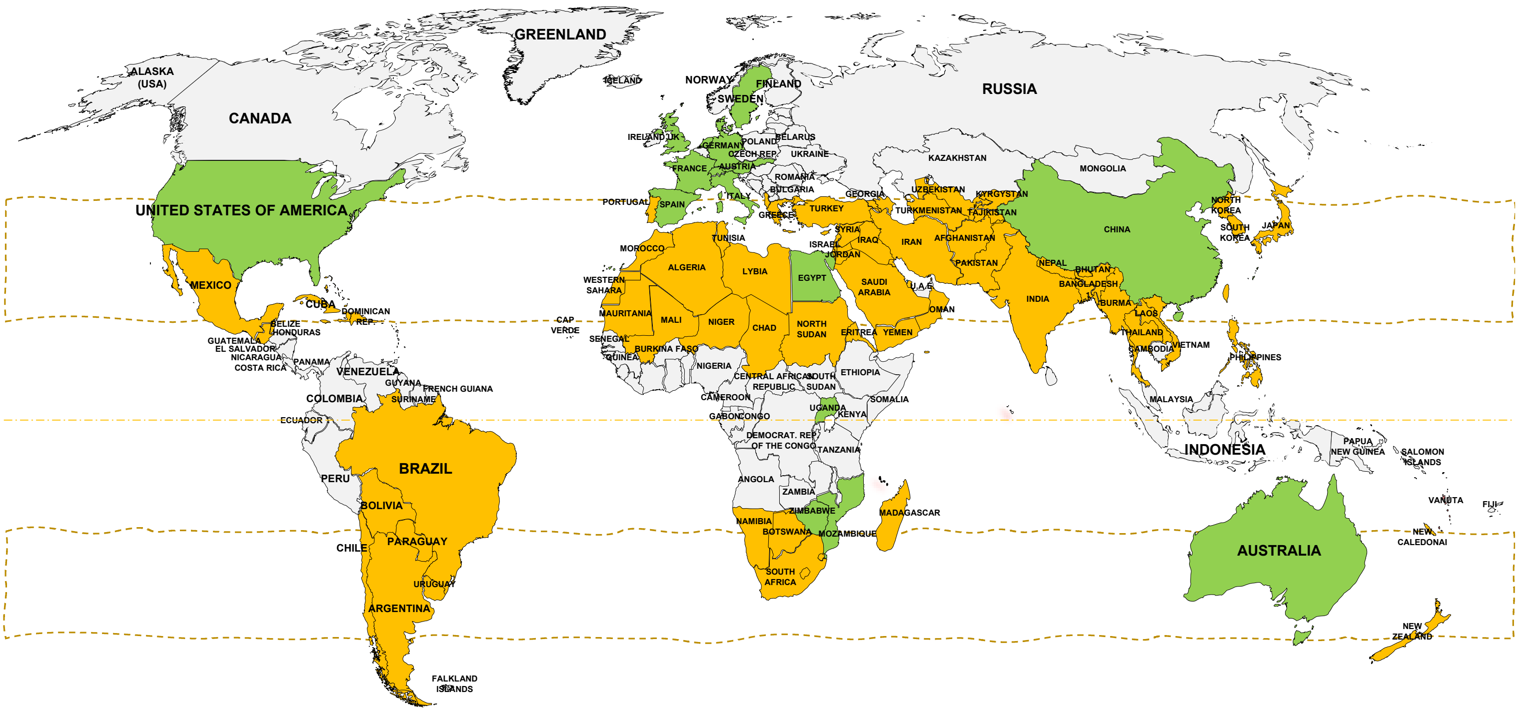
Climatic Conditions & Applications



IEA SHC TASK 65 | SOLAR COOLING FOR THE SUNBELT REGIONS

Technology Collaboration Programme
by iea

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Climatic Conditions & Applications

This is a report from SHC Task 65: Solar Cooling for the Sunbelt Regions and work performed in Subtask A: Adaption

Richard Gurtner, Tobias Schmetzer & Manuel Riepl (ZAE Bayern)
Date: 23 June 2023
Report D-A1, DOI: 10.18777/ieashc-task65-2023-0002

Cover photo credit: World map with Sunbelt regions (marked yellow) and the 18 countries of the participating Task 65 experts (marked green), source: Neyer Brainworks & JER

Solar Heating & Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives (*"*Implementing Agreements*"*) of the International Energy Agency.

Our mission is *"Through multi-disciplinary international collaborative research and knowledge exchange, as well as market and policy recommendations, the IEA SHC will work to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers."*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54, 69)
- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64, 72)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61, 70)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46, 71)
- Storage of Solar Heat (Tasks 7, 32, 42, 58, 67)

In addition to our Task work, other activities of the IEA SHC include our:

- SHC Solar Academy
- *Solar Heat Worldwide*, annual statistics report
- SHC International Conference

Our members

Australia	European Commission	SACREEE
Austria	France	SICREEE
Belgium	Germany	Slovakia
Canada	International Solar Energy Society	South Africa
CCREEE	Italy	Spain
China	Netherlands	Sweden
Denmark	Norway	Switzerland
EACREEE	Portugal	Türkiye
ECREEE	REEECH	United Kingdom

Contents

1 Executive Summary

In general, climatic conditions and typical applications for (solar) cooling heavily depend on the location. In order to be able to deduce regionally specific requirements for solar cooling systems, it is therefore obvious to use geographical data. To process such data a Geographic information system (GIS) is needed. GIS are able to capture, store, check, and display data related to positions on Earth's surface. Most geographical data relevant for this application are already available from various sources, such as solar radiation data, climatic data, population data etc.

In activity A1 a GIS software was used to combine geographic data in a way that local reference boundary conditions for solar cooling systems in the Sunbelt regions can be determined and also used for evaluation. The developed method can also be used to create information about possible locations and potentials of specific solar cooling systems. By additionally using for example population density and purchase power data a base for future market potential studies on certain products / technologies is provided. As a result potential sites can be identified as well as economic factors can be considered in order to identify (future) markets.

Many results from the ongoing research project "Solar thermal energy system for cooling and process heating in the sunbelt region – SBC" have been included into this Task. The project is carried out by two partners: Industrial Solar GmbH and the Bavarian Center for Applied Energy Research (ZAE Bayern). It was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) under the project number 03ETW026. The developed method was used to determine possible locations and potentials for the SBC system as a first example. It is planned to use the developed method in the further course of the task work.

2 Scope of Activity A1 and Methodology

The collection of the climatic conditions and typical applications aims to understand the reference boundary conditions for adaptation of the components and solar cooling systems. Related climatic and typical loads e.g. building cooling, and processes cooling (industry) are documented and therefore give a base for future market potential studies on certain products / technologies. Existing meteorological data is supplemented with relevant information for installations in difficult climatic conditions (water availability, etc.).

Enormous amounts of (pre-processed) sensor data from research satellites, corresponding maps and from other sources are available. In the first step appropriate geographic data has been searched for. The data found can then be analyzed by the use of a Geographic Information System (GIS). This work has been conducted using the *QGIS software* (QGIS, 2023) that makes use of several other GIS processing tools and frameworks. This work aims at combining the data based on the various conditions defined to finally analyze boundary conditions and/or appropriate regions.

2.1 Data Sources

The data sources used are explained in the following sections. A data source can contain multiple layers that represent data on specific topics or numbers. Each data layer consists of 145 million grid cells and is approximately 1.5 gigabytes in size. The following conditions and sources were taken into account:

- Considered geographic areas that are regarded to require cooling include latitudes between 48°N and 44°S
- Various Solar irradiances (DNI, GHI, DIF) and photovoltaic power potential (PVOUT)
- Population density/Settlement levels
- Climate zones (Köppen–Geiger climate classification system)
- Water availability
- Market risk covered by Environmental Social Governance (ESG)
- Purchasing Power Parity / Gross Domestic Product

2.1.1 Geographic Areas

Due to the structure of the data, a country-specific evaluation (as defined for the sunbelt) and thus a Sunbelt region exclusive analysis was not possible. An adaptation of the data structure could not be implemented due to the limited time available. The focused area in this work is the region between coarsely 40°N and 40°S latitudes as a rule of thumb, which includes the Sunbelt region. As during the work interesting locations outside that range were found (such as the Washington state in the Unites States, the Chubut province in Argentina, the Lago Maggiore in Italy, the Aktogay district in Kasachstan, the Bayan-Ölgii province in Mongolia and the Devon Land District in Tasmania) the focused area was enlarged to 48°N and 44°S latitudes.

2.1.2 Solar Irradiance

The World Bank Group has published raster maps representing solar irradiance. The most relevant published data layers (ESMAP, 2019) include the Global Horizontal Irradiation (GHI), Photovoltaic power potential of 1 kWp freestanding PV system (PVOUT), Diffuse Horizontal Irradiation (DIF) and Direct Normal Irradiation (DNI) as part of the Global Solar Atlas package created by SolarGIS (SolarGIS). It has been released with a nominal spatial resolution of 250 m.

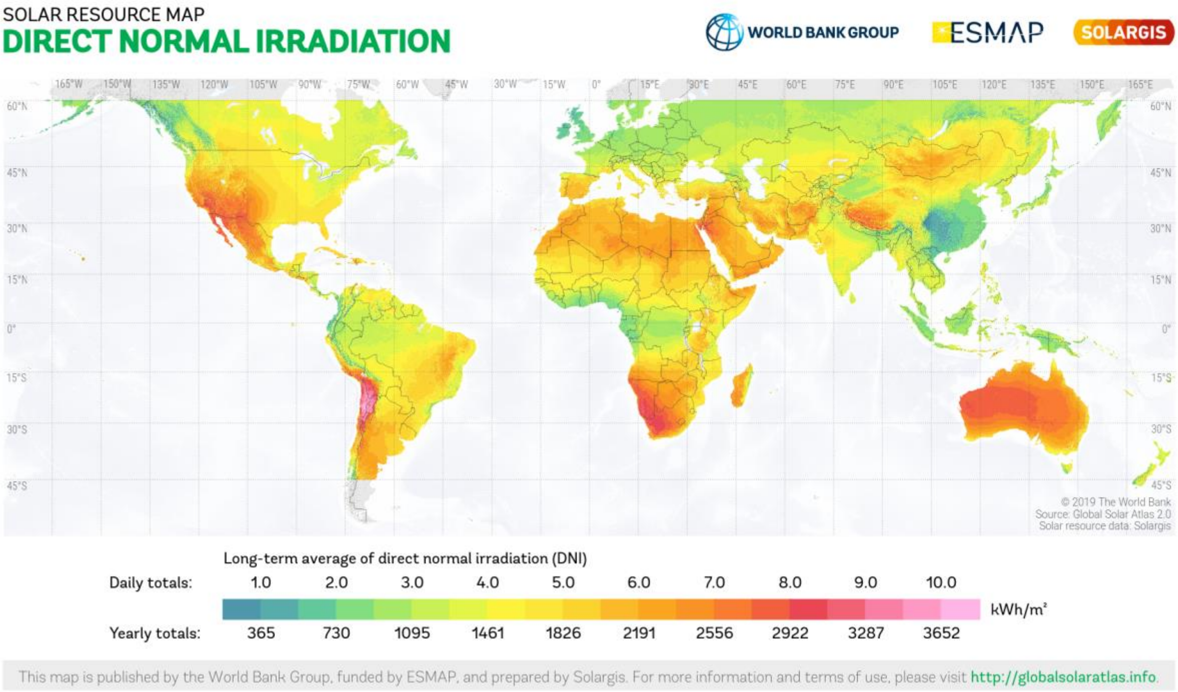


Figure 1: Map of direct normal irradiation from the Global Solar Atlas package created by SolarGIS (https://globalsolaratlas.info/download/world)

2.1.3 Population Density & Settlement Categories

Population density is one of the key figures that supports the analysis regarding the system's boundary conditions and the demand. Stationary cooling demand often exists where people live. The Global Human Settlement Layer (GHSL) project produces global spatial information about the human presence on the planet over time. It was initialised by the Joint Research Centre (JRC) the European Commission's science and knowledge service. The data published by the GHSL includes information about population and degree of urbanization (settlement model, SMOD) which were used within this work (Table 1, Table 2).

Table 1: List of used Global Human Settlement Layer (GHSL) data

Model	Description	Unit	Creation
Population (POP)	The spatial raster dataset depicts the distribution of population, expressed as the number of people per cell (Schiavina M. F. S., 2022); (Freire S., 2016)	Absolute number of inhabitants per cell	Gridded Population of the World; disaggregated from census or administrative units to grid cells
Settlement Model (SMOD)	The layers present the application of the degree of urbanisation stage methodology recommended by UN Statistical Commission to the global population grid generated by the JRC in the epochs 1975-2030 (5 years timestep) (Schiavina M. M. M., 2022); (European Commission, 2021)	Classification	Combined built-up area densities and census

Table 2: SMOD classes according to (Florczyk A.J., 2019)

SMOD class id	***SMOD class description***
10	Water
11	Very low density rural
12	Low Density Rural
13	Rural cluster
21	Suburban
22	Semi-dense Urban Cluster
23	Dense Urban Cluster
30	Urban Centre grid cell

This Global Human Settlement Layer (GHSL) data can be used to estimate in which areas of the Sunbelt regions the demand for cooling and cooling technologies is likely. This provides a basement for future market potential studies.

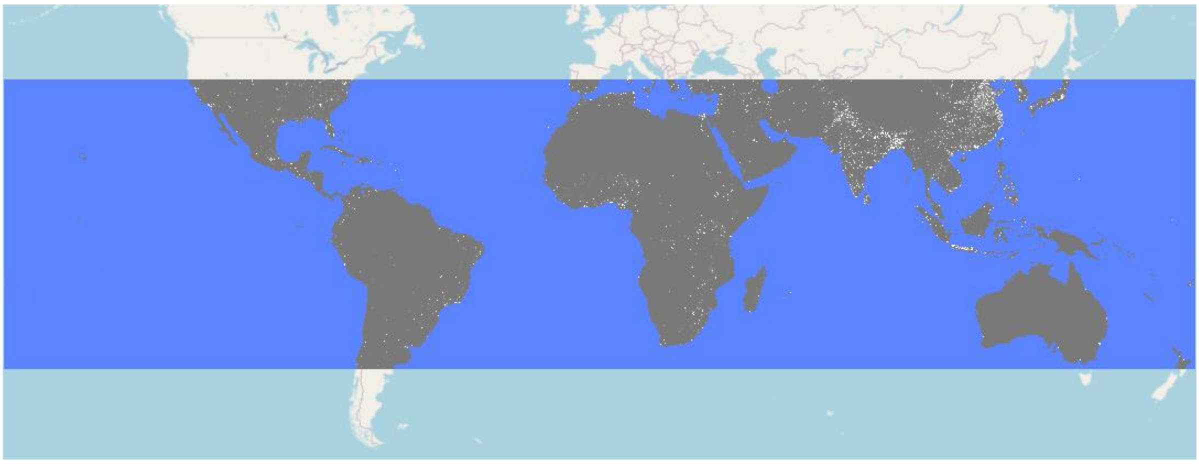


Figure 2: Population values between 48°N and 44°S. Whitish pixels at areas with higher population density. (Source: Own representation based on GHSL population data)

2.1.4 Industrial Areas and Industrial Density

Besides a cooling demand for living in certain areas based on population industrial areas usually indicate a high likelihood for process cooling demand. This is why industrial areas in the Sunbelt region have also been chosen for a first research focus. Other areas were not considered (e.g. non-residential buildings) but can be included in the future. In the same way that population data is used to identify potential cooling demand locations for climatization, data on industrial locations and industrial density is used to identify possible locations for cooling demand in the context of industrial processes.

2.1.4.1 Data Source

The OpenStreetMap (OSM) provides data about building types and their size. The project (OpenStreetMap) creates and distributes free geographic data. It has been built by volunteers and is released with an open-content license. Its map data can be accessed and processed by attributes to predefined geographic objects.

2.1.4.2 Data Generation

The attribute+value pair “building=industrial” has been used to identify relevant objects from the OSM data. In order to prepare that data for later incorporation into the method-wide used grid scheme the total area of industrial buildings within each 1km x 1km sampling grid area was recollected and associated accordingly. Examples of identified industrial buildings (red) within the 1km x 1km grid cells are shown in Figure 3 and Figure 4.

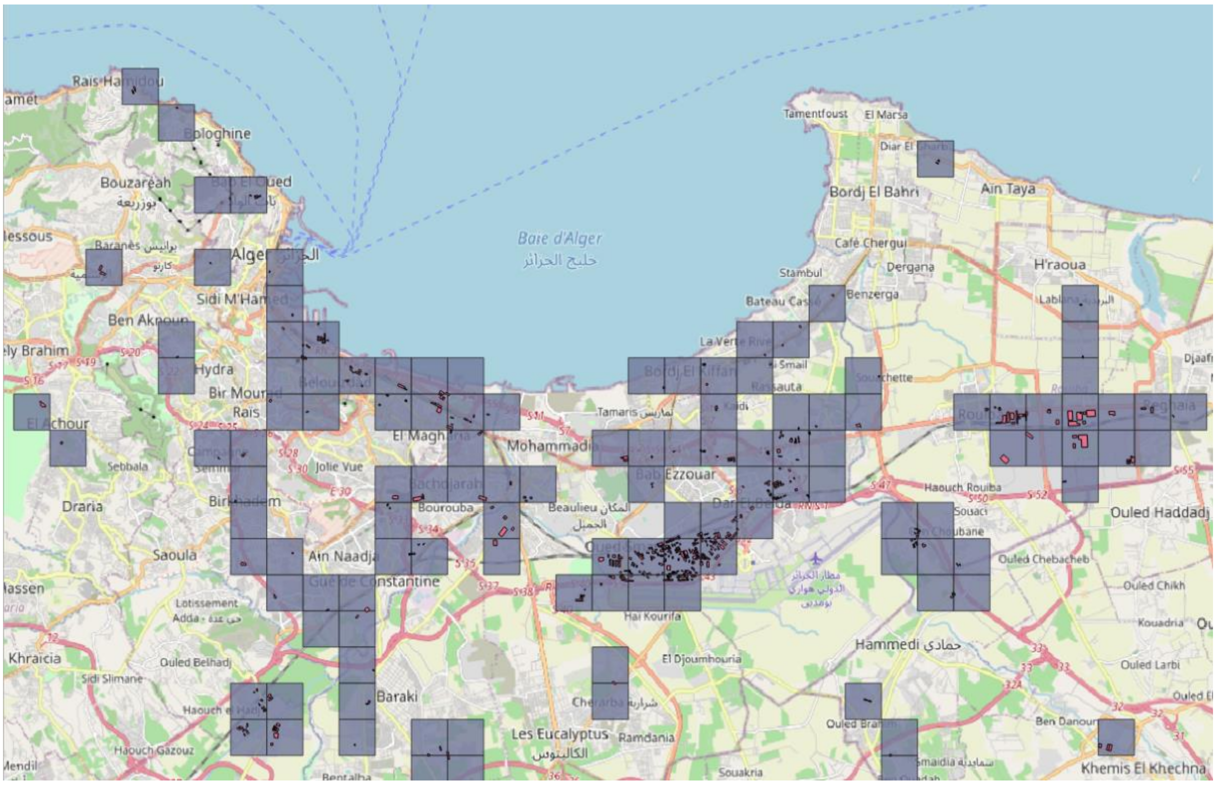


Figure 3: Industrial buildings (red) within 1km x 1km grid cells (grey) in Algir (ZAE Bayern, 2022)

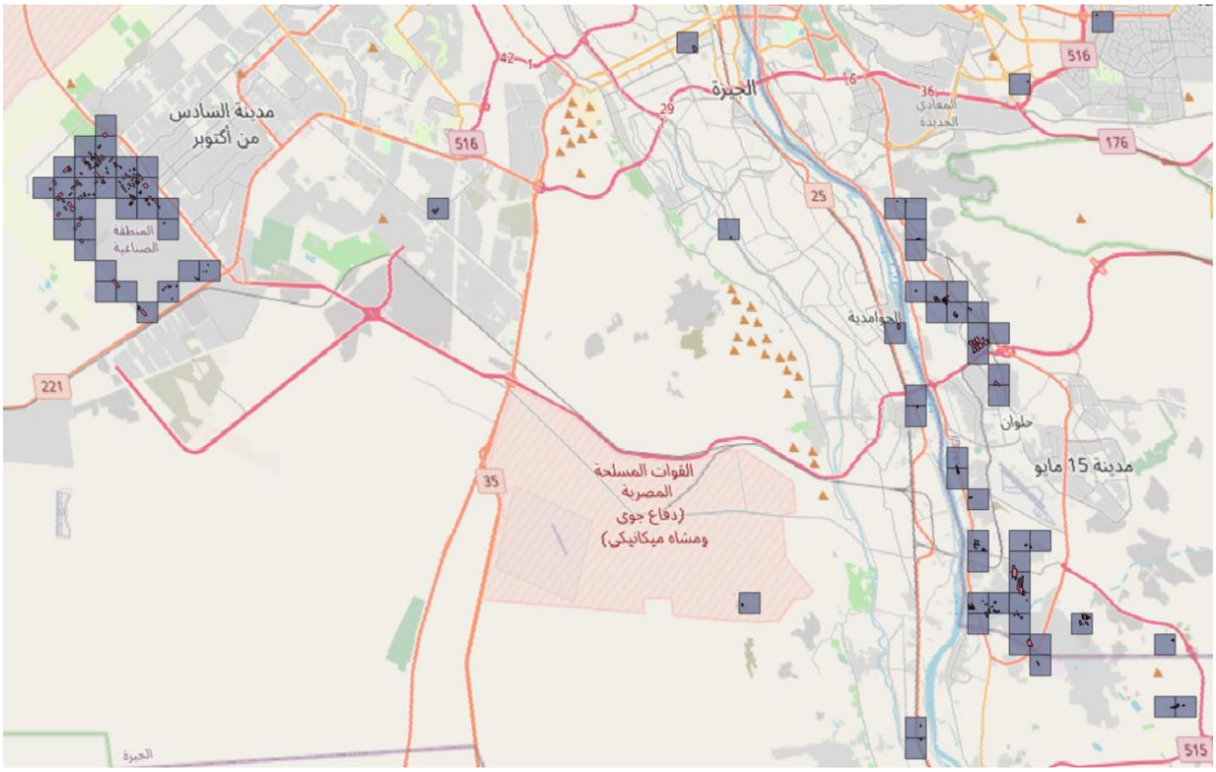


Figure 4: Industrial buildings (red) within 1km x 1km grid cells (grey) in Kairo (cut-out) (ZAE Bayern, 2022)

2.1.5 Climate Zones

Cooling for buildings is probably the best known and most widely used cooling application besides industrial process cooling. Geographic locations with a probably high demand for building cooling can be delimited and qualified by the use of climate zones. The availability of climate data is the key to a successful analysis to this end. Köppen-Geiger (Beck, 2018) have defined the so-called Köppen-Geiger climate zones with the intention to provide a classification system with prevalent major climate conditions.

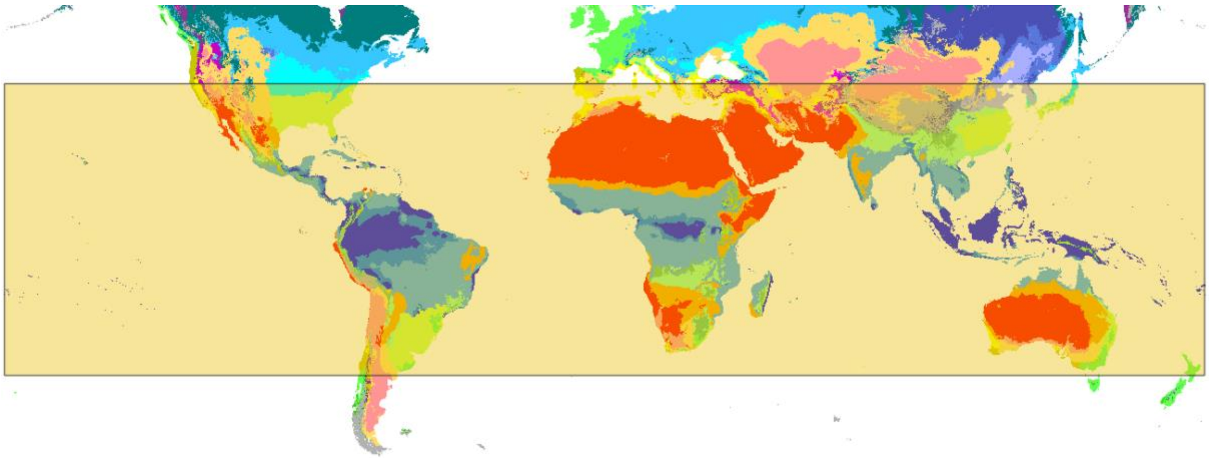


Figure 5: World map showing the various climates according to Köppen-Geiger with the area between 48°N and 44°S marked in yellow (Beck, 2018)

The Köppen-Geiger (KG) classification scheme covers the full range of climate conditions and realities on the planet (Table 3). Climate zones relevant for cooling applications must been identified and selected. Some classes may remain in doubt as they could not yet clearly be assigned to whether or not that climate might require relevant amount of cooling.

Table 3: List of the climate classes according to Köppen-Geiger (KG)

Color	KG class	KG description	KG abbreviation
	1	Tropical, rainforest	Af
	2	Tropical, monsoon	Am
	3	Tropical, savannah	Aw
	4	Arid, desert, hot	BWh
	5	Arid, desert, cold	BWk
	6	Arid, steppe, hot	BSh
	7	Arid, steppe, cold	BSk
	8	Temperate, dry summer, hot summer	Csa
	9	Temperate, dry summer, warm summer	Csb
	10	Temperate, dry summer, cold summer	Csc
	11	Temperate, dry winter, hot summer	Cwa
	12	Temperate, dry winter, warm summer	Cwb
	13	Temperate, dry winter, cold summer	Cwc
	14	Temperate, no dry season, hot summer	Cfa
	15	Temperate, no dry season, warm summer	Cfb
	16	Temperate, no dry season, cold summer	Cfc
	17	Cold, dry summer, hot summer	Dsa
	18	Cold, dry summer, warm summer	Dsb
	19	Cold, dry summer, cold summer	Dsc
	20	Cold, dry summer, very cold winter	Dsd
	21	Cold, dry winter, hot summer	Dwa
	22	Cold, dry winter, warm summer	Dwb
	23	Cold, dry winter, cold summer	Dwc
	24	Cold, dry winter, very cold winter	Dwd
	25	Cold, no dry season, hot summer	Dfa
	26	Cold, no dry season, warm summer	Dfb
	27	Cold, no dry season, cold summer	Dfc
	28	Cold, no dry season, very cold winter	Dfd
	29	Polar, tundra	ET
	30	Polar, frost	EF

2.1.6 Water Availability for Cooling Applications

Another important consideration is the local water demand as cooling systems often require a wet cooling tower for efficiency and/or for system availability at all conditions. The World Resources Institute (WRI) Markets and Enterprise Program developed the Aqueduct Water Risk Atlas, a comprehensive and publicly available global database and interactive mapping tool that provides information on water-related risks worldwide. The Aqueduct Water Risk Atlas provides a set of indicators that capture a wide range of variables, and aggregates them into comprehensive scores using the Water Risk Framework. To evaluate water availability the Baseline Water Stress data (BWS) and additionally the market risk indicator (RRI) from the Aqueduct water risk framework are used in this work (Hofste, 2019). The code, data and methodology behind Aqueduct are documented and available for download. All the products, methodologies and datasets that make up Aqueduct are available for use under the Creative Commons Attribution International 4.0 License.

2.1.6.1 Baseline Water Stress (BWS)

The aqueduct water risk framework defines Baseline Water Stress to measure the ratio of total water withdrawals to available renewable surface and groundwater supplies. Water withdrawals include domestic, industrial, irrigation, and livestock consumptive and non-consumptive uses. Available renewable water supplies include the impact of upstream consumptive water users and large dams on downstream water availability. Higher values indicate more competition among users.

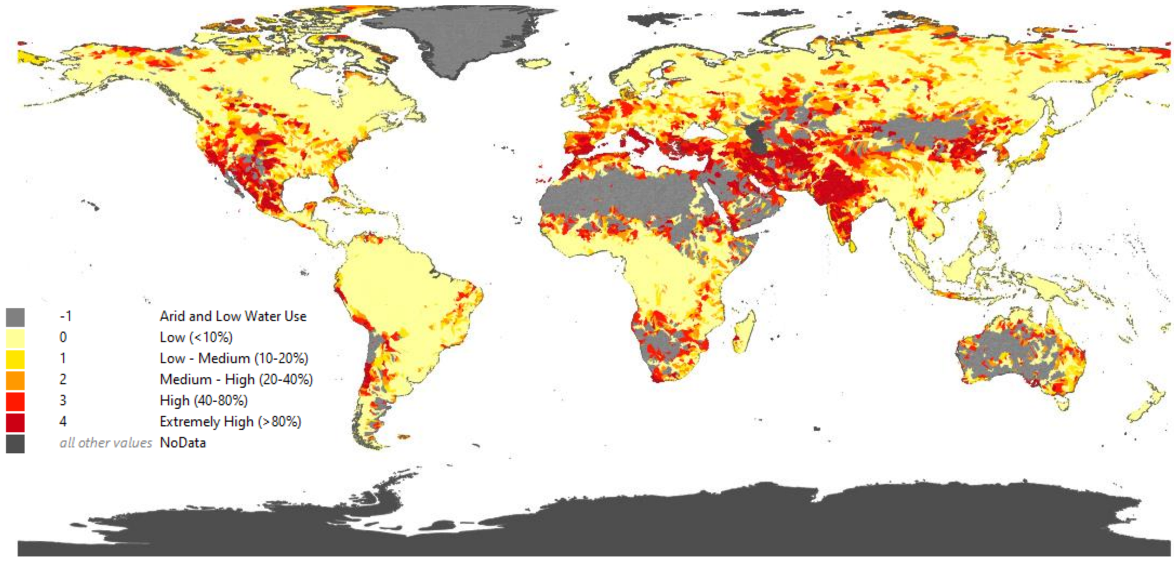


Figure 6: World map showing the distribution of the Baseline Water Stress (BWS) according to the Aqueduct database (Hofste, 2019)

2.1.7 Market Risk Covered by Environmental Social Governance (ESG)

When identifying locations where to set up a solar cooling system the investment should be safe and secure. This refers not only in a technological sense to an expected and safe system's cooling energy output but also in a political and environmental sense including sociopolitical stability and the access to required resources.

To identify regions that provide security for infrastructural investments and that do not constitute a high risk regarding financial, reputational and compliance issues, such as human rights violations and environmental destruction the Reputational Risk Index (RRI) is used by this project. It quantifies business conduct risk exposure related to environmental, social, and governance (ESG) issues in the corresponding country.

The Reputational Risk Index (RRI) is also included in the Aqueduct (Hofste, 2019) water risk framework which in turn originates from the Peak RepRisk country ESG risk index as an external source.

The peak value equals the highest level of the index in a given country over the last two years. The higher the value, the higher the risk exposure.

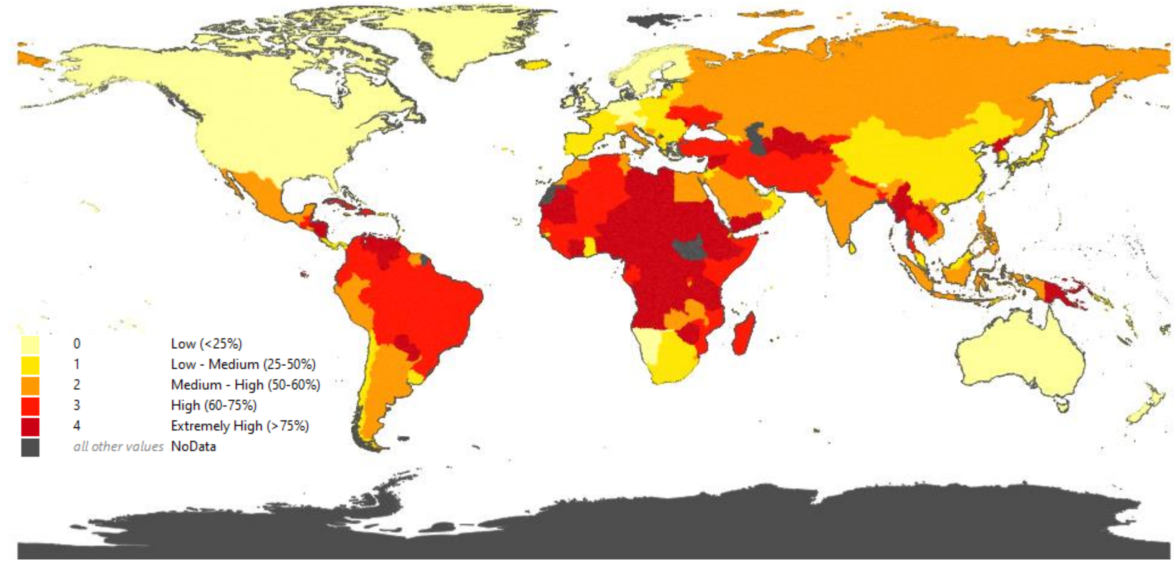


Figure 7: World map showing the distribution of the Reputational Risk Index (RRI) according to the Aqueduct database (Hofste, 2019)

2.1.8 Gross Domestic Product

Another aspect to consider is whether the regions of potential cooling demand are able to generate the financial power for solar cooling systems. This question has been addressed by considering the purchasing power parity also known as the gross domestic product (GDP) per capita.

A dataset with a resolution of 5 arc minutes for the period 1990-2015 was used to describe the gross domestic product (GDP) (Kummu, Dryad Digital Repository, 2017). The sub-national data was only used indirectly, scaling the reported national value and thus, remaining representative of the official statistics. This work is licensed under a CC0 1.0 Universal (CC0 1.0) Public Domain Dedication license. The GDP value classification shown in Figure 8 is used.

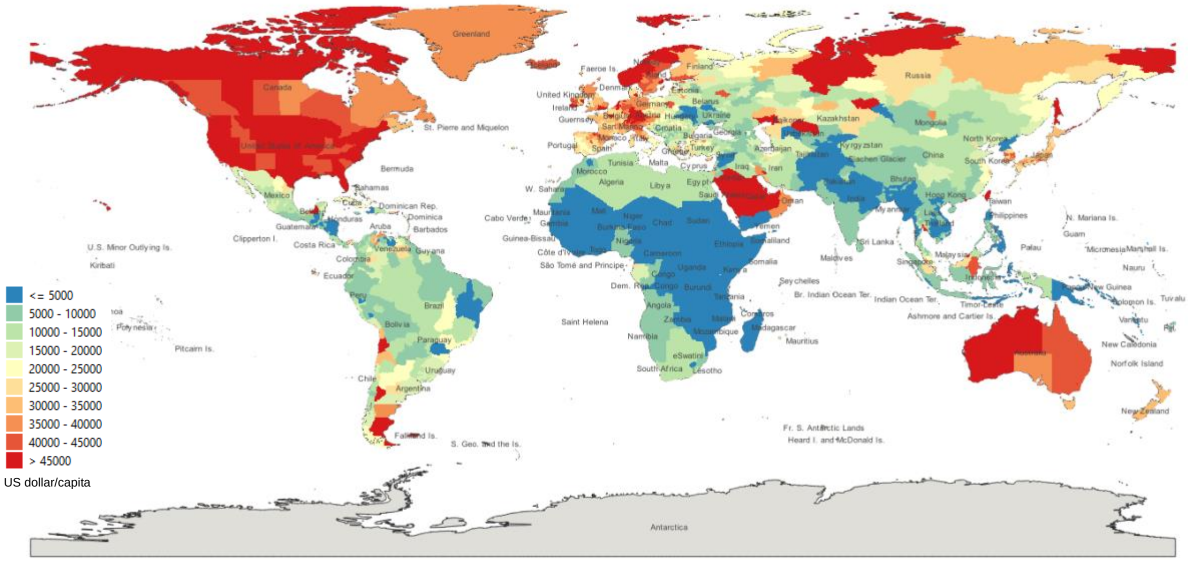


Figure 8: World map showing the distribution of the gross domestic product (GDP) per capita according to (Kummu, Dryad Digital Repository, 2017)

2.1.9 Further and Future Sources

The database used allows fundamental statements about the boundary conditions (technical and market) and about potentials that solar cooling systems will find in the SunBelt region. However, it is difficult to make more in-depth statements about e.g. profitability, applications and localization with the database available today.

For example, for future work it would be very helpful to have better information about the cooling demand. At the moment the method identifies relevant regions for cooling applications based on climate zones (Figure 9) for which a high demand for cooling is very likely. More precise information about the amount and location of the cooling demand is not available yet. This could be derived and compared by using the number of cooling degree days (CDD). They are calculated as a sum of daily temperature differences between the local exterior temperature and the average room temperature. According to the current state of knowledge, uniformly calculated CCDs worldwide are currently not available and would first have to be collected or created for future work.

By using data on purchasing power, initial statements about market potential can be made. Information on regional energy prices is essential for assessing the economics of solar cooling systems in the Sunbelt region in more detail in the future. At the time the work was carried out, however, no freely accessible data on energy prices were available. The need for cooling is currently being localized using data on industrial locations (OSM) and population density. The OpenStreetMap (OSM) data used enables a detailed analysis of building use such as residential, commercial, hospital, university, etc. However, due to the limited time, the data could not be considered and should be included in future work.

2.2 Combination of the Different Data Source

This section is to address the evaluation of the aforementioned various data sources and presents the methodology for identifying boundary conditions and how to find locations where solar cooling systems are favorable and where market potentials exists. The grid base from the population and settlement model data source (1km x 1km grid area) has been used as standard. The data of all the other various sources have been sampled using this grid and have then gradually been combined and filtered using a Geographic Information System Software (QGIS). The filter can be selected individually. The results can be processed by non-spatial tools. As result by default statistics of population over GDP and industrial area over GDB are chosen as it can be directly linked to cooling demand and market potential. Furthermore a map representation is available about these results. Two different analyzes are available. The population data is used to determine the potential for building cooling and the data for industrial sites is used to determine the potential for cooling in an industrial context (air conditioning and/or process cooling). In the following tables the selectable filters can be regarded alongside with the available values and results.

Table 4: Selectable filter and their range for analyzing air conditioning potentials based on population data

Data source	**Filtered range**	
Köppen-Geiger climate classes	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 …	**Filter**
Direct Normal Irradiance [kWh/m²/year] (Global Horizontal Irradiation (GHI), Photovoltaic power potential (PVOUT))	0 1000 1500 2000 2500 3000 …	
Settlement Model classes	10 11 12 13 21 22 23 30	
Baseline Water Stress	-1 0 1 2 3 4	
Reputational Risk Index	0 1 2 3 4 5	
Gross Domestic Product (Map representation)	**Results**	
Population over Gross Domestic Product (Statistics representation)		

By applying a technology-specific selection of the filters potential locations of individual solar cooling systems can be determined. The illustrated data output is flexible and other previously selected data can be used as well. This flexibility of the methodology allows to identify general boundary conditions for solar cooling systems by setting the filters in an appropriate way. In addition, or instead of the data source *Direct Normal Irradiance* the data sources *PV output* and *Global Horizontal Irradiance* could be used for further analysis and evaluation.

Table 5: Selectable filter and their range for analyzing the potential for cooling in an industrial context based on industrial area data

Data source	**Filtered range**	
Köppen-Geiger climate classes	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 …	**Filter**
Direct Normal Irradiance [kWh/m²/year] (Global Horizontal Irradiation (GHI), Photovoltaic power potential (PVOUT))	0 1000 1500 2000 2500 3000 …	
Industrial area per building [m²]	0 ...	
Baseline Water Stress	-1 0 1 2 3 4	
Reputational Risk Index	0 1 2 3 4 5	
Gross Domestic Product (Map representation)	**Results**	
Industrial area over Gross Domestic Product (Statistics representation)		

3 Analysis and Results to Identify General Boundary Conditions for Solar Cooling Systems

The developed method was used to generate results to identify climatic conditions and general boundary conditions for solar cooling systems operating at climatic zones which are located in the Sunbelt region based on the available data base.

Due to the limited time available, the results are only presented below but not discussed and interpreted in detail. This is to be done later in the Task work.

3.1 Selected/Suitable/Appropriate Climate Zones

As relevant climate classes for solar cooling in general the classes 3,4,5,6,8,9,11,12 and 14 have been selected (Table 6 and Figure 9). For these classes, a high demand for cooling and suitable solar radiation is very likely.

Table 6: Selected climate classes (blue background) for solar cooling

Color	***KG class***	***KG description***	***KG abbreviation***
	1	Tropical, rainforest	Af
	2	Tropical, monsoon	Am
	3	Tropical, savannah	Aw
	4	Arid, desert, hot	BWh
	5	Arid, desert, cold	BWk
	6	Arid, steppe, hot	BSh
	7	Arid, steppe, cold	BSk
	8	Temperate, dry summer, hot summer	Csa
	9	Temperate, dry summer, warm summer	Csb
	10	Temperate, dry summer, cold summer	Csc
	11	Temperate, dry winter, hot summer	Cwa
	12	Temperate, dry winter, warm summer	Cwb
	13	Temperate, dry winter, cold summer	Cwc
	14	Temperate, no dry season, hot summer	Cfa
	15	Temperate, no dry season, warm summer	Cfb
	16	Temperate, no dry season, cold summer	Cfc
	17	Cold, dry summer, hot summer	Dsa
	18	Cold, dry summer, warm summer	Dsb
	19	Cold, dry summer, cold summer	Dsc
	20	Cold, dry summer, very cold winter	Dsd
	21	Cold, dry winter, hot summer	Dwa
	22	Cold, dry winter, warm summer	Dwb

In Figure 9 a world map showing the selected climate zones is illustrated. The selected areas representing a large part of the Sunbelt region.

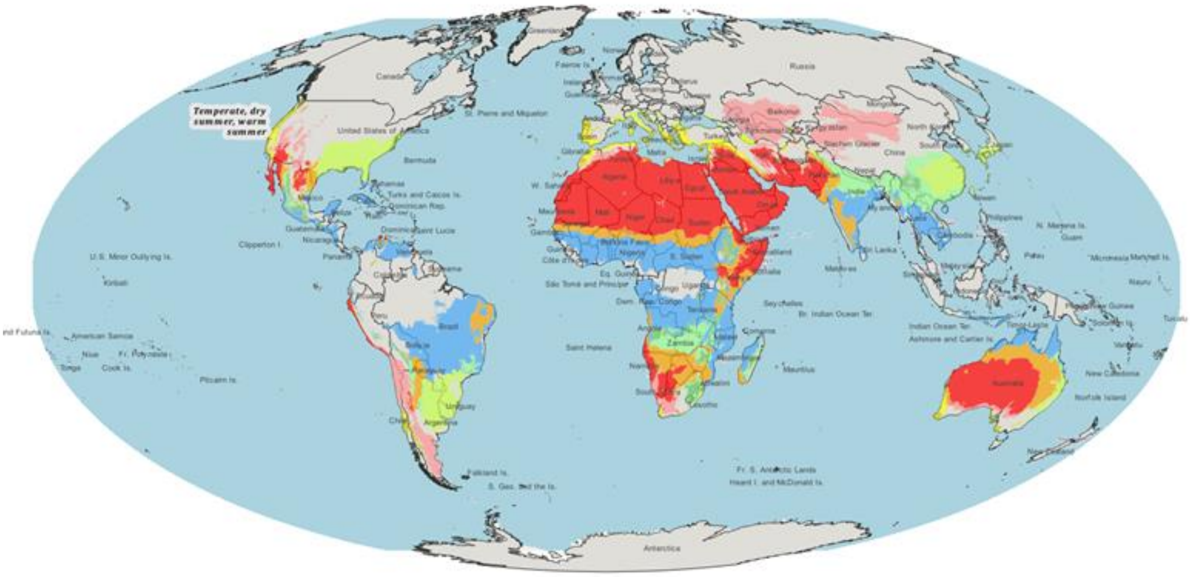


Figure 9: Illustration of the selected climate zones for solar cooling (ZAE Bayern, 2022)

For the population and industrial area based analysis no additional filter was set. The filters used and the results available in principle are listed in Table 7. Results are marked in gray that are not yet available but will be created and available promptly.

Table 7: Filter and population or industrial area based results of the analysis to identify general boundary conditions for solar cooling systems

Data source	**Filtered range**	
Köppen-Geiger climate classes	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 …	**Filter**
(Statistics representation) **Population** or **Industrial area** over • Climate classes • Direct Normal Irradiance [kWh/m²/year] • Global Horizontal Irradiation (GHI) • Photovoltaic power potential (PVOUT) • Gross Domestic Product • Settlement Model classes • Baseline Water Stress • Reputational Risk Index	**Results**	

3.2 Results

The results of the analysis are shown as numerical results within diagrams. Currently available are results with regard to climate zones and population/industrial area. Further results will be available in the final report of the SunBeltChiller project at the latest. From this can derived what conditions (climatic, economic, technical) solar cooling systems will be exposed to in the Sunbelt region. In addition, it is possible to evaluate the conditions quantitatively and thus with regard to their relevance. This helps to understand the reference boundary conditions for adaptation of the components and solar cooling systems and forms a base for future market potential studies on certain products / technologies. The results presented here form the basis for this work. The presented results show the current status of work. Further analyses can be carried out.

The figure below shows the distribution of the identified population (total 4.86 billion people) across the climate zones that are considered relevant for solar cooling in the SunBelt region. Accordingly, the focus is on the following climate zones:

- Tropical, savannah (Aw)
- Temperate, dry winter, hot summer (Cwa)
- Temperate, no dry season, hot summer (Cfa)

Around 80 percent of the total population considered lives in these three climate zones. Solar cooling systems to cover the cooling needs of the population should therefore be particularly adapted to the conditions of these climate zones.

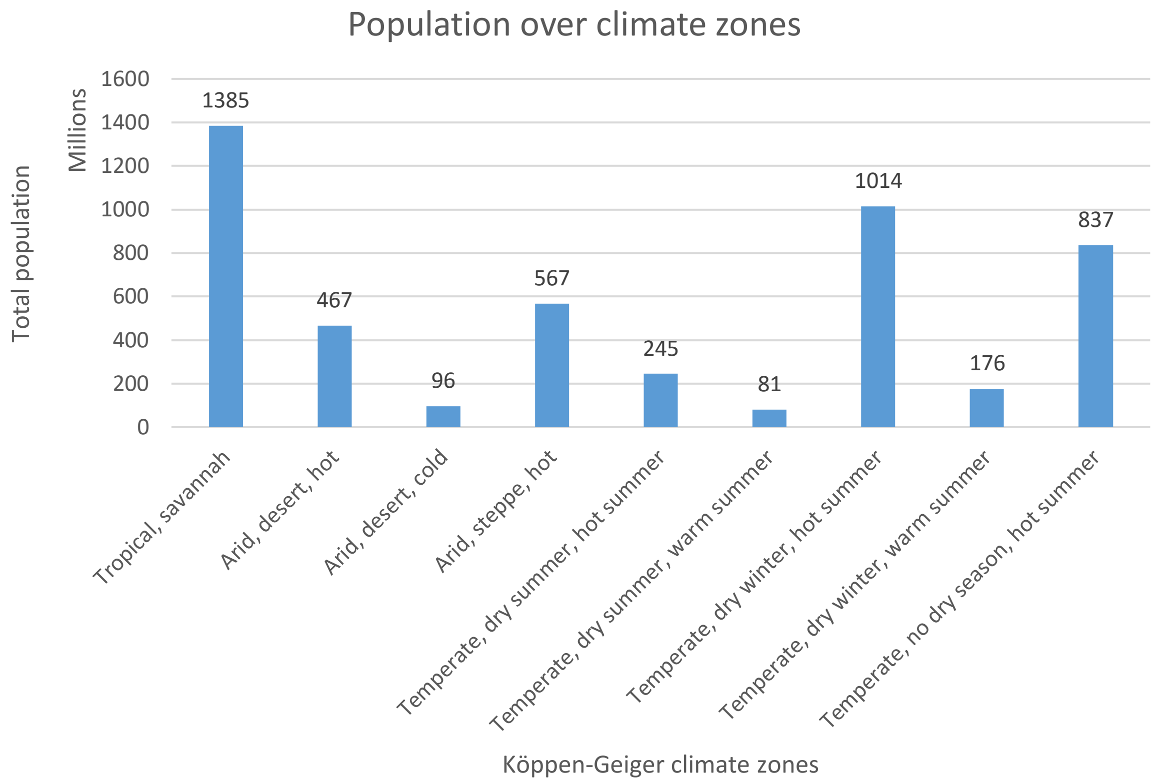


Figure 10: Results of the analysis for solar cooling systems with regard to population and climate zones (ZAE Bayern, 2022)

The figure below shows the distribution of the identified industrial area (total 1.2 billion m²) across the climate zones that are considered relevant for solar cooling in the SunBelt region. Accordingly, the focus is on the following climate zones:

- Temperate, no dry season, hot summer (Cfa)
- Temperate, dry summer, hot summer (Csa)

Around 70 percent of the total industrial area considered are in these two climate zones. Solar cooling systems to cover the cooling needs of the industry should therefore be particularly adapted to the conditions of these climate zones.

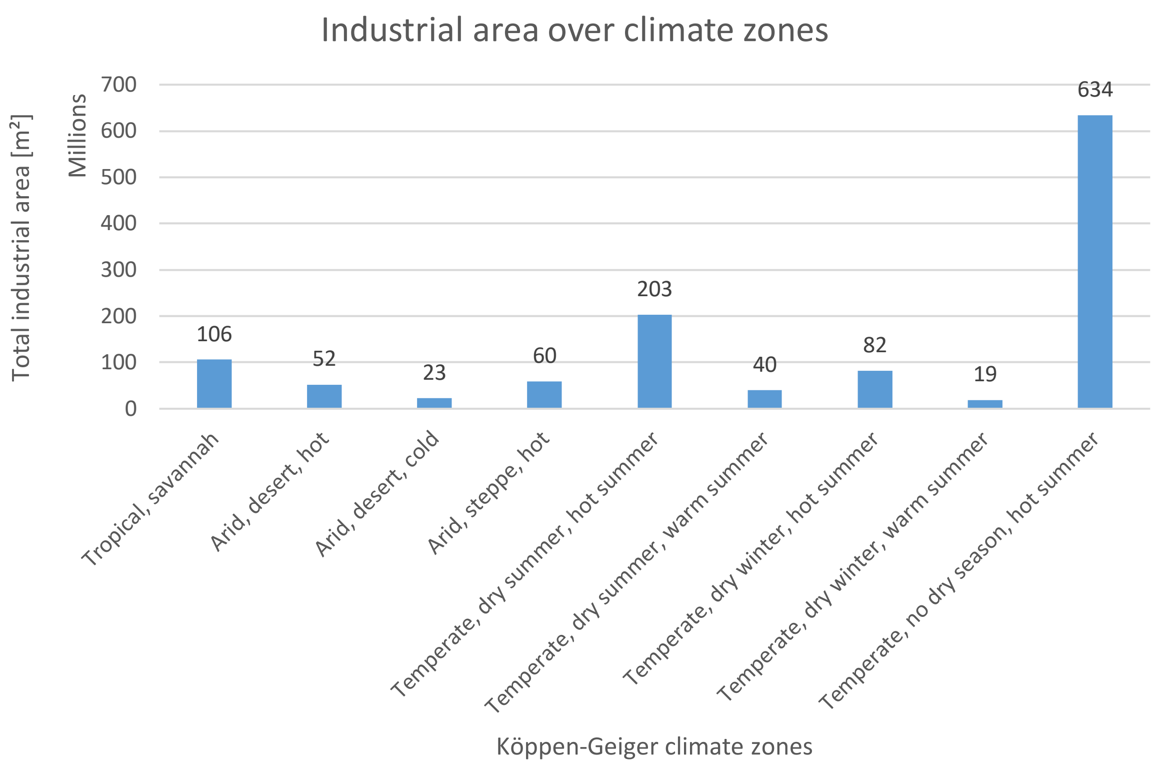


Figure 11: Results of the analysis for solar cooling systems with regard to industrial area and climate zones (ZAE Bayern, 2022)

4 Determination of Possible Locations and Potentials for the SunBeltChiller System as Application Examples

The results of the ongoing research project "Solar thermal energy system for cooling and process heating in the sunbelt region – SunBeltChiller (SBC)" have been included into this work. The project is carried out by two partners: Industrial Solar GmbH and the Bavarian Centre for Applied Energy Research (ZAE Bayern). It was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) under the project number 03ETW026. The developed method was used to determine possible locations and potentials for the SBC system as a first example. In the following the system and the results are presented. In the further course of the Task, the developed method can also be used to analyse other solar cooling systems.

4.1 SBC Cooling Technology

There are different ways of solar cooling. The most common and well-known variants are shown in *Table 8*. In addition, the SunBeltChiller is shown. It is powered by solar thermal energy and uses absorption technology to generate cold. A major challenge for all (solar) cooling systems are the ambient temperatures and the associated re-cooling conditions. The higher the re-cooling temperature, the lower the efficiency of a compression chiller or the lower the cooling capacity of an absorption chiller. If the re-cooling temperature is too high, the absorption chiller can no longer be operated.

Table 8: Different ways of Solar Cooling (ZAE Bayern, 2022)

CCh: Compression Chiller AbCh. AbsorptionChiller SE: Single Effect DE: Double Effect SE-DL: Single Effect / Double Lift	**Ambient temperature**	**PV + CCh**	**Solar thermal cooling**		
			AbCh SE	**AbCh DE**	**AbCh SE-DL**
System's efficiency of solar plant η		16%	55%	45%	45%
COP of chiller	25 °C	4,6	0,75	1,35	1,35
	35 °C	3,4			
Conversion efficiency „Sun to cold" = η·COP	25 °C	0,61	0,41	**0,61**	**0,61**
	35 °C	0,46	(0,41)	(0,61)	**0,61**

PV: mean. Module efficiency 20 %, Performance Ratio 80% (high amb. temp.), *Aktuelle Fakten zur Photovoltaik in Deutschland, FhG ISE, 2023, Current version available at www.pv-fakten.de.*
Solar thermal option: SE, flat plate collectors at 90° C, DE: concentrating systeme at 180°C (e.g. Fresnel)
COP of CCh: Carnot-COP at 5° C cold water und resp. Ambient temp. , internal temperatures each 5 K cat, Carnot-efficiency x 50 %

This problem can be solved or at least reduced by using a wet cooling tower. The disadvantage of this re-cooling technology is the high water consumption. Wet cooling towers can therefore not be used (or only to a very limited extent and at high cost) in regions with water shortages. Furthermore wet cooling towers by design only work to a limited extent at high humidity. This means that solar cooling systems using absorption chillers can only be used to a very limited extent in warm regions with a lack of water or high humidity. Solar cooling systems with compression chillers are less efficient in these regions.

The SunBelt Chiller (SBC) solar cooling system offers a solution to this problem. The SBC is powered by concentrating solar collectors at temperatures higher than 160° C. In the first step, the solar collectors drive a special absorption chiller called Double Lift (DL) machine which can be re-cooled at very high temperatures (approx. 90° C). In the second step, the waste heat from the DL machine drives a "classic" single effect (SE) absorption chiller, which is re-cooled against the ambience. The overall efficiency of these two steps is equivalent to a Double Effect (DE) absorption chiller (Figure 12).

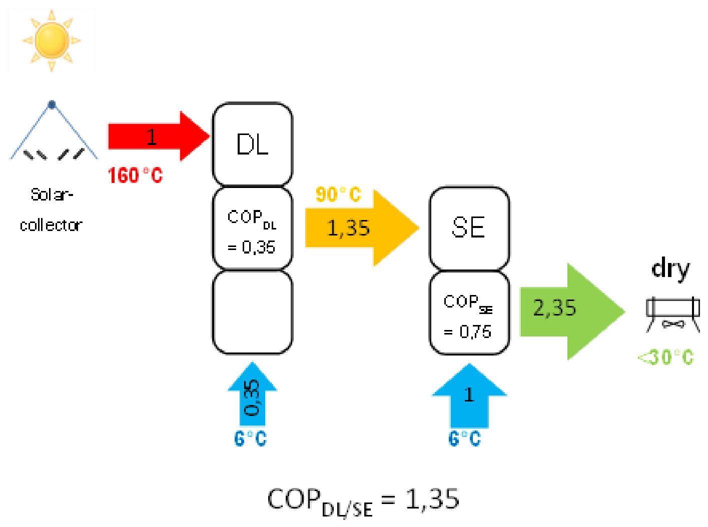


Figure 12: SunBeltChiller: A combination of a double lift and a single effect chiller (ZAE Bayern, 2022)

Thanks to the two-stage generation of cold and by using heat and cold storages, the operation of the Single Effect can be shifted to the night hours and thus to periods with lower outside temperatures. This eliminates the need for a wet cooling tower. In addition, the SunBeltChiller system can provide additional heat at around 90° C (Figure 13).

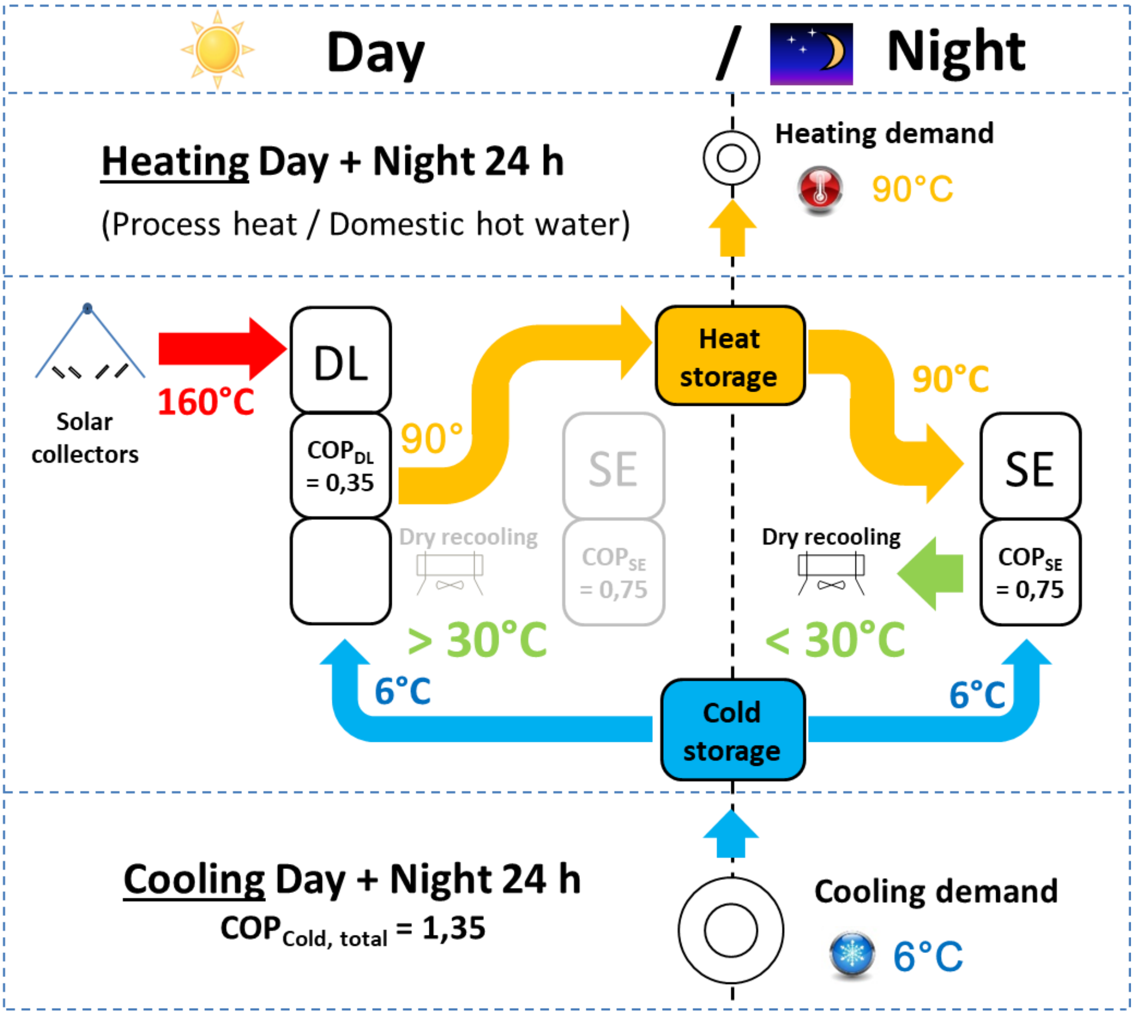


Figure 13: The SunBeltChiller System (ZAE Bayern, 2022)

The SunBeltChiller is therefore a solar thermal cooling (and heating) system that, despite high ambient temperatures, does not require a wet cooling tower and promises high efficiency.

4.2 Application of the Method on SBC

In the following the results of the analysis of possible locations and potentials of the SunBeltChiller system are presented. Two different analyses were carried out. The population data was used to determine the potential for building cooling and the data for industrial sites was used to determine the potential for cooling in an industrial context (air conditioning and/or process cooling). In the first step, the specific boundary conditions for both analyses are determined and based on this, the filter for the application of the developed method is defined. As result population over GDP and industrial area over GDP are chosen as it can be directly linked to cooling demand and market potential. Furthermore a map representation about the result is shown.

4.2.1 Boundary Conditions and Filter Definition

4.2.1.1 Selected/Suitable/Appropriate Climate Zones

Additional to climate zones described in 3.1 the climate zones 1, 2 and were considered (Table 9 and Figure 14).

Table 9: Selected climate classes (blue background) for the SunBeltChiller

Color	KG class	KG description	KG abbreviation
	1	Tropical, rainforest	Af
	2	Tropical, monsoon	Am
	3	Tropical, savannah	Aw
	4	Arid, desert, hot	BWh
	5	Arid, desert, cold	BWk
	6	Arid, steppe, hot	BSh
	7	Arid, steppe, cold	BSk
	8	Temperate, dry summer, hot summer	Csa
	9	Temperate, dry summer, warm summer	Csb
	10	Temperate, dry summer, cold summer	Csc
	11	Temperate, dry winter, hot summer	Cwa
	12	Temperate, dry winter, warm summer	Cwb
	13	Temperate, dry winter, cold summer	Cwc
	14	Temperate, no dry season, hot summer	Cfa
	15	Temperate, no dry season, warm summer	Cfb
	16	Temperate, no dry season, cold summer	Cfc
	17	Cold, dry summer, hot summer	Dsa
	18	Cold, dry summer, warm summer	Dsb
	19	Cold, dry summer, cold summer	Dsc
	20	Cold, dry summer, very cold winter	Dsd
	21	Cold, dry winter, hot summer	Dwa
	22	Cold, dry winter, warm summer	Dwb
	23	Cold, dry winter, cold summer	Dwc
	24	Cold, dry winter, very cold winter	Dwd
	25	Cold, no dry season, hot summer	Dfa
	26	Cold, no dry season, warm summer	Dfb
	27	Cold, no dry season, cold summer	Dfc
	28	Cold, no dry season, very cold winter	Dfd
	29	Polar, tundra	ET
	30	Polar, frost	EF

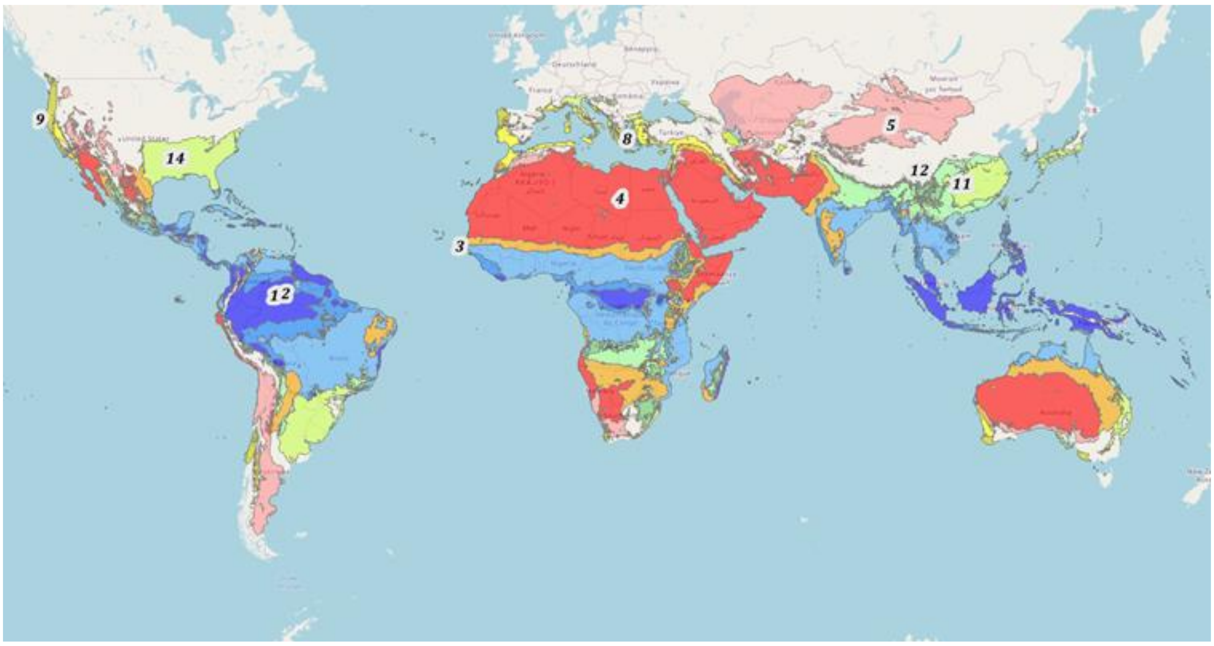


Figure 14: Illustration of the selected climate zones for the SunBeltChiller system (ZAE Bayern, 2022)

4.2.1.2 Solar Irradiance

The SunBeltChiller system uses concentrating solar panels, which can only be operated economically in regions with direct solar radiation of more than 1,500 kWh/m² per year. Therefore, the corresponding filter was set to a minimum value of 1,500 kWh/m² per year.

4.2.1.3 Population Density (Settlement Categories) and Industrial Areas

The SunBeltChiller system is designed for high cooling demands. Accordingly, large open spaces or larger contiguous roof areas are necessary for a cost-efficient installation of the solar collectors. For climatization purposes these conditions can most likely be met in either less populated areas or medium to highly populated areas. In very densely populated areas (urban centers) there are often high-rise buildings that are unsuitable for the use of the SunBeltChiller. Likewise, an application in very sparsely populated areas is ruled out due to the presumably low demand for cold.

Table 10: Selected Settlement classes (SMOD) in blue

SMOD class id	SMOD class description
11	Very low density rural
12	Low Density Rural
13	Rural cluster
21	Suburban
22	Semi-dense Urban Cluster
23	Dense Urban Cluster
30	Urban Centre grid cell

For the same reasons as above within the analysis of the potential for cooling demand in the industry only industrial buildings larger than 1,000 m² were considered.

4.2.1.4 Water (Un)Availability

Since the SunBeltChiller does not require a wet cooling tower despite the high ambient temperatures, it is ideal for hot and dry regions. The Baseline Water Stress (BWS) level is used to identify regions that cannot rely on readily available water resources in general. The BWS is classified into six categories by the Aqueduct Water Risk Framework. This scheme is also used as a filter. From these categories, the classes "High" to "Arid" and low water use" (3, 4 and -1) were selected for both analyses.

Table 11: Selected Baseline Water Stress (BWS) levels on blue background

BWS value	*Class name*
0	Low
1	Low-medium
2	Medium-high
3	High
4	Extremely high
-1	Arid and low water use

4.2.1.5 Market Risk

Investors into a SBC system will most likely tend to invest into stable countries with well enough ESG criteria. For the reputational risk levels up to “medium-high” are considered for both analyses.

Table 12: Selected reputational risk levels (RRI) on blue background

RRI value	***Classification***
<=1	Low
<=2	Low-medium
<=3	Medium-high
<=4	High
<=5	Extremely high

4.2.1.6 Filter Definition

Table 13: SBC specific filter classes for analyzing the potential for building cooling

Data source	**Filtered range**	
Köppen-Geiger climate classes	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 …	**Filter**
Direct Normal Irradiance [kWh/m^2/year]	0 1000 1500 2000 2500 3000 …	
Settlement Model classes	10 11 12 13 21 22 23 30	
Baseline Water Stress	-1 0 1 2 3 4	
Reputational Risk Index	0 1 2 3 4 5	
Gross Domestic Product (Map representation)	**Results**	
Population over Gross Domestic Product (Statistics representation)		

Table 14: SBC specific selected filter classes for analyzing potential for cooling in an industrial context

Data source	**Filtered range**	
Köppen-Geiger climate classes	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 …	**Filter**
Direct Normal Irradiance [kWh/m^2/year]	0 1000 1500 2000 2500 3000 …	
Industrial area per building [m^2]	>1000	
Baseline Water Stress	-1 0 1 2 3 4	
Reputational Risk Index	0 1 2 3 4 5	
Gross Domestic Product (Map representation)	**Results**	
Industrial area over Gross Domestic Product (Statistics representation)		

4.2.2 Graphical and Numerical Results

Numerical and graphical results of the analysis of the potential for air conditioning and cooling in an industrial context (air conditioning and/or process cooling) is shown in this chapter and shortly discussed. Due to the limited time available, no further results could be presented. It is planned to make up for this in the further course of the Task.

4.2.2.1 Numerical Results

Above in Figure 15 and Figure 16 the results of the two different analyses are presented. To make a statement about the potentials of the SBC for building cooling the total population over GDP is shown in Figure 15. According to this, around 430 million people live in regions where the SunBeltChiller can potentially be used. The distribution of the GDP is very uneven. A very low potential for SBC exists where a GDP between 15,000 and 45,000 US dollars per capita is produced. Higher potential for the SBC exists for people (approx. 45 million) with a GDP over 45,000 US dollars per capita. The vast majority of people (approx. 300 million) for whom the SunBeltChiller is potentially useful have a GDP below 15,000 US dollars per capita, with a third even below 5,000 US dollars per capita.

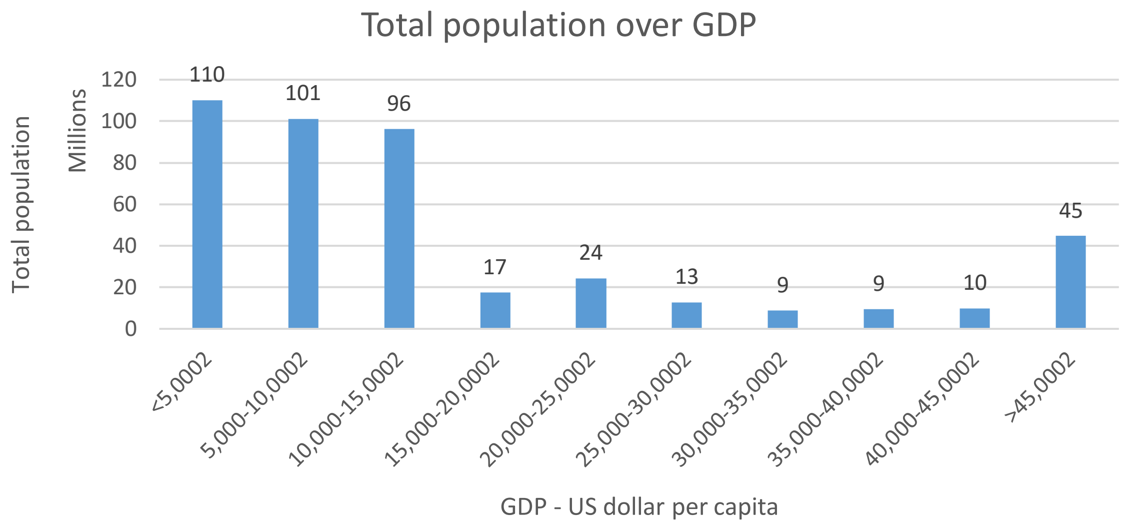


Figure 15: Results of the analysis of the SBC potentials for building cooling based on Population and GDP (ZAE Bayern, 2022)

The potential for the SunBeltChiller for building cooling is therefore considerable. However, most potential users most likely lack the financial resources at the moment. Nevertheless, there is potentially already a smaller but very solvent market today. Both these findings are important insights for future marketing and funding strategies.

The potentials of the SBC for cooling in an industrial context (air conditioning and/or process cooling) is presented in Figure 16. Shown is the total industrial area in square meters over the GDP.

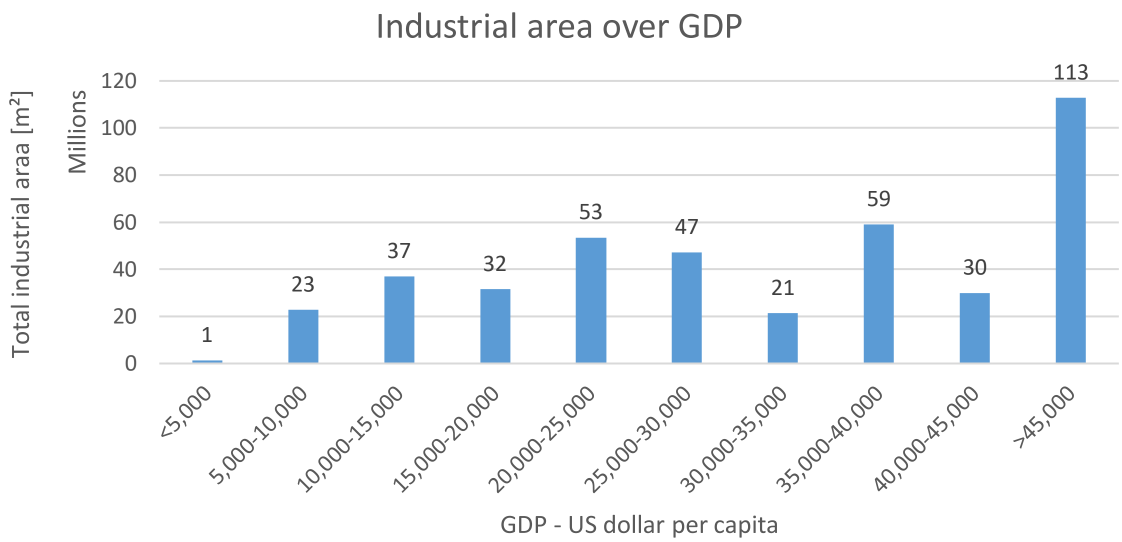


Figure 16: Results of the analysis of the SBC potentials for cooling in an industrial context based in industrial area and GDP (ZAE Bayern, 2022)

According to this, around 420 million square meters of industrial area can potentially be used for SBC cooling. Over 100 million square meters are in regions with a GDP of over 45,000 US dollars per capita. Another 150 million square meters in regions with a GDP from 25,000 to 45,000 US dollars per capita. From this it can finally be concluded that there is already considerable market potential for the SBC to provide cooling in an industrial context.

4.2.2.2 Graphical Results

In addition to a numerical view of the results, a graphical evaluation of the results is just as important. The identified potential for building cooling have been depicted on a world map (Figure 14). The figure shows the cells colored according to the level of the GDP, in which the use of the SBC seems potentially possible. Due to the limited space and the low resolution the locations are not well recognizable. Larger agglomerations can be detected, for detailed single locations cut-outs need to be made. Further below exemplary cut-outs of the Mediterranean and African Regions are also presented.

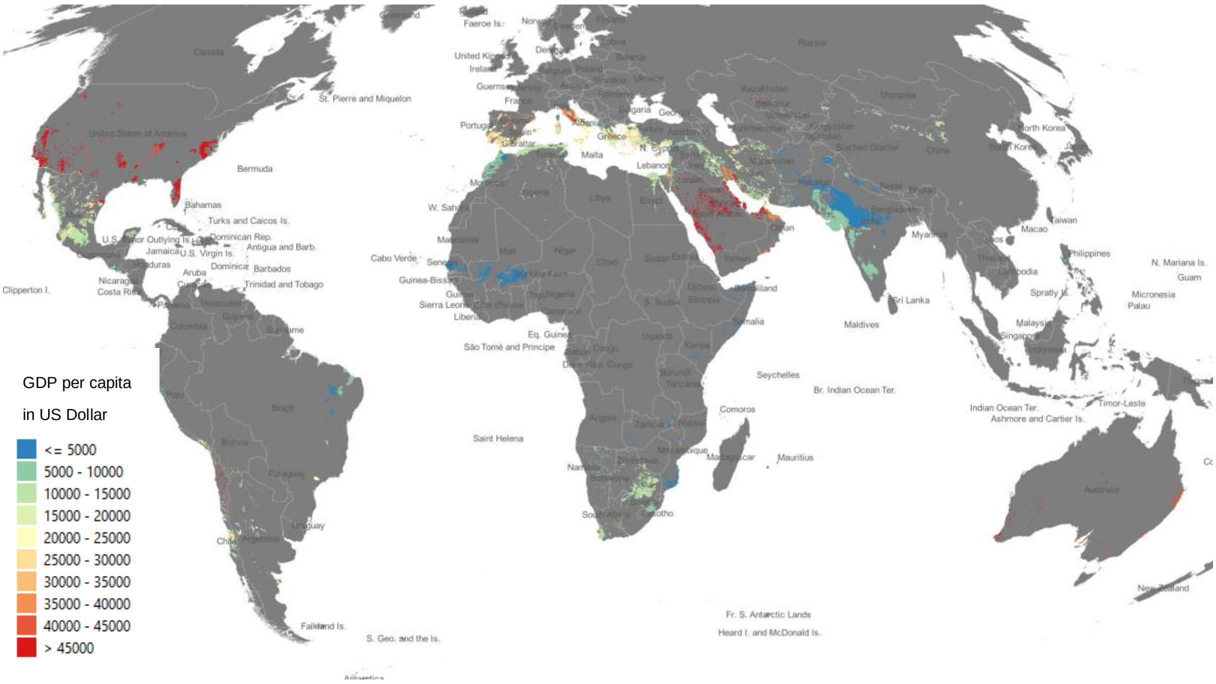


Figure 17: World map identifying SBC potential for air conditioning in a 10km raster grid considering the level of the GDP (ZAE Bayern, 2022); a high resolution map is found in the annex.

It is easy to see that there are potentially more places for building cooling than for cooling in the industrial context, especially in Africa. On the one hand, this is due to the locally lower economic output of the selected region, but also to the fundamentally small number of industrial buildings compared to residential buildings. Nevertheless, the graphical evaluation is very well suited to localizing potential locations and markets.

4.2.2.3 World Map Cut-Outs for Identifying SBC Potentials for Building Cooling

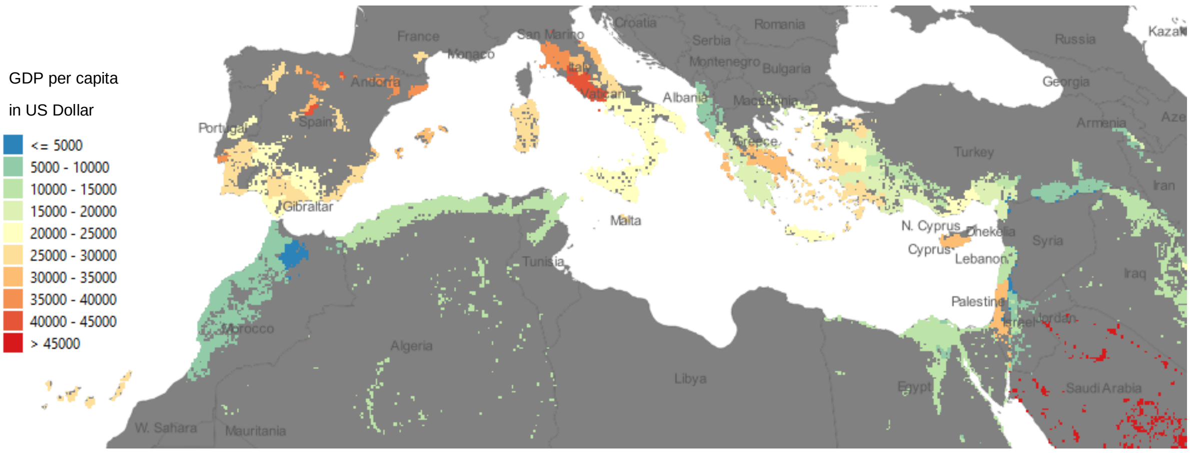


Figure 18: World map cut-out (Mediterranean) for identifying SBC potential for building cooling in a 10km raster grid considering the level of the GDP (ZAE Bayern, 2022); a high resolution map is found in the annex.

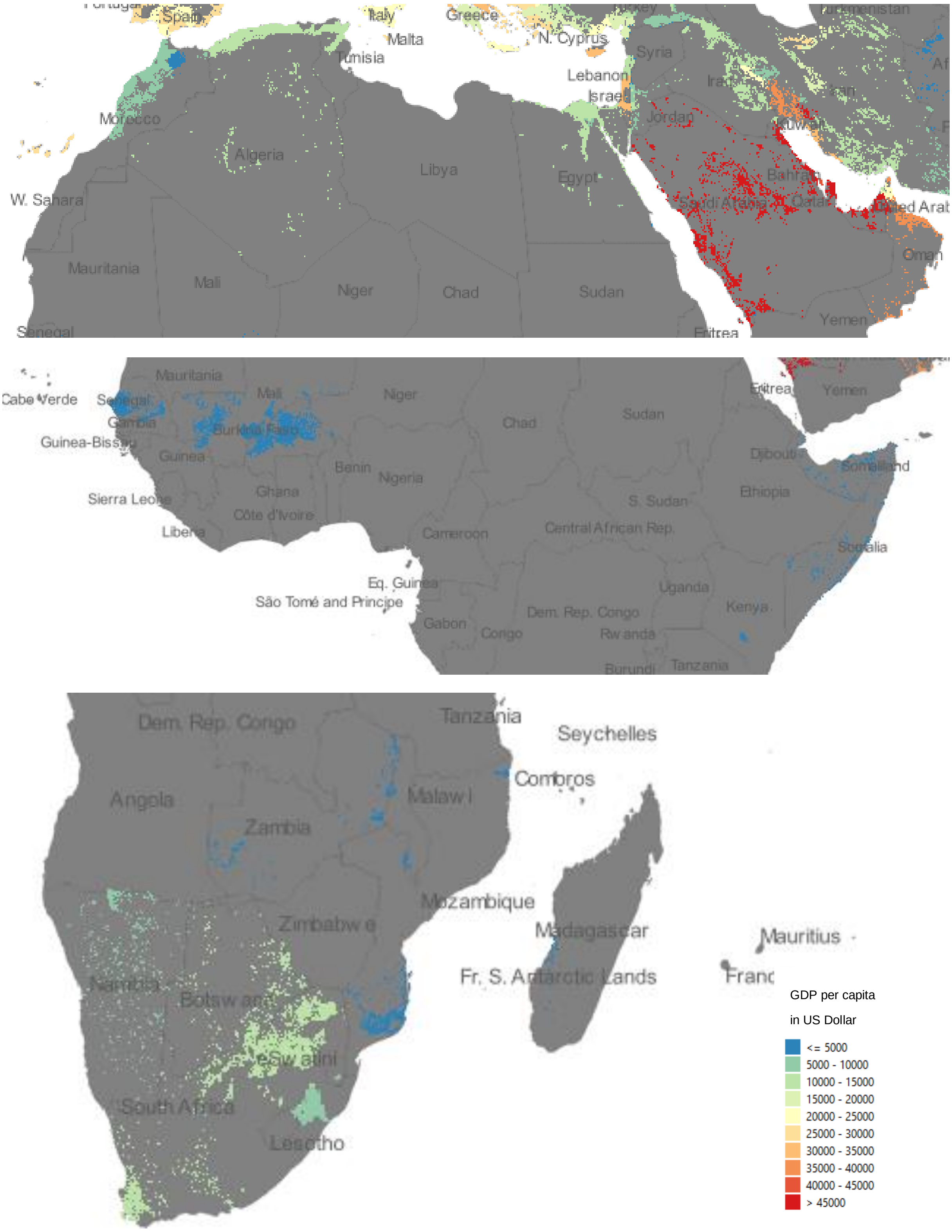


Figure 19: World map cut-out (Africa) for identifying SBC potential for building cooling considering the level of the GDP (ZAE Bayern, 2022)

4.2.2.4 World Map Cutouts for Identifying SBC Industrial Cooling Potentials

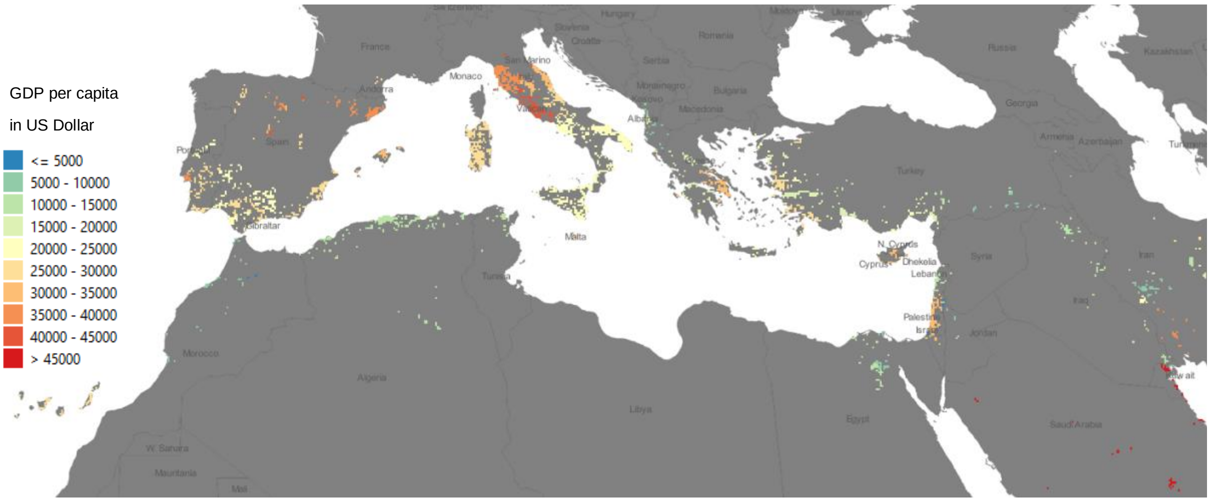


Figure 20: World map cut-out (Mediterranean) for identifying SBC industrial cooling potential in a 10 km raster grid considering the level of the GDP (ZAE Bayern, 2022); a high resolution world map is found in the annex.

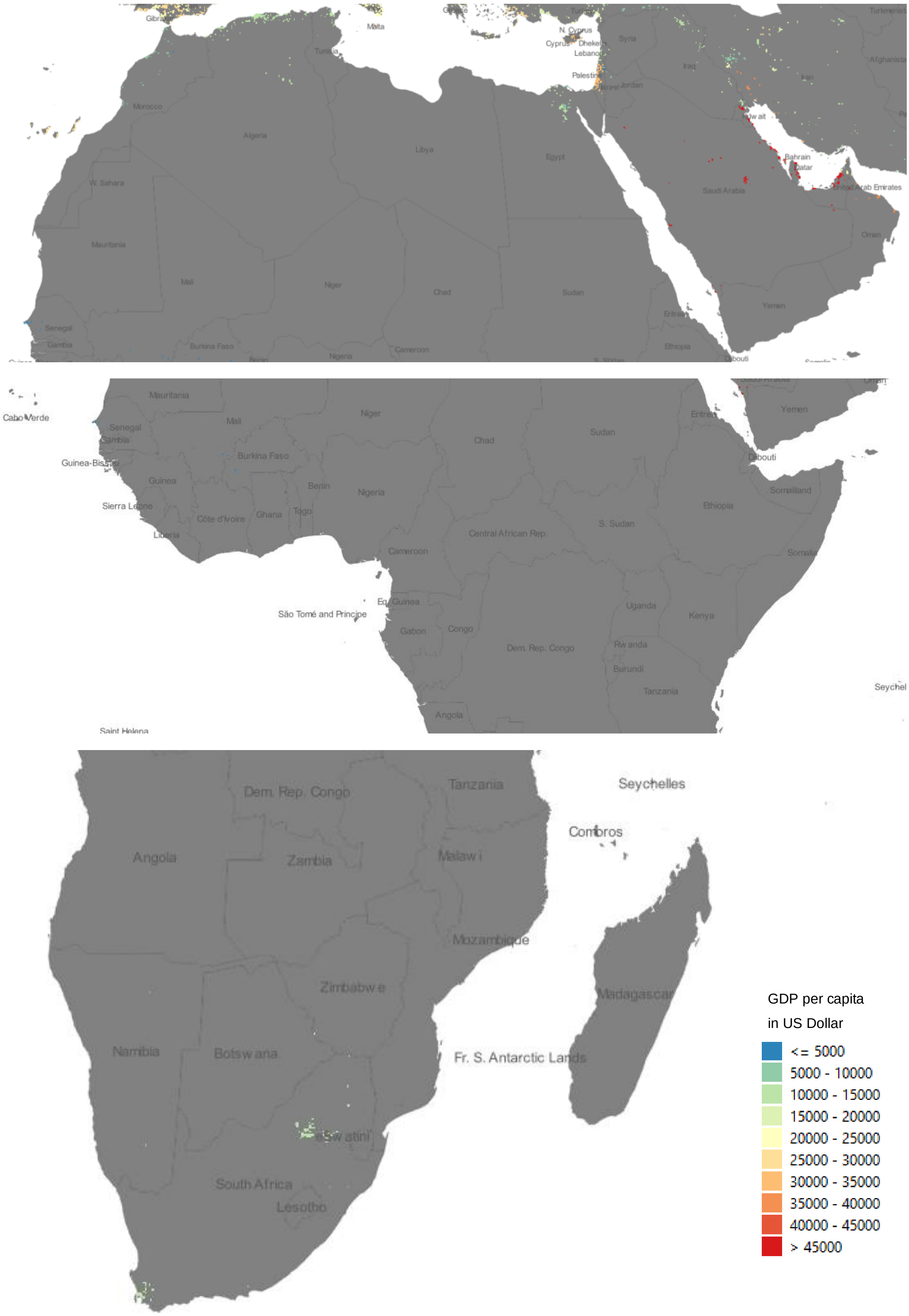


Figure 21: World map cut-out (Afrika) for identifying SBC industrial cooling potential considering the level of the GDP (ZAE Bayern, 2022)

5 Conclusions and Prospect for Further Investigation

In activity A1 a GIS software was used to combine geographic data in a way that climatic conditions and local reference boundary conditions for solar cooling systems in the Sunbelt regions can be determined. The developed method can also be used to identify possible locations and potentials of specific solar cooling systems. By additionally using for example purchase power data a base for future market potential studies on certain products / technologies is provided. As a result, potential sites can be identified, and economic factors can be considered in order to identify (future) markets.

In the first step general climatic conditions were identified based on climate zones. Around 80 percent of the identified population and 70 percent of the identified industry were located at four following climate zones:

- Tropical, savannah (Aw)
- Temperate, dry winter, hot summer (Cwa)
- Temperate, no dry season, hot summer (Cfa)
- Temperate, dry summer, hot summer (Csa)

Solar cooling systems to cover the cooling needs in the SunBelt region should therefore be particularly adapted to the conditions of these climate zones.

In the second step a specific solar cooling systems was considered. The so-called SunBeltChiller SBC is a solar thermal cooling (and heating) system that, despite high ambient temperatures, does not require a wet cooling tower and promises high efficiency. It could be shown that around 430 million people live in regions where the SunBeltChiller can potentially be used for residential cooling with around 300 million people having a GDP below 15,000 US dollars per capita. Additional to this it could be shown that around 420 million square meters of industrial area exist that potentially can use the SBC as a solar cooling (and heating) system with around 100 million square meters in regions with a GDP over 45,000 US dollars per capita and 150 million square meters in regions with a GDP from 25,000 to 45,000 US dollars per capita. Additionally, to the numerical evaluation a graphical evaluation using world maps for localization was made.

Following prospects for further investigation are:

- The method can currently only generate statistics reflecting the global situation and cannot be limited to selected regions or countries. This could be a valuable contribution for future work and would increase the quality of the results.
- The distribution of industrial areas and population could be analyzed more precisely and specifically to identify clusters of large buildings, which could be used to illustrate the potential of cooling networks, for example.
- Additional data sources such as cooling degree days could increase the significance of the results and data on energy prices would strengthen the method by taking economic factors into account.
- As previously addressed examining other building types besides industrial buildings (residential, commercial, hospital, university, etc.) would add value, particularly with regard to the potential of cooling networks.
- In principle, the methodology can be transferred to other renewable energy technologies for heating and electricity supply.
- Static images of maps, selected map sections and statistics/histograms were presented in this document. These were created manually. An atlas with many small-scale map images could be made to cover the whole world. While this is theoretically possible given certain filter properties, it would be a significant amount and not very reader-friendly. There are tools to develop interactive maps on the web. This can be very helpful for users who want to explore the information. Depending on the requirements and the details to be illustrated, this can be more or less extensive.

6 Bibliography

Beck, H. N. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data 5:180214, doi:10.1038/sdata.2018.214*.

ESMAP. (2019). Global Solar Atlas 2.0 Technical Report.

European Commission, E. (2021). Applying the degree of urbanisation : a methodological manual to define cities, towns and rural areas for international comparisons : 2021 edition. (P. Office, Ed.) doi:10.2785/706535

Florczyk A.J., C. C. (2019). *GHSL Data Package 2019.* EUR 29788 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN. doi:10.2760/290498

Freire S., M. K.-W. (2016). Development of new open and free multi-temporal global population grids at 250 m resolution. Geospatial Data in a Changing World. (AGILE, Ed.)

Hofste, R. S. (2019). Aqueduct 3.0: Updated DecisionRelevant Global Water Risk Indicators. Washington, DC: World Resources Institute. Retrieved from https://www.wri.org/research/aqueduct-30-updated-decision-relevant-global-water-risk-indicators

Kummu, M. T. (2017). *Dryad Digital Repository.* Retrieved from https://doi.org/10.5061/dryad.dk1j0.

Kummu, M. T. (2020). Data from: Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015. Dryad Digital Repository. Retrieved from https://doi.org/10.5061/dryad.dk1j0

OpenStreetMap. (n.d.). Retrieved 2022, from https://www.openstreetmap.org.

QGIS. (2023). Retrieved 2023, from https://www.qgis.org

Schiavina M., F. S. (2022). GHS-POP R2022A - GHS population grid multitemporal (1975-2030). (J. R. European Commission, Ed.) doi:10.2905/D6D86A90-4351-4508-99C1-CB074B022C4A

Schiavina M., M. M. (2022). GHS-SMOD R2022A - GHS settlement layers, application of the Degree of Urbanisation methodology (stage I) to GHS-POP R2022A and GHS-BUILT-S R2022A, multitemporal (1975-2030). (J. R. European Commission, Ed.) doi:10.2905/4606D58A-DC08-463C-86A9-D49EF461C47F

SolarGIS. (n.d.). Retrieved 2019, from https://globalsolaratlas.info/download/world.

ZAE Bayern. (2022). ZAE Bayern-Bavarian Center for Applied Energy Research.

7 Nomenclature

Abbreviation/Term	Description
BUILT	Built-up area
BWS	Baseline Water Stress
CDD	Cooling Degree Days
DIF	Diffuse Horizontal Irradiation
DNI	Direct Normal Irradiation
DHI	Diffuse Horizontal Irradiation
ESG	Environmental Social Governance
Geodetic	Science of measuring the size and shape of Earth
GHI	Global Horizontal Irradiation
GHSL	Global Human Settlement Layer
GIS	Geo Information System
KG	Köppen-Geiger climate zone
LCOE	levelized cost of energy
OSM	OpenStreetMap

8 Annex

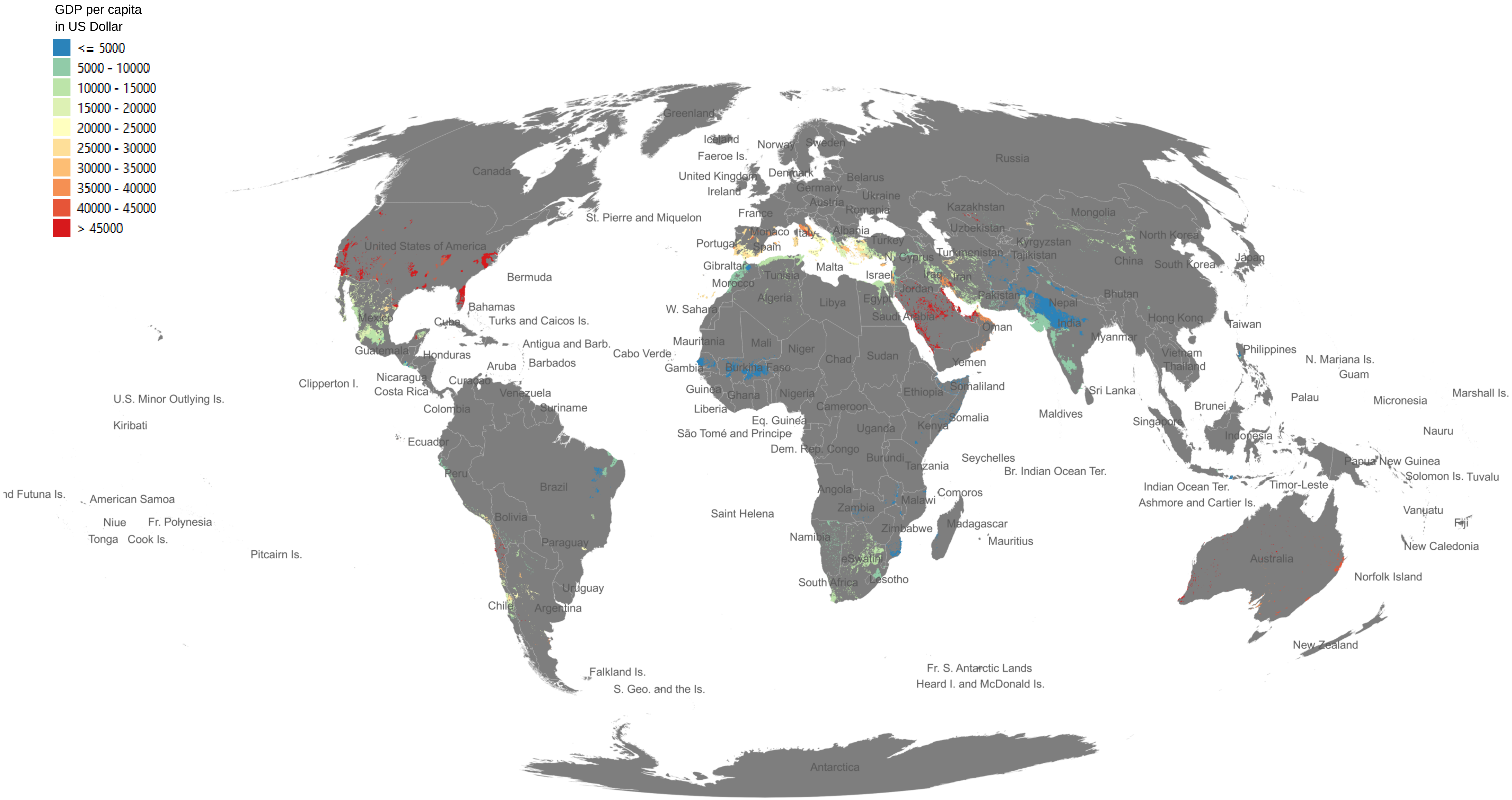


Figure 22: High resolution world map for identifying SBC potential for air conditioning in a 10km raster grid considering the level of the GDP (ZAE Bayern, 2022)

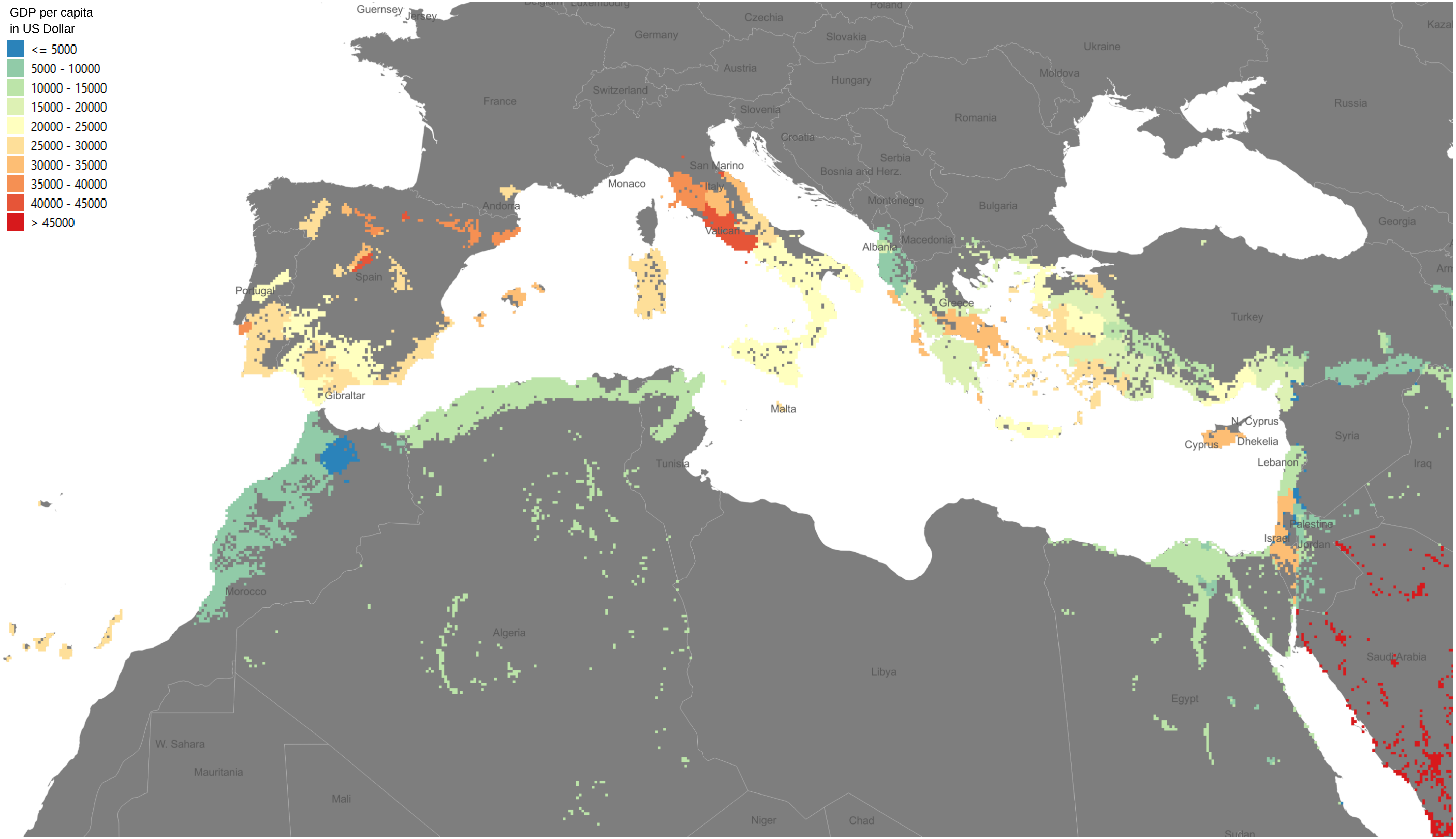


Figure 23: World map cut-out (Mediterranean) for identifying SBC potential for building cooling in a 1kmx1km raster grid considering the level of the GDP (ZAE Bayern, 2022)

High resolution world map for identifying SBC industrial cooling potential in a 10 km raster grid considering the level of the GDP (ZAE Bayern, 2022)

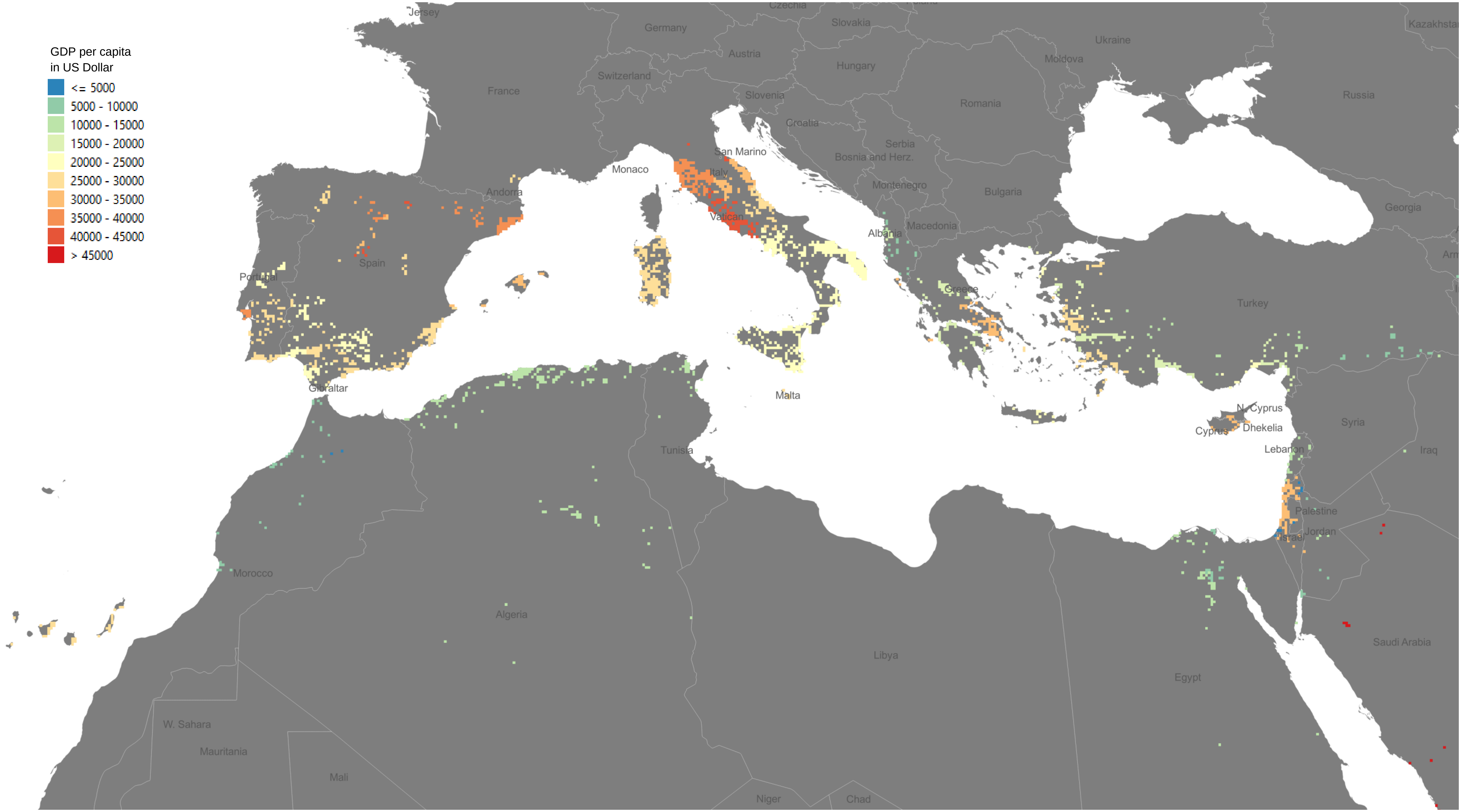


Figure 24: High resolution world map cut-out (Mediterranean) for identifying SBC industrial cooling potential in a 1 km raster grid considering the level of the GDP (ZAE Bayern, 2022