SOLAR POWER ROOFTOP POTENTIAL TOOL: AN ASSET FOR COMMUNAL HEAT GRID PLANNING

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Abstract

Heating requirements for residential space and water heating result in significant CO2 emissions in central and northern Europe. Certain cities benefit from established heat grids that reduces the need for individual planning and responsibility in residential heating. However, this infrastructure is lacking in smaller towns and suburban regions, making the goal of decarbonisation harder to achieve. As a result, individuals in these areas bear the costs associated with decarbonisation instead of leaving it to the experts in the field. With open access to building data and historic weather data, it is possible to estimate how much heat could be produced through solar thermal or electricity through photovoltaic sources to reduce the required loads for heat demand or increased electrical load from the use of heat pumps, for example. The use-case for the presented tool would be to inform and inspire the citizens of communally organized municipalities about the solar potential of the region and visualize the potential cost saving compared to a baseline plan of a municipal heat grid. The aim of this paper is to present a tool that utilizes open access sources for assessing the potential of generating electricity and heat using solar thermal and photovoltaic panels installed on residential rooftops in suburban areas. The tool will depend on the Python package, atlite, and data from the open source weather dataset, Copernicus ERA5, to provide accurate energy output estimations. Validation was conducted using data from Solarkataster Diepholz. With an included sensitivity analysis it is possible to compare different combinations of technologies in regard to demand coverage and over production.

1 Introduction

Heating requirements for residential space and water heating result in significant CO2 emissions in central and northern Europe (Coma et al., 2019). Certain cities benefit from an established heat grid or district heating systems which reduce the need for individual planning and responsibility in residential heating. However, such infrastructure is lacking in smaller towns and suburban regions, making the goal of decarbonisation harder to achieve. As a result, individuals in these areas bear the costs associated with decarbonisation instead of leaving it to the experts in the field. With ca. 25% of the population living in rural regions (United Nations - Department of Economic, 2019), the impact of expanding district heating systems is not negligible.

As part of the SubWW II research project (the follow up project to SubWW (Bachmann et al.,2021)), the aim is to design a district heating system with low emissions for the town center of Leeste in the municipality of Weyhe, near Bremen, Germany. In order to meet state funding requirements for heat grids, at least 75 % of the heat produced must come from renewable or low-emission energy sources[1]. As part of the project an identification method is to be developed for identifying the municipalities or

1 Information regarding the funding can be found when visiting : https://www.foerderdatenbank.de/FDB/Content/DE/Foerderprogramm/Bund/BMWi/bundesfoerderung-effiziente-waermenetze.html (22.05.2024)

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regions compatible with the built heat grid planning system. Due to the focus on low emissions, options for heating sources are limited, being geothermal (geographically dependent), solar thermal heating (weather dependent) and various types of heat pumps. The increased electrical load associated with heat generation through heat pumps cannot be understated. With heat pumps still not being a fully matured technology (Schloesser et al., 2020) in regard to the economics, a cost-effective approach would include the installation of the weather and geographically dependent technologies in support.

To address this issue, Photovoltaic (PV) panels could be a viable solution. Instead of constructing smaller PV parks, Rooftop PV-Panels could be considered due to the availability of usable space. When discussing solar energy, the conversation often focuses on PV technology, while solar thermal technologies are often overlooked. However, in the context of heating, the connection between the two should not be so distant. Due to the smaller residential scale of the solar thermal heating, as opposed to an industrial scale, the heating via solar thermal collectors shall only be considered for domestic hot water heating. For domestic hot drinking demand remains relatively stable throughout the year, as opposed to space heating.

To properly include PV and solar thermal technologies in the planning of a heat grid system, detailed information regarding the individual buildings, roof size, and global irradiation direction is necessary. However, this information may not be available until later in the planning phase. A tool[2] to estimate rooftop solar power potential could provide the necessary information to include this option in the overall planning of the heat grid and incentivize corresponding stakeholders to consider inclusion. To enable the reuse of this tool in various rural and municipal areas, it would be ideal to avoid purchase costs associated with necessary information. Therefore, the intention is to utilize open-source data. The tool is developed using Python.

In terms of weather data, there exists a geo-dataset that contains historical weather data, including global radiation, provided by Copernicus[3]. This dataset is known as ERA5 (Hersbach et al., 2018). Currently, there is a Python library available, called atlite (Hofmann et al., 2021), that can extract the necessary data from ERA5 in a commonly viewable format. When provided with a specific geoshape, atlite can extract the weather data for the selected region, thereby reducing the size of the dataset.

Atlite works with both raster and vector data. With the use of Copernicus datasets, such as land coverage data, specific types of surfaces can be included or excluded depending on the desired result. One such dataset is the Built-up data, which presents areas with buildings (European Environment Agency & European Environment Agency, 2020). Most Copernicus land coverage datasets provide a resolution of 100x100 m, but the dataset used for this paper has a higher resolution of 10x10 m. To properly estimate the solar potential in rural/municipal regions, a higher resolution is essential. Atlite already has a feature that calculates the PV potential for the designated geoshape with possible excluders. The user has some control over the results through tweaking parameters, with the main factor being the energy density in MW/km^2. To determine that factor, a validation/comparison will be made using the Solarkataster Diepholz[4] as an example.

2 Preparatory Work

When defining the geoshape of Leeste, the .tif file from the Copernicus dataset is used as a negative excluder and an includer to extract weather data for the selected area. The area can be seen in Fig. 1.

2 Example available to view at https://github.com/KarimHShawky/SolarPowerRoofTopPotential
3 The earth observation component of the European Union’s space program https://www.copernicus.eu/en (22.05.2024)
4 https://solarkataster.diepholz.de/ (22.05.2024)

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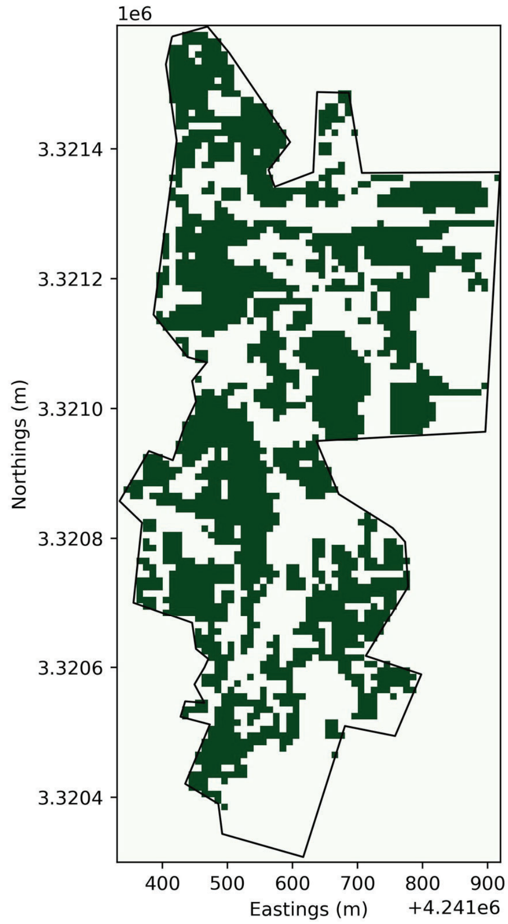

Figure 1. Built Area within the selected region of Leeste

The typical use case for atlite is to determine PV and wind turbine power potential. Although these features are well-developed, this paper aims to also consider solar thermal potential. The only implemented methods in atlite that considers any solar thermal technology are parabolic troughs and solar towers. The solar tower method will be disregarded due to the difference in scale. Due to the scarcity of parabolic trough systems for residential use, a slight alteration is necessary. In (Kalogirou, 2009), a comparison was made between the efficiencies of different solar thermal technologies, once for each technology with an irradiation of 500 W/m^2 and once for 1000 W/m^2. Flat plate solar collectors are a more common technology for solar thermal residential heating systems. Efficiency is a function of the temperature difference between the inlet and outlet of solar thermal technology. The standard supply and return temperatures for household drinking water range between 60° C and 20° C (Brand, 2014). Therefore, the efficiency values for a temperature difference of 40 K are compared. The resulting ratio of efficiencies for the 500 W/m^2 graphs is 25 % and 60 %. For perspective, the efficiency ratio for the 1000 W/m^2 case is 50 % and 65 %. Due to the location of the test region in northern Germany, one might assume that the lower value is a realistic average of the irradiation. However, according to PVGIS (Šúri et al., 2005) when including only daylight hours an average of 550 W/m^2 was determined. In the summer months, the average global irradiation levels can reach up to 800 W/m^2. Therefore, taking the ratio of 25/60 shall provide a more conservative assumption while

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taking the ratio 50/65 would be a more optimistic assumption which could be used for summer months exclusively.
When viewing the municipality of Leeste in the Solarkataster Diepholz and selecting the relevant area of Leeste a sum of 2.04 GWh would potentially be produced within a year. The estimation being based on the historical average of global solar irradiation of the last 20 years for the given region. The estimation of the Solarkataster Diepholz considers shadings based on surrounding vegitation and the impact of the orientation of the roof. Having completed calculation for the PV-Potential using atlite with a capacity density of 1 MW/km^2 as reference, it is possible to compare the sum of produced energy and therefor get a reference on how to adjust the parameter of the capacity density.

Before proceeding, it is important to consider the already installed PV-modules. These should not be included in the power estimation when assessing the potential solar expansion for use within a heat grid. The German Solar register is outdated by over 10 years and therefore cannot be relied upon for accurate information. Instead, the Solarkataster Diepholz provides a more recent estimate. According to this source, only 4% of the available solar potential in the municipality region of Weyhe, which includes Leeste, has been installed.

Therefore, the finalized value for the capacity density would be 8 MW/km^2. While having partially validated the magnitude of production in terms of PV and considered the difference in efficiencies for the solar thermal power production the Potentially produced values for a given year can be presented.

In scope of SubWW (Bachmann et al., 2021) the demands for domestic hot water and space heating were simulated for an hourly resolution using TEASER (Remmen et al. 2018). A direct comparison can be made between simulated load and simulated production for the respective considerations.

Solar thermal energy can be used to heat domestic hot water directly in households. However, using electricity produced by photovoltaic panels for heating is not straightforward. Preliminary results from the SubWW II research project indicate that air heat pumps will be a significant source of heat for space heating. Hourly COP values based on temperature have been calculated.[5] This is because the COPs of air heat pumps fluctuate depending on outside and/or heating temperatures. Air source heat pumps are being considered due to fewer restrictions compared to geothermal or wastewater heat pumps. Geothermal sourced heat pumps have limited outputs based on the available area, while wastewater powered heat pumps have limited outputs based on the available water. In contrast, air sourced heat pumps are limited by the ambient temperature, which restricts their output at given ambient temperatures rather than their installed capacity. By multiplying these with the potential PV electrical output calculated with atlite, an estimate can be made for the potential heat from air-sourced heat pumps powered by PV instead of electricity purchased from the grid.

3 Results

3.1 Baseline Demand coverage

Fig. 2 and Fig. 3 visualize the load coverage of the respective technology based on the given hourly demand and production[6]. The intent is to present the difference between production and consumption for a given technology and corresponding demand. The data has been resampled using the daily average values for the sake of clarity, otherwise due to day/night differences the production curve would lose its clarity because of the noise. In Fig. 2 and Fig 3. positive values represent over production and negative values represent under production. It is assumed that each technology, solar thermal and PV powered heat pumps) would only be used for one of the heating requirments, domestic hot water and space heating respectively.

5 COP values were calculated according to DIN EN 15316-4-2 with a machine quality factor of 0.5
6 The year 2014 was chosen at random for the weather data

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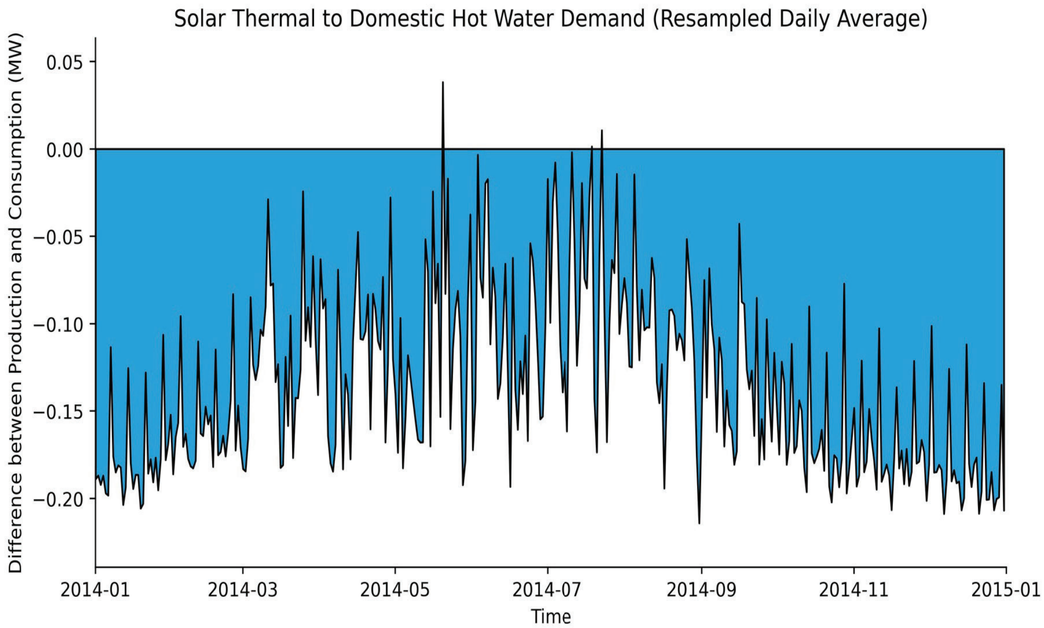

Figure 2: Difference between Production and Consumption Solar Thermal to Domestic Hot Water Demand

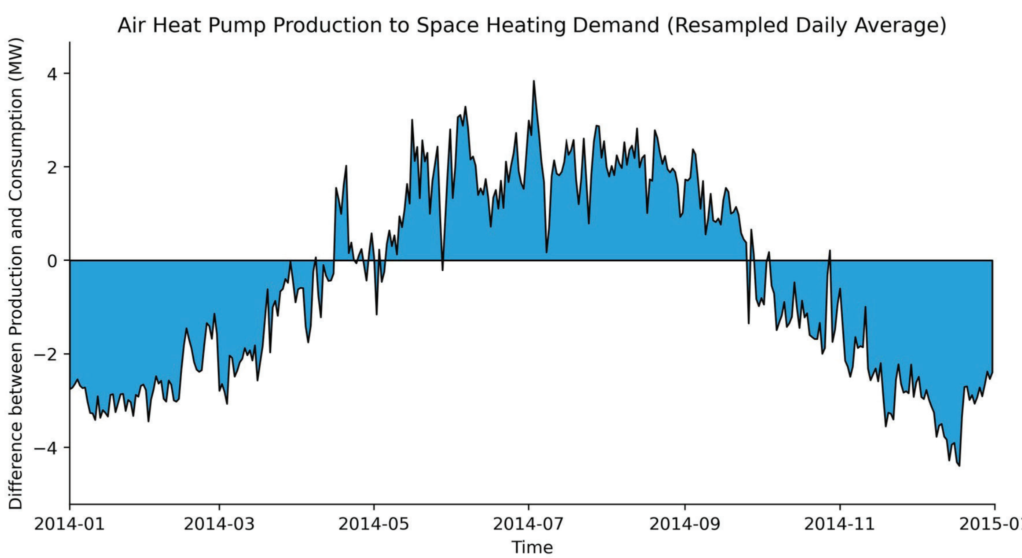

Figure 3: Difference between Production and Consumption PV powered Air Heat Pump Heat to Space Heating Demand

For the given example of Leeste, the solar thermal heating solution for domestic hot water would not provide a full load coverage, whereas the PV- powered air heat pumps would provide a proper coverage between the months of May and October. These being the months with lower heating demand as well as the higher global irradiation levels compared to the rest of the year.

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3.2 Sensitivity Analysis

As the calculation of solar thermal and PV potential is based on the same sum of area, Fig. 2 and Fig. 3 only represent 100 % usage of each technology. Therefore, it may be interesting to consider a combination of the technologies during the planning phase. Including a buffer or overproduction is a proper precaution, but it may not be cost-effective if overdone. To gain insight into which combination of technologies would meet the demands while avoiding overproduction, the tool includes a sensitivity analysis. The sensitivity parameter 'a' is defined as a percentage of the total installed PV compared to the maximum. The value of '(1-a)' represents the amount of installed solar thermal capacity. The production potentials of the technologies were scaled using their respective factors of 'a' or '(1-a)' and compared to the hourly demand time series of the corresponding use case. It is important to note that both sensitivity analyses were performed on the actual time series of potential production and demand, not on the resampled data as shown in Fig. 2 and Fig. 3. For reference the magnitude of the yearly demand of domestic hot water is 1.6 GWh and for space heating is 13.5 GWh.

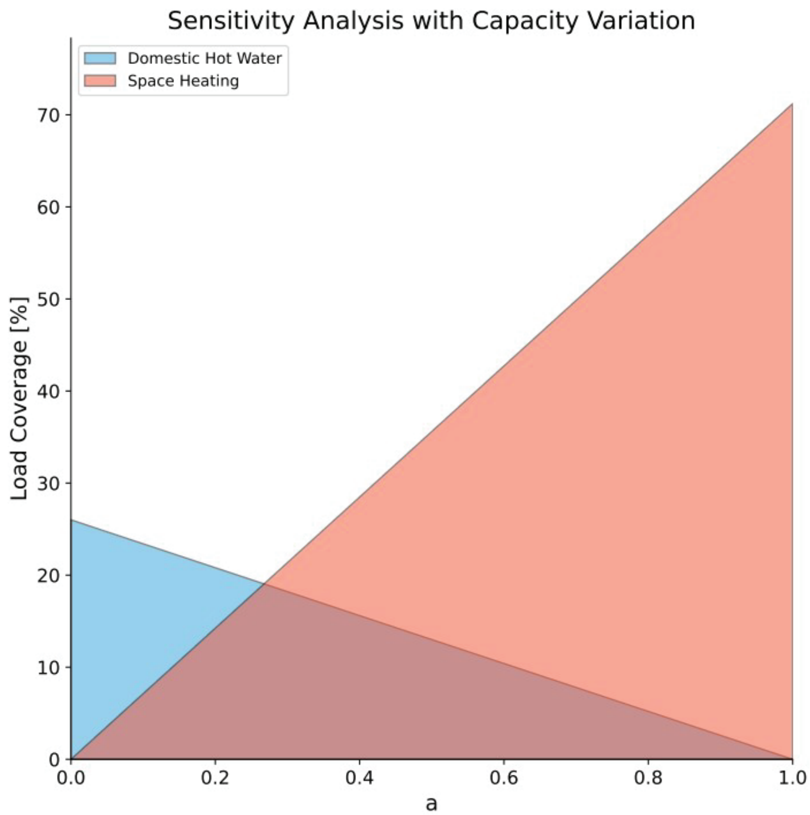

Figure 4: Sensitivity Analysis: Load Coverage [%] of the respective heating demand based on the installed capacity mixture

Upon viewing Fig. 4, one may assume that utilizing the rooftop space for PV systems to power air heat pumps would be the ideal option based on the given data. However, upon further consideration of the information presented in Fig. 3, it becomes clear that such a configuration would result in overproduction. Fig. 4 displays the sum of potentially produced power compared to the sum of demand, which explains the counterintuitively high load coverage values for space heating. As a result, Fig. 5 is presented.

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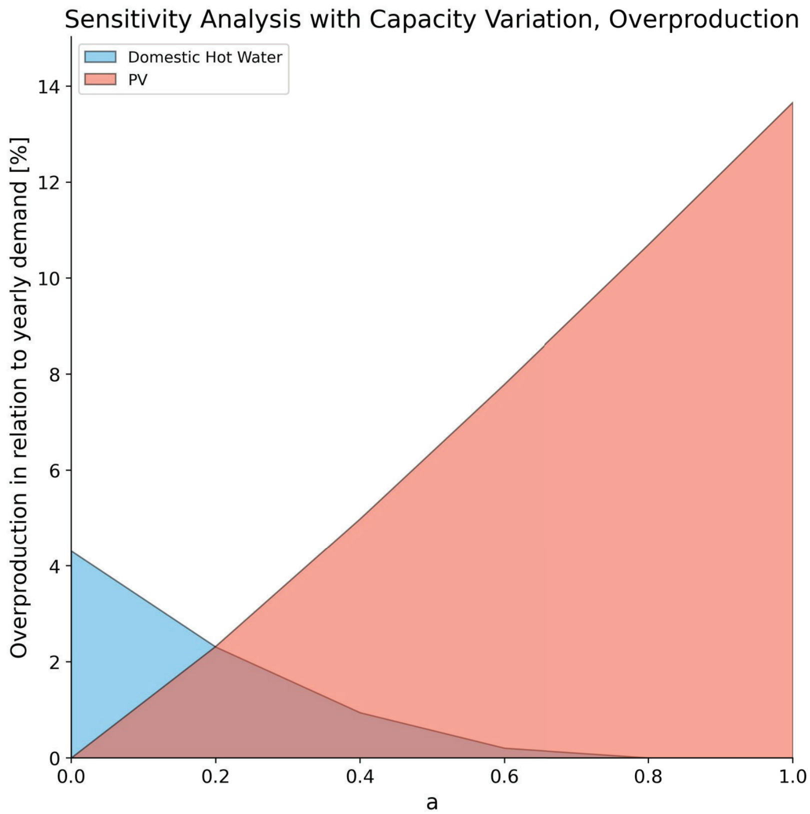

Figure 5: Sensitivity Analysis: Over production compared to the respective heating demand on the installed capacity mixture

It should be noted that the displayed overproduction only considers the overproduction of PV electricity, not the heat from the air source heat pumps. To provide an overview of the actual installed impact of the PV, the overproduction of heat for space heating was divided by the average COPs for the provided year, representing the possible electricity that could be sold to the electrical grid. Fig. 2 shows the ca. The reported 4 % overproduction value for solar thermal domestic hot water heating may seem incorrect. However, this higher value can be attributed to the fact that the sensitivity analysis was performed using hourly data instead of the resampled data mentioned above.
The overproduction of the solar thermal heat would not have such a benefit however in the given example even a maximum of 5 % overproduction could be considered a safety precaution in case of fluctuating conditions such as weather and demand. Without consideration of the difference in magnitudes the optimal combination of technologies would be at a value of a between 0.2 and 0.3, due to still covering a substantial amount of the domestic hot water demand while providing a 20 % of load coverage of the space heating demand.

With the given sensitivity analysis further decisions could be made based on the priorities of the planner, for example having a focus on the electricity saving factor or the low temperature load coverage.

4 Conclusion

When providing a shapefile of a specific region with known heat demand, an educated guess of the possible to be installable capacity density, an estimate of the average global irradiation (being closer

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to 500 W/m^2 or to 1000 W/m^2) and estimated COPs for heat pumps (or other small scale power-to-heat technologies) for a given location in Europe (due to the Copernicus Built-up Area .tif file only containing values for Europe) it is possible to provide an overview of potential heat-demand coverage for domestic hot water and space heating based on flat bed solar thermal collectors and PV provided electricity to power-to-heat systems. With a possible sensitivity analysis of how much of the available area for rooftop solar energy should be allocated to which technology. Also, with a consideration of possible overproduction. A possible expansion to the tool would be the inclusion of investment costs and running costs for the technologies, a connecting interface with oemof (Hilpert et al., 2018) or pypsa (Brown et al., 2018) could also be viable.
For the given example of Leeste, with partial tuning/validation using the Solarkataster Diepholz, the tool was able to visualize the possible missmatch in solar production and heating consumption, therefore emphasizing the fact that these technologies would only have a supporting role in such a district heating network. Nevertheless, every effort towards decarbonization is beneficial. The sensitivity analysis provided insight to a possible combination of installed technologies being able to provide a portion for each heating demand as well as not over scaling the installation of PV.
In the current state the tool provides a simple outlook for planning with minimal input parameters.

Nomenclature

Abbreviation

PV	Photovoltaic	
COP	Coefficient of Performance	(-)
a	Sensitivity Parameter	(-)

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