (costs approx. 266,000 euros).
More positive effects - Positive impact on biodiversity, - Optical beautification, - Dust binding due to increased humidity, - Relief of the sewer system during heavy rainfall, - Increasing connectivity between habitats, - Rivers can serve as cold air corridors.

Sources: Brandenburg et al. 2015; University City of Siegen 2016

9. Shadowing of open spaces and paths
Brief description: - The shadowing of open spaces and paths reduces the heating of surfaces, thus leading to a slight improvement in the microclimate and can thus increase people's well-being. Due to the reduced heating, the nocturnal heat radiation is also reduced. Shadowing is particularly important for large squares, as people would otherwise avoid them. - The following measures were rated as particularly suitable for achieving these goals: o Provision of shaded seating, o Shadowing of open spaces in buildings, o Shadowing of open spaces away from the building. - Shadowing of open spaces away from the building by means of sun sails or similar is particularly suitable for larger open spaces such as parking lots or public squares. This measure is primarily an alternative when the planting of trees due to e.g. installations is not possible. - Shadowing can also be provided by covering the areas with PV modules. However, the dark colour of the modules causes heat development, so that an additional UHIE occurs.
Limitations - However, depending on the design of the shadowing elements, nocturnal heat radiation and ventilation is prevented. - Heat build-up and deterioration in air quality are possible due to reduced air circulation.
Applicability by climate zones - Potentially applicable to other climates as well.
Legal aspects - Building code, land use plans
Practical examples - Urban Loritz Square, Vienna o A generous membrane roof spans and protects the individual waiting areas and the footpaths in between.
More positive effects - Protection against weather influences such as rain or snow. - Possibility of generating energy when photovoltaic systems are used as shadowing elements or are installed on them.

Source: Brandenburg et al. 2015

A.2 Interview guide

Block 1: Brief presentation of the project

The project "Sustainable building air conditioning in Europe - concepts for avoiding heat islands and for a comfortable indoor climate" deals with the problem of urban heat islands and strategies for avoiding them (e.g., green roofs and facades, water management, shadowing, brightening of surfaces, trees, etc.) on behalf of the Federal Environment Agency. The project involves, among other things, quantifying the effectiveness of various measures and simulating the influence of these measures on the urban microclimate over the course of the year. In addition, the opportunities and obstacles in the implementation of measures at the municipal level are to be examined.

Block 2: Overview of measures and stakeholders in your area of responsibility

- Which strategies and measures to avoid urban heat island effects have already been implemented or are being planned?
- Who are the most important stakeholders in this area in your municipality?
- How does the coordination/cooperation between stakeholder take place (e.g. cross-departmental processes)?

Block 3: Importance of the topic

- How important is the avoidance of urban heat island effects in the urban planning process in your municipality?
- How do you see the importance of the topic compared to other municipalities?
- In your opinion, how important should avoiding urban heat islands be?

Block 4: Availability of data

- What data is available for planning measures to avoid urban heat islands?
- Are spatially resolved data on temperature development regularly collected and processed?

Block 5: Opportunities and obstacles

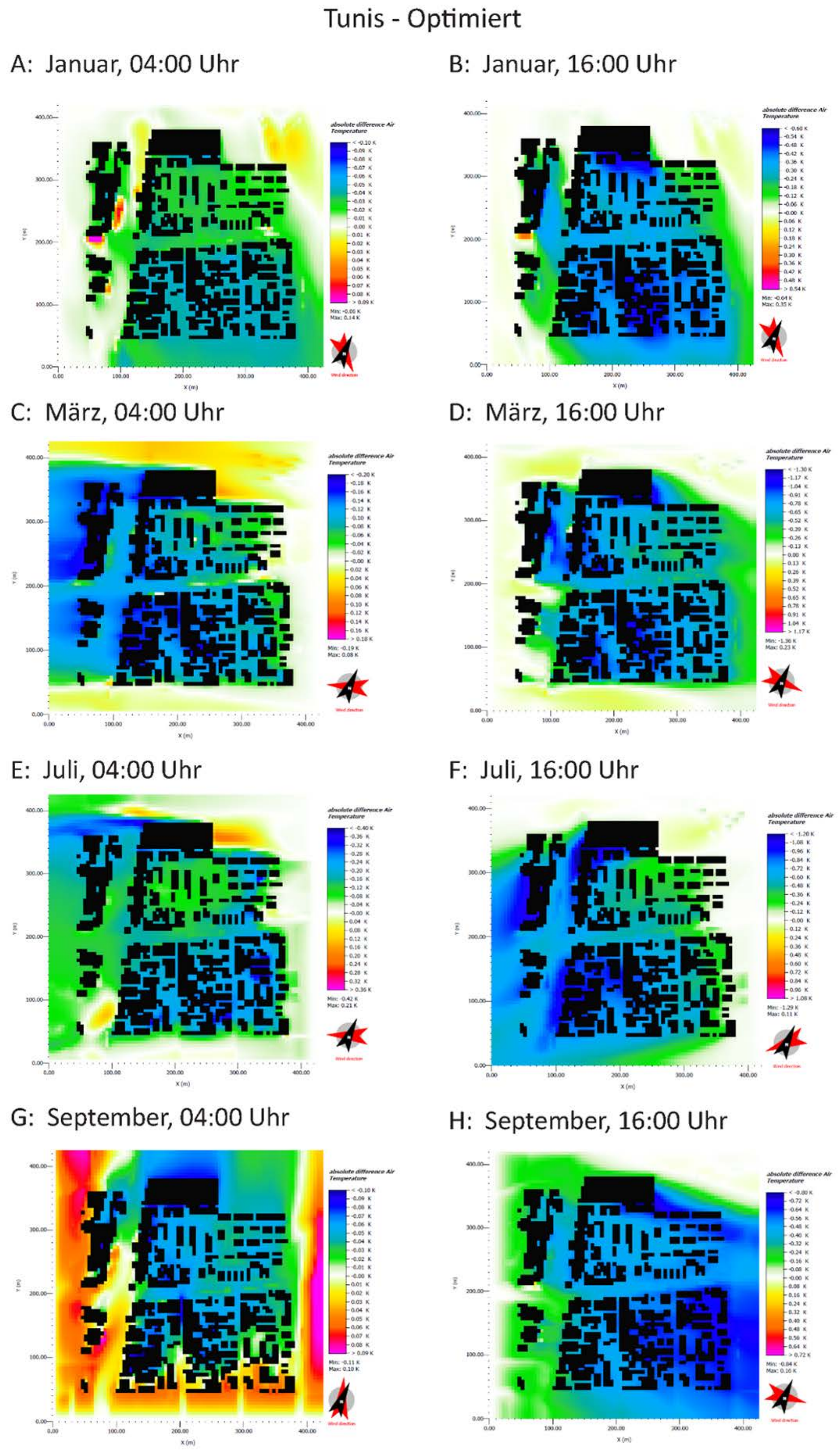
- Which factors inhibit the implementation of measures to avoid urban heat island effects at the municipal level? (e.g., stakeholder level, planning level)
- Are there elements of the national regulatory framework that promote or inhibit the implementation of measures at the municipal level?
- In your view, which political instruments at federal level would be necessary/helpful to further promote the topic?

A.3 Colour charts microclimate simulations

Figure 118: Panel_1_a_Tunis_SQ

Source: Own illustration, ENVI-MET

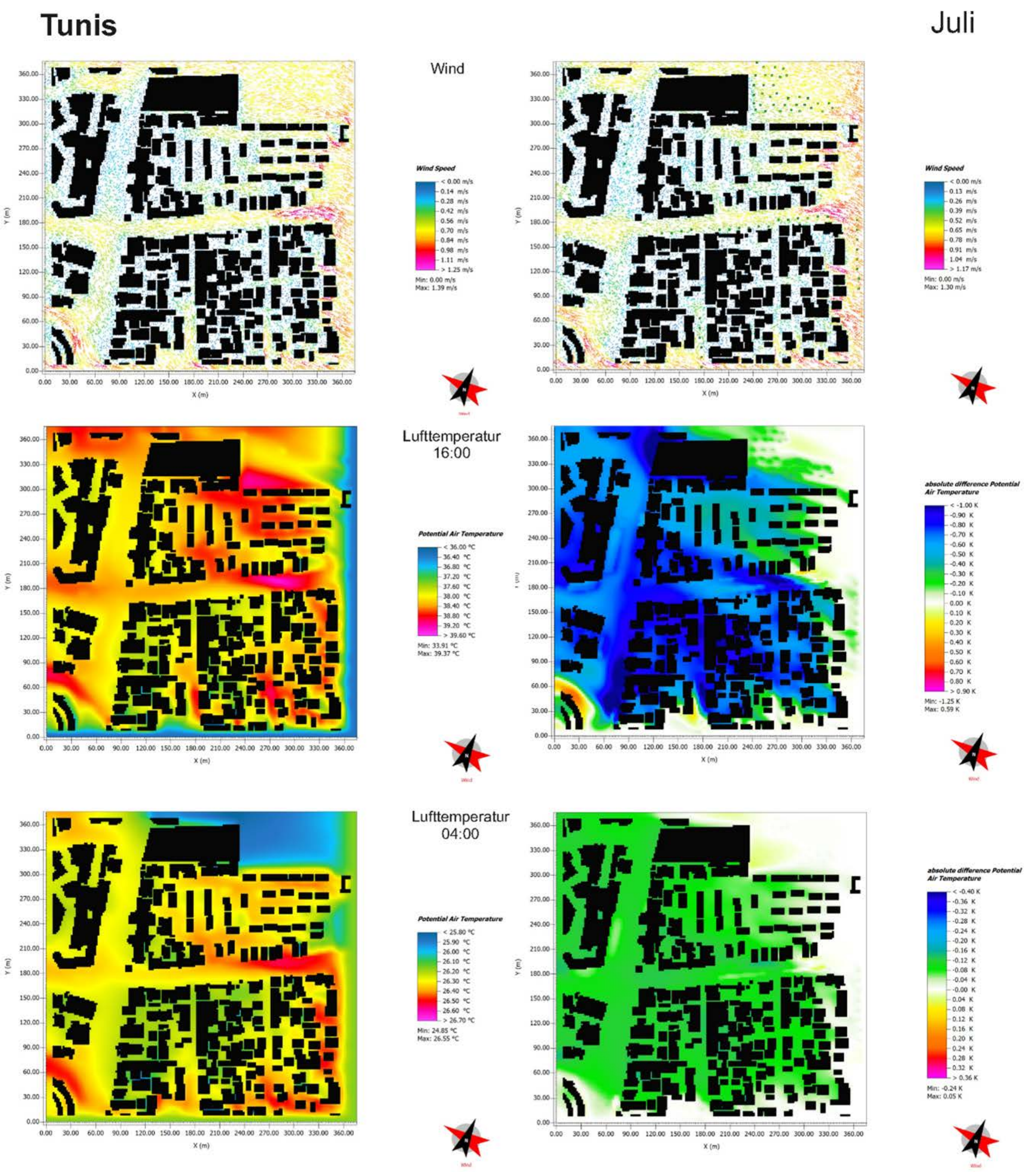
Figure 119: Panel_1_b_Tunis_OPT



Tafel 1b: Jahresübersicht Tunis (Differenzen)

Source: Own illustration, ENVI-MET

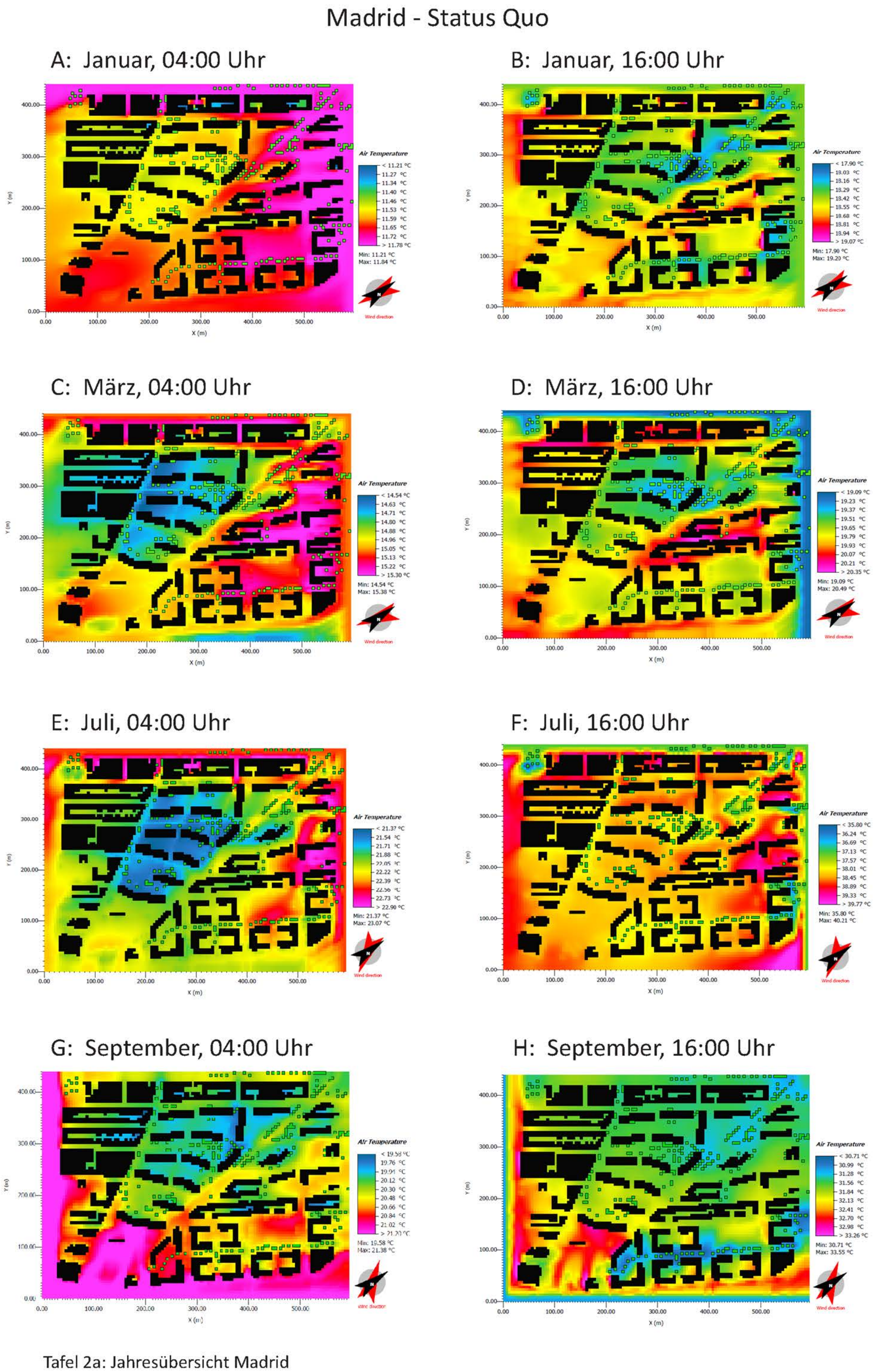
Figure 120: Panel_1_c_Tunis_Detail



Tafel 1 c: Detailsimulationen Juli

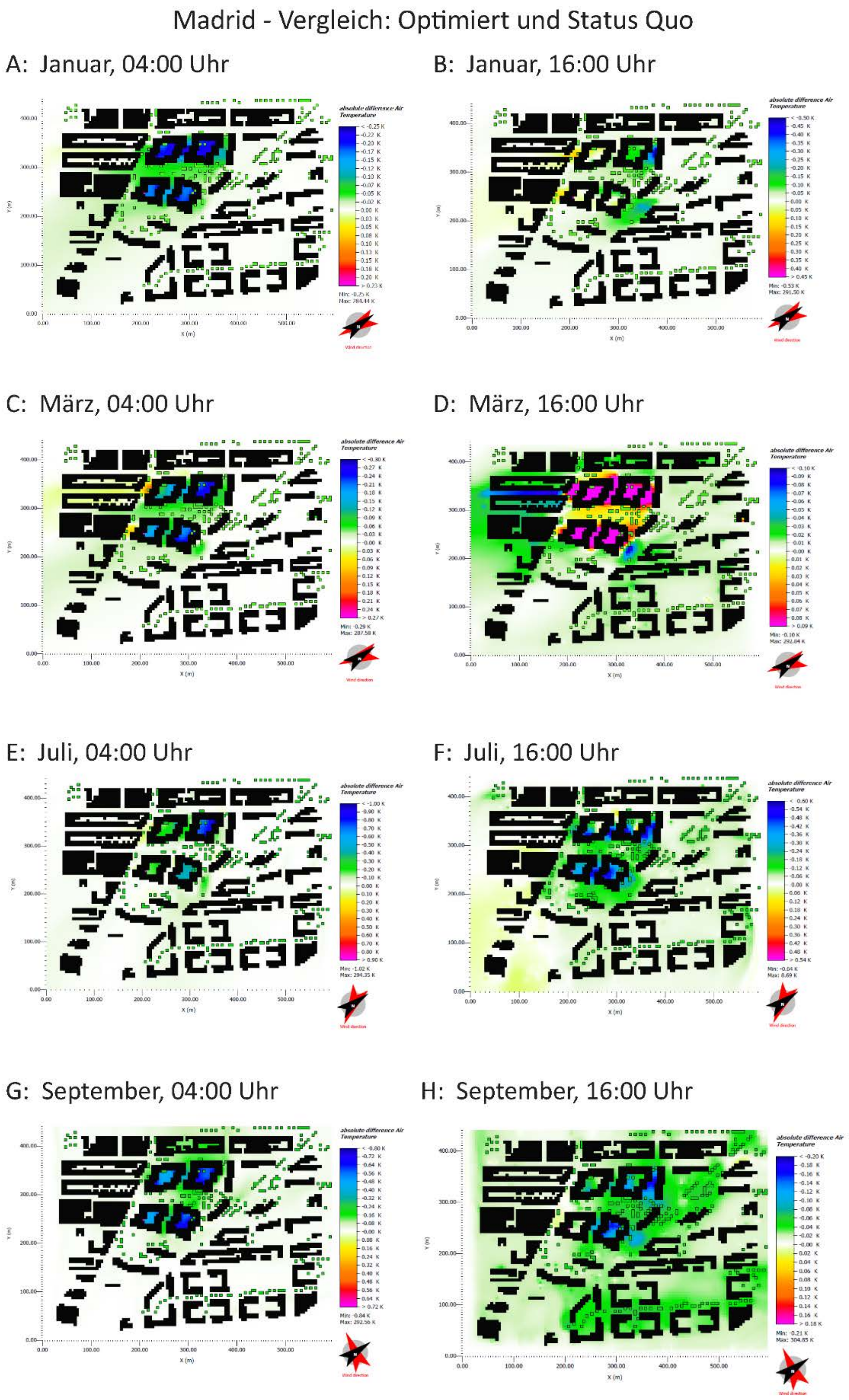
Source: Own illustration, ENVI-MET

Figure 121: Panel_2_a_Madrid_SQ



Source: Own illustration, ENVI-MET

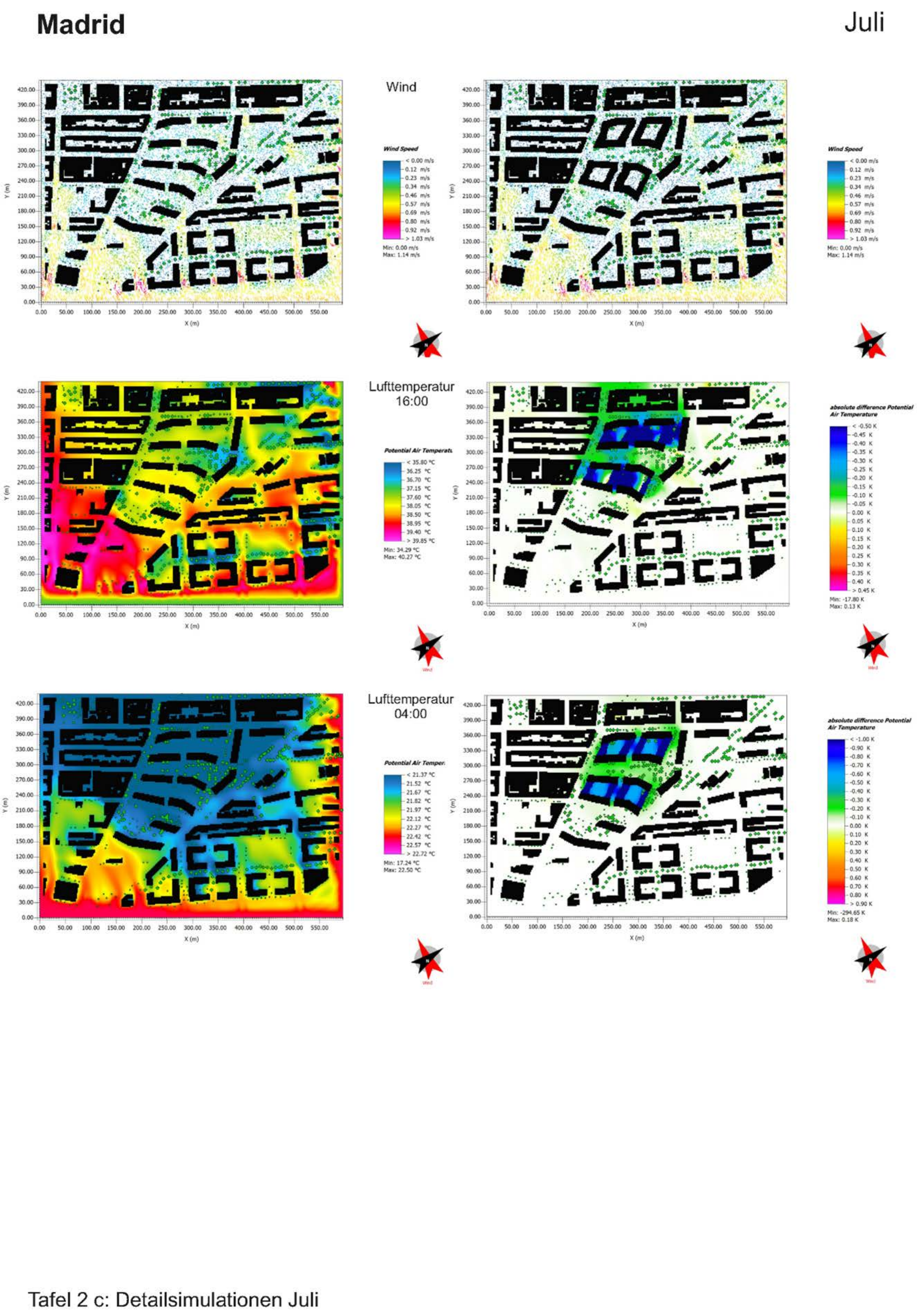
Figure 122: Panel_2_b_Madrid_OPT



Tafel 2b: Jahresübersicht Madrid (Differenzen)

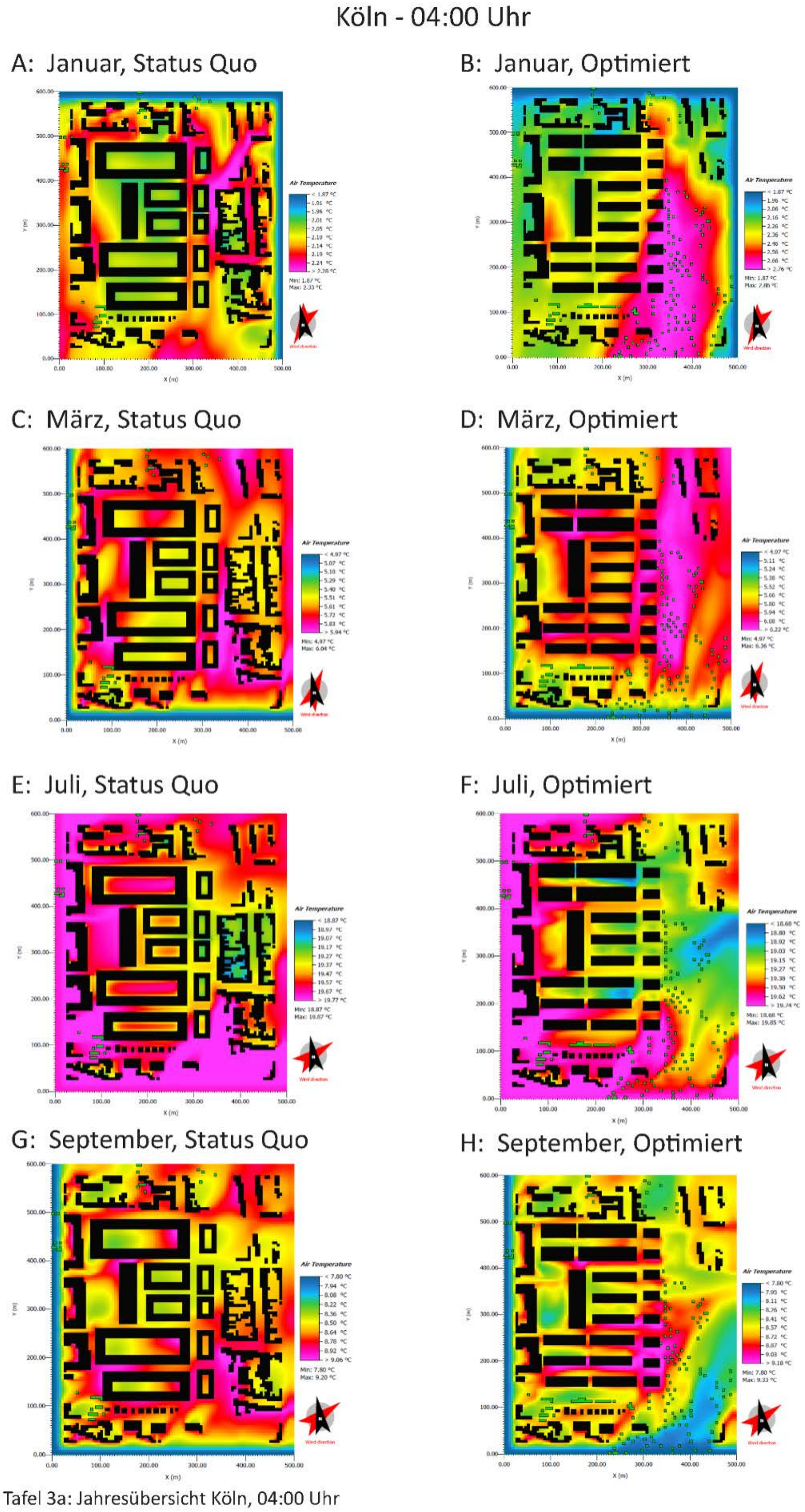
Source: Own illustration, ENVI-MET

Figure 123: Panel_2_c_Madrid_Detail



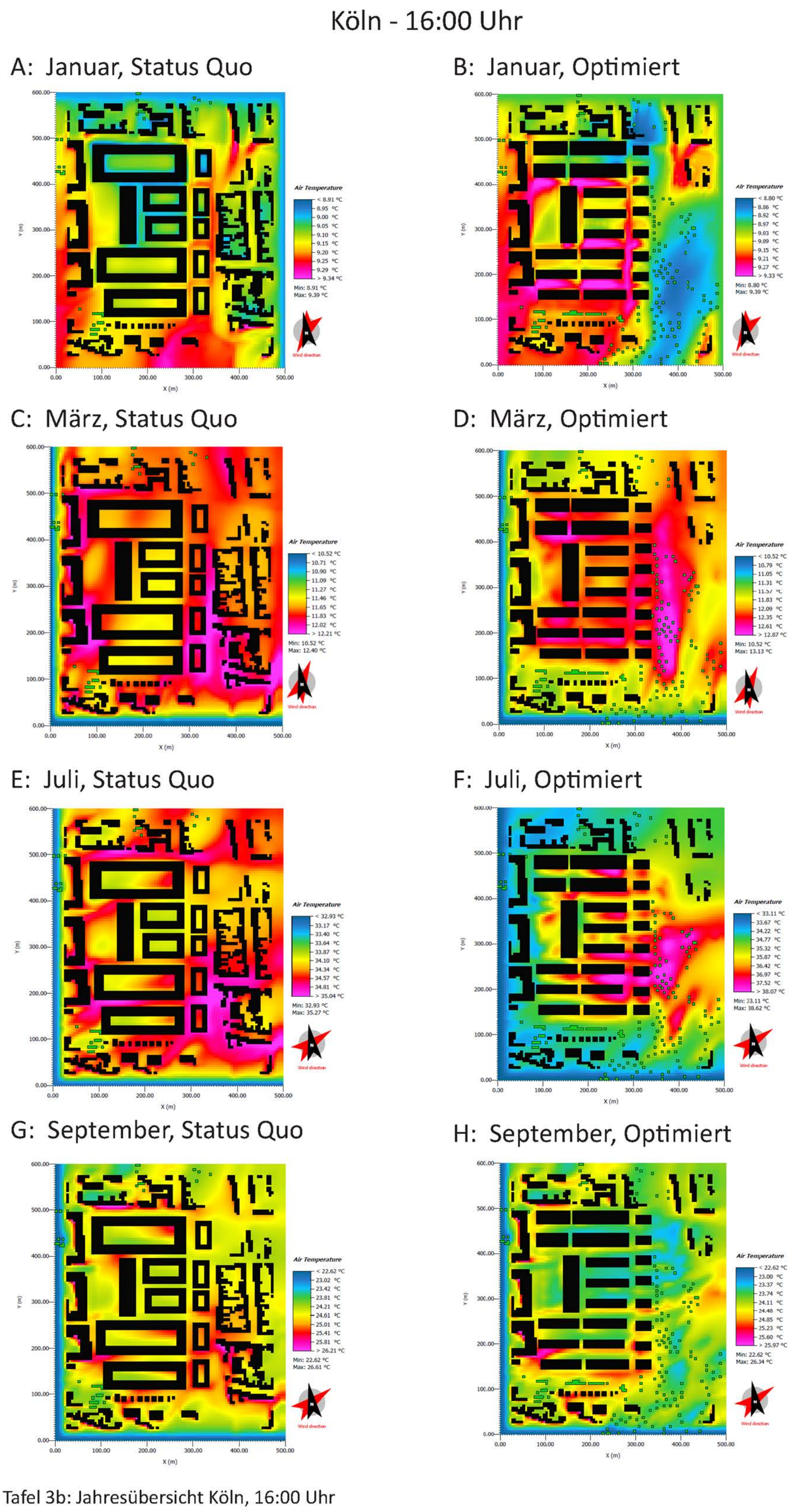
Source: Own illustration, ENVI-MET

Figure 124: Panel_3_a_Koeln_04h



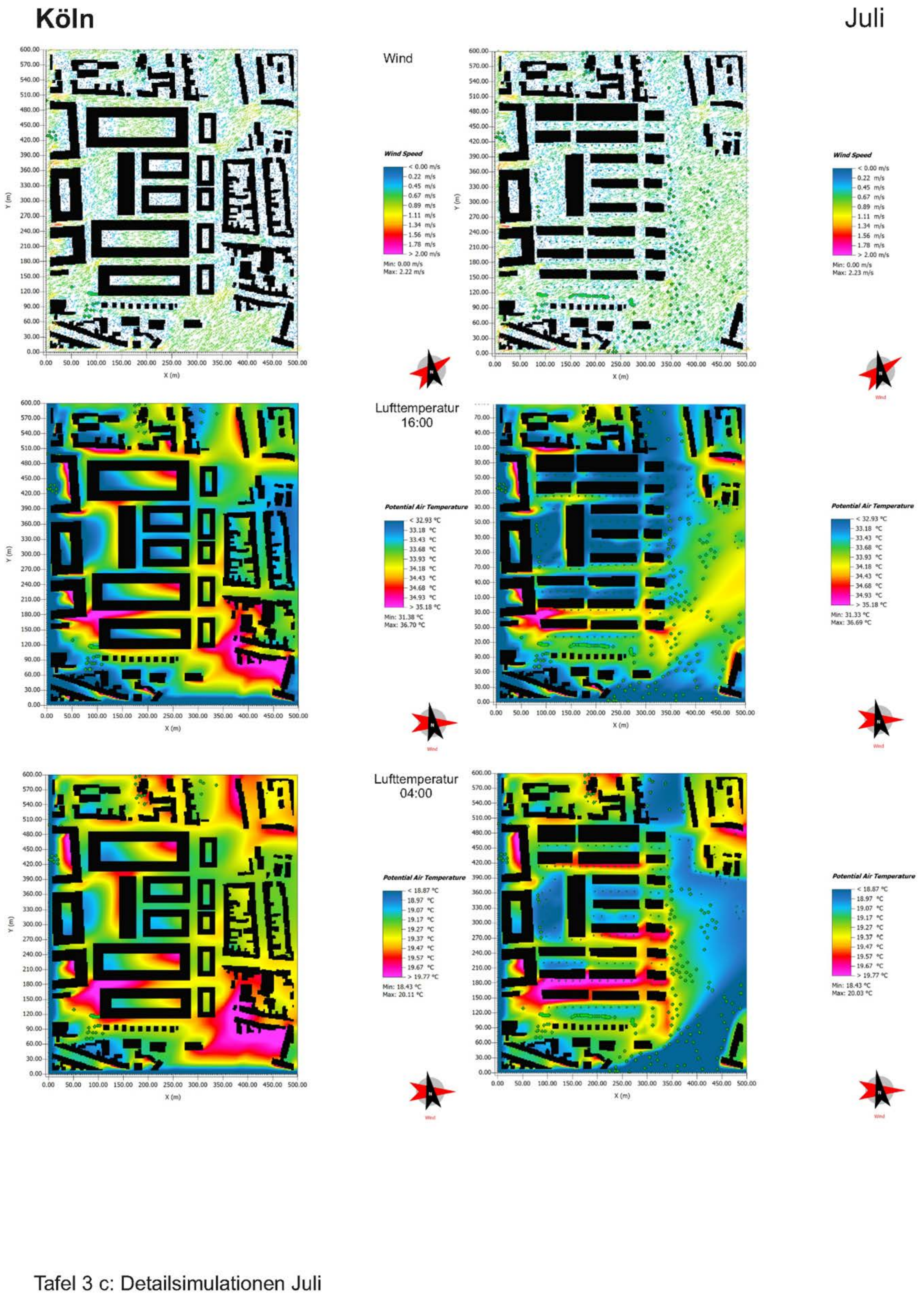
Source: Own illustration, ENVI-MET

Figure 125: Panel_3_b_Koeln_16h



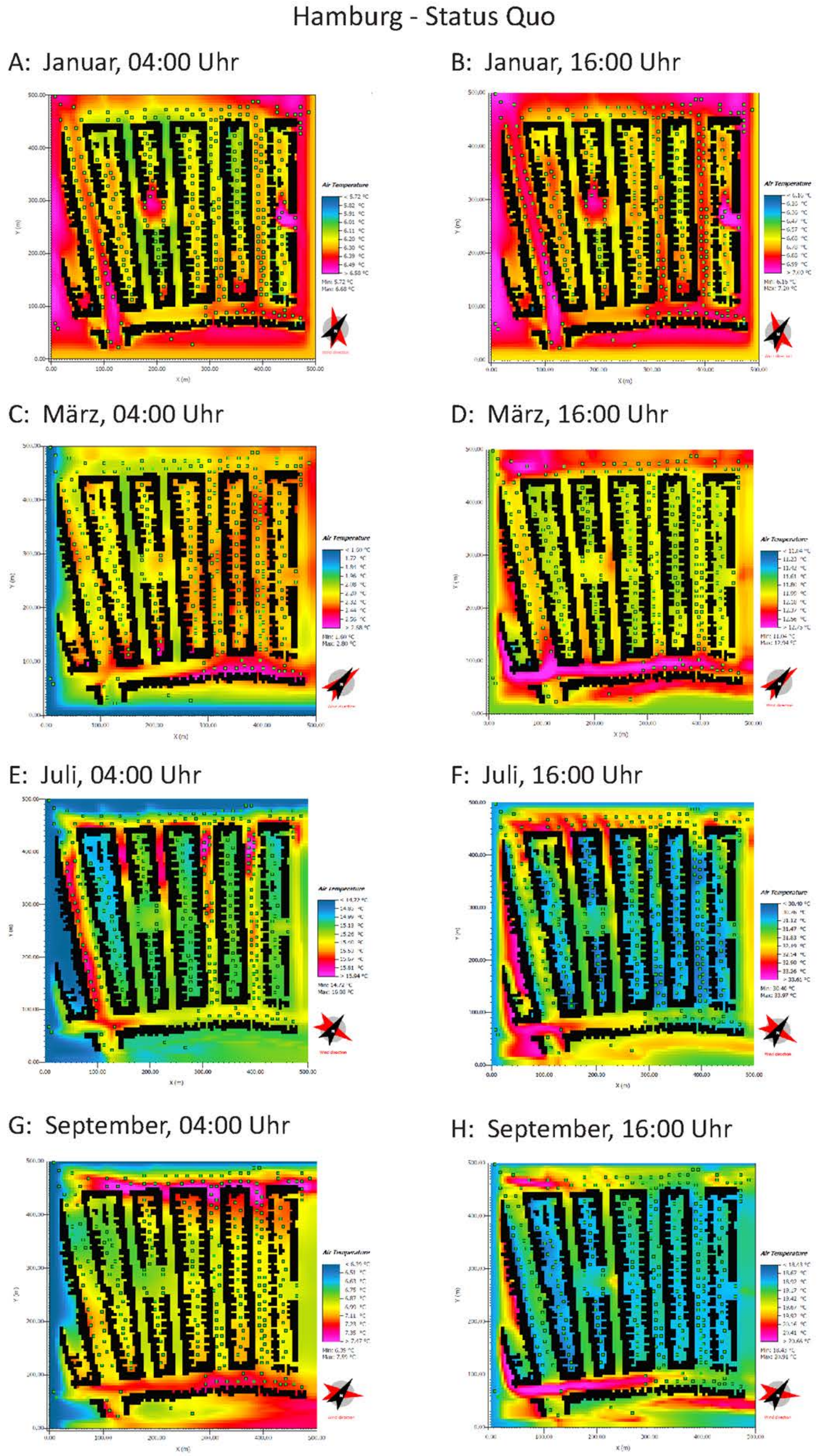
Source: Own illustration, ENVI-MET

Figure 126: Panel_3_c_Koeln_Detail



Source: Own illustration, ENVI-MET

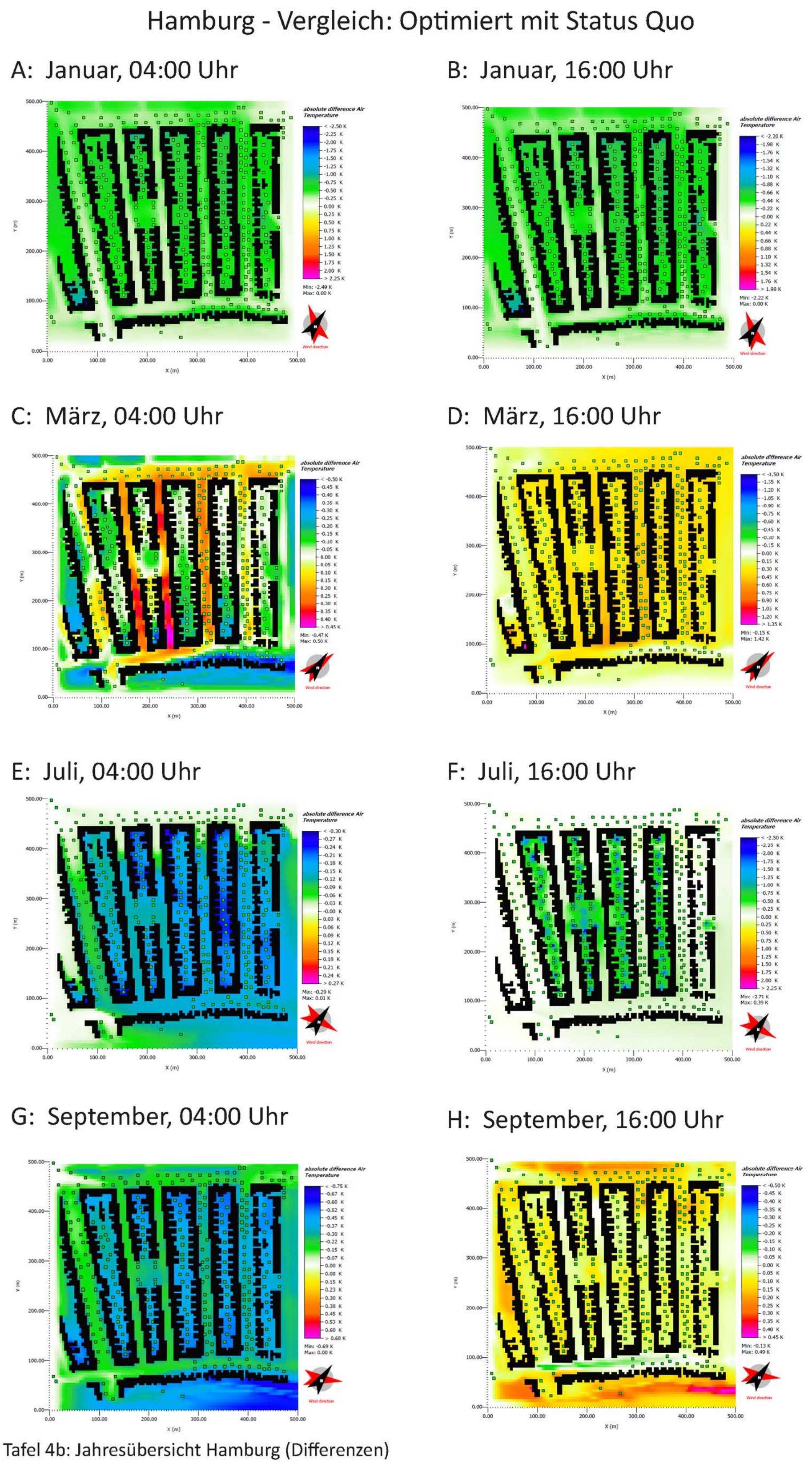
Figure 127: Panel_4_a_Hamburg_SQ



Tafel 4a: Jahresübersicht Hamburg

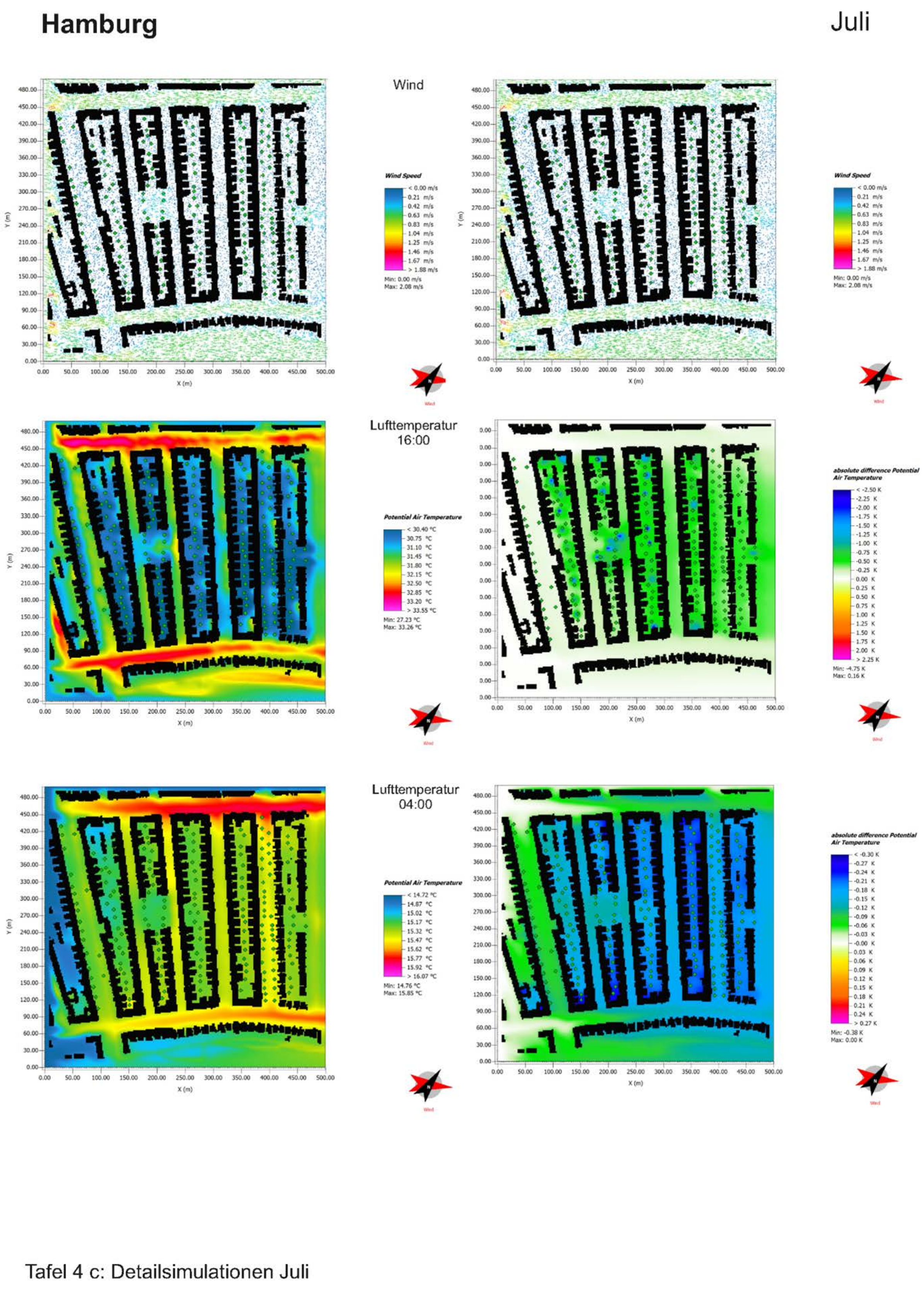
Source: Own illustration, ENVI-MET

Figure 128: Panel_4_b_Hamburg_OPT



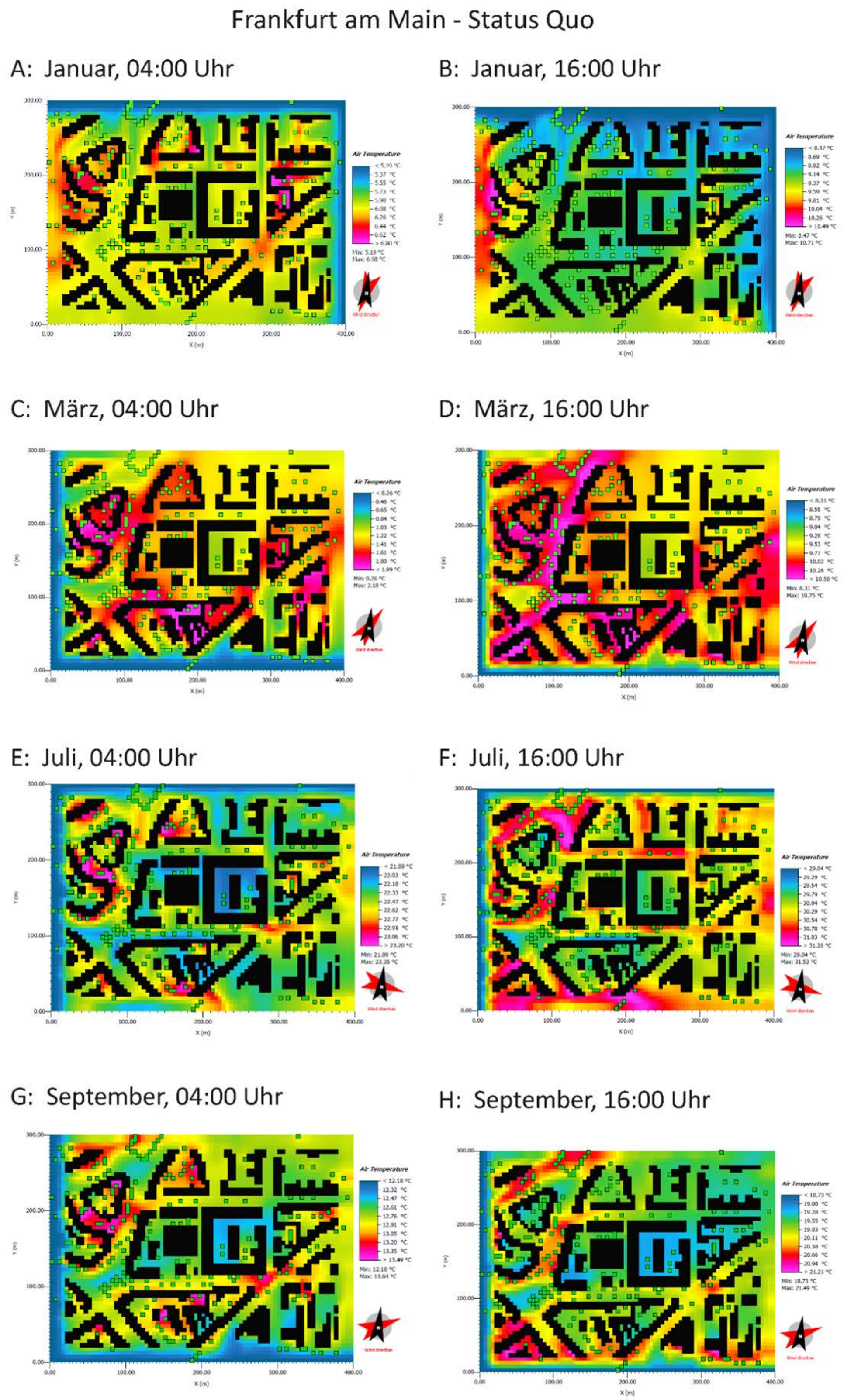
Source: Own illustration, ENVI-MET

Figure 129: Panel_4_c_Hamburg_Detail



Source: Own illustration, ENVI-MET

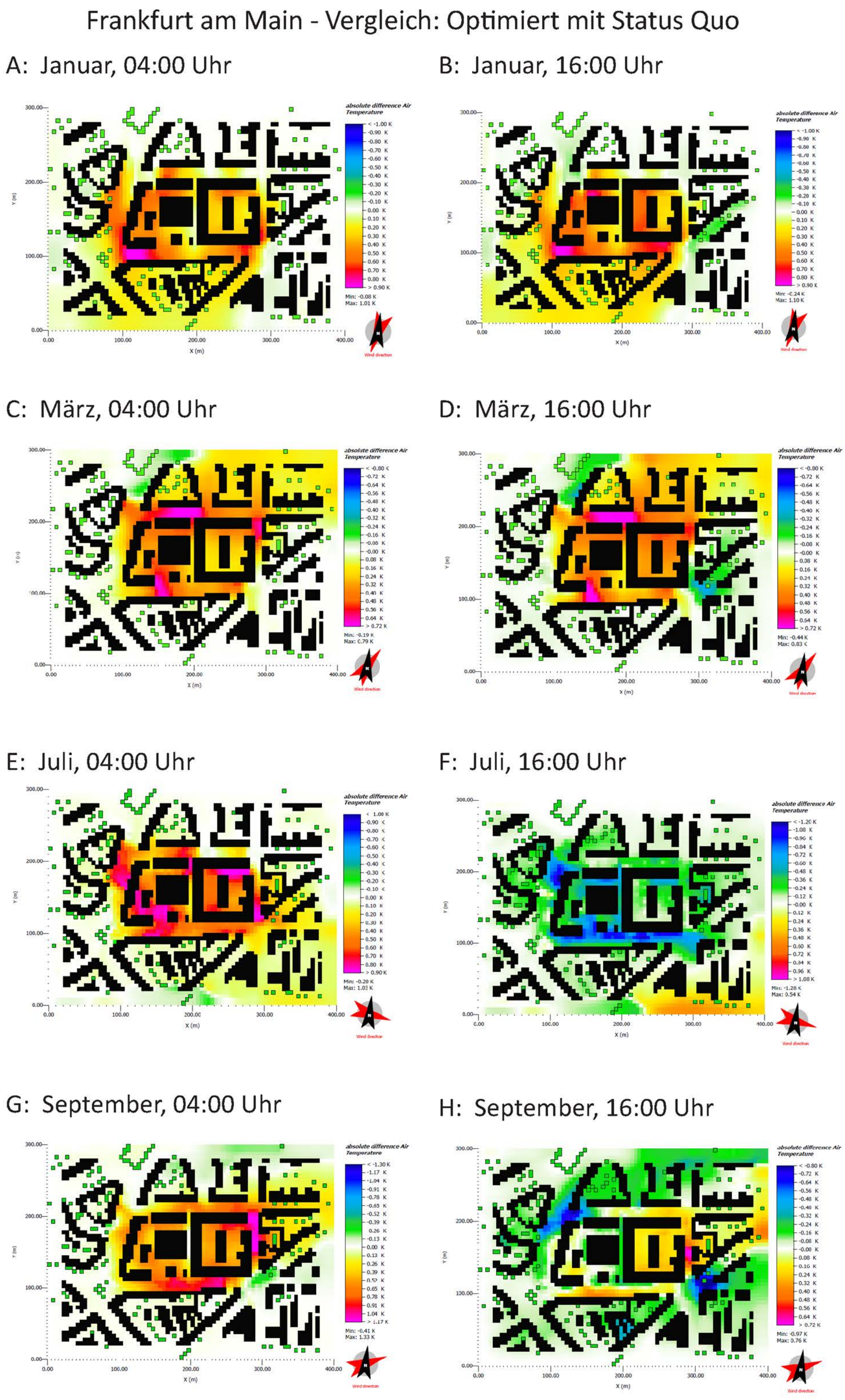
Figure 130: Panel_5_a_Frankfurt_SQ



Tafel 5a: Jahresübersicht Frankfurt am Main

Source: Own illustration, ENVI-MET

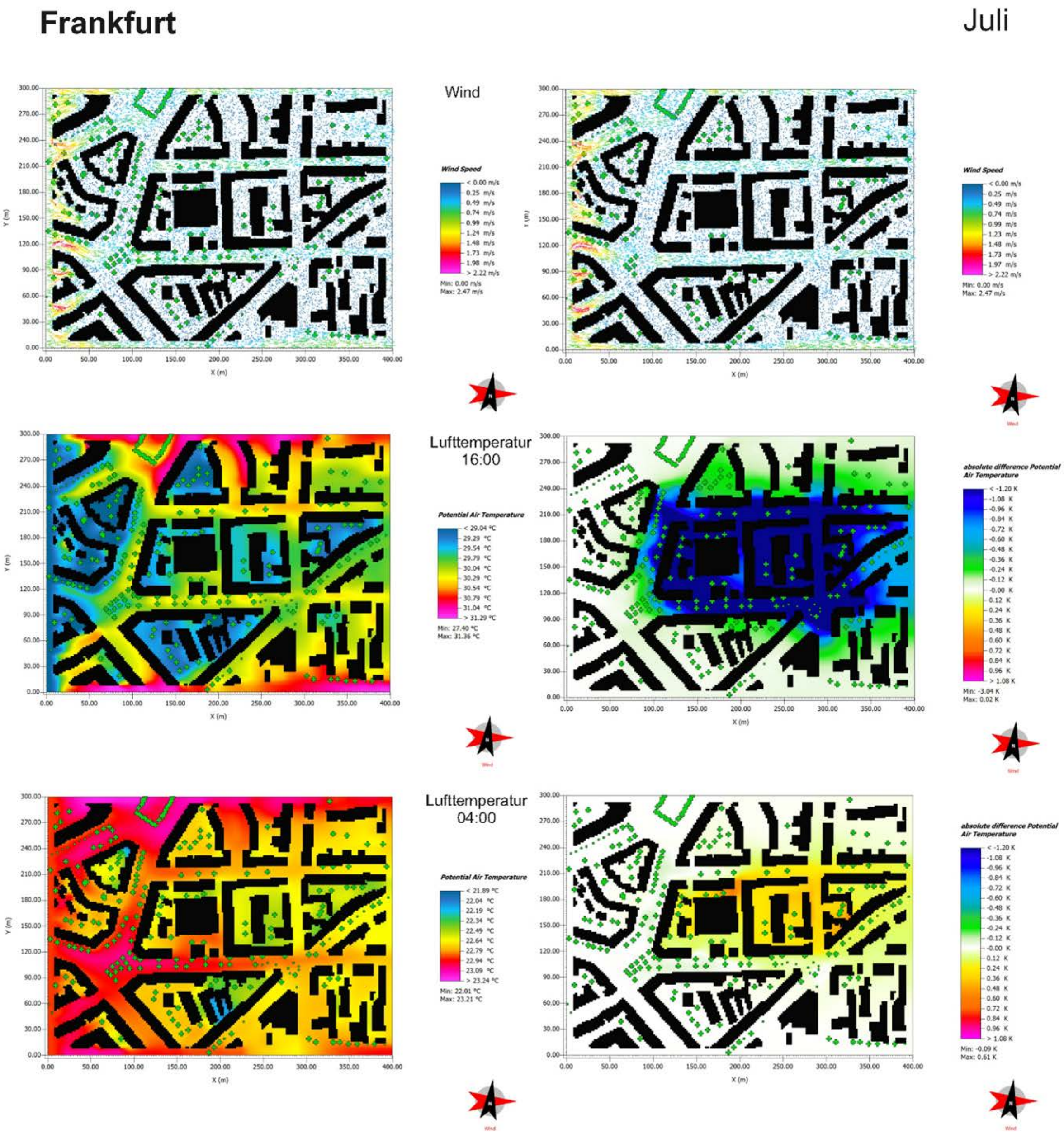
Figure 131: Panel_5_b_Frankfurt_OPT



Tafel 5b: Jahresübersicht Frankfurt am Main (Differenzen)

Source: Own illustration, ENVI-MET

Figure 132: Panel_5_c_Frankfurt_Detail



Tafel 5 c: Detailsimulationen Juli

Source: Own illustration, ENVI-MET

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