Bottom-up Analysis of the Solar Photovoltaic Potential for a City in the Netherlands
A Working Model for Calculating the Potential using High Resolution LiDAR Data

B. B. Kausika[1], O. Dolla[1], W. Folkerts[2], B. Siebenga[3], P. Hermans[4] and W. G. J. H. M. van Sark[1]
[1]*Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands*
[2]*Solar Energy Application Centre (SEAC), High Tech Campus 21, Eindhoven, The Netherlands*
[3]*I-Real, Stationsweg 30, Terborg, The Netherlands*
[4]*Aurum Europe, Zandsteen 6, Hoofddorp, The Netherlands*

Keywords: Solar Photovoltaic Potential, LiDAR Data, Bottom-up Approach.

Abstract: This paper presents a working model to estimate the solar photovoltaic potential using high- resolution LiDAR data and Geographic Information Systems. This bottom-up approach method has been selected to arrive at the potential as this gives a better estimate than a top-down approach. The novelty of the study lies in estimating the potential at high resolution and classifying the rooftop as suitable or not for solar photovoltaic installations based on factors like irradiation, slope and orientation. The city of Apeldoorn in the Netherlands has been selected as the study area. The model was able to successfully locate suitable sites for photovoltaic installations at rooftop level. In addition, the area feasible for the installations and the potential power output has also been calculated. We conclude that the city has a potential of 319 MWp capacity, which would yield 283.9 GWh/yr in relation to the 304 GWh/yr consumption from residential buildings in the area.

1 INTRODUCTION

Photovoltaic (PV) solar energy in Europe has been increasing rapidly in the past few years. Technological developments and research efforts have brought PV in the renewable energy sector to a new level. Estimation of the actual potential of PV in the residential sector creates various business opportunities and would assist in policy making. In addition, consumers are also increasingly aware of how PV could benefit them, as in many countries retail grid parity is present (Olson et al. 2014). Several top-down studies have been performed on solar PV potential in the Netherlands, sometimes in conjunction with potential studies for Europe (Alsema and Brummelen 1992; Bergsma 1997; De Noord et al. 2004; Krekel et al. 1987). Many studies also mention different capacities based on different top-down approaches. (Krekel et al. 1987), (Alsema and Brummelen 1992), (Corten and (Bergsma 1997). De Noord *et al.* re-assessed these potential estimates and presented the realistic potential of solar PV in the Netherlands to be 400 km^2 (80-120 GWp) for building integrated PV (BIPV) and 200 km^2 (40- 60 GWp) for ground-based PV (GBPV). The latest figure for PV potential is presented by Lemmens et al., at 150 GWp and is based on the present electricity consumption in the Netherlands of 120 TWh (Lemmens et al. 2014).

To summarize present top-down estimates for BIPV potential, in the Netherlands it ranges from 200- 400 km^2, or 40-80 GWp. Land based PV installations would perhaps add another 200 km^2. Total country potential thus ranges from 80-120 GWp. At the end of 2013, the total amount of installed PV was estimated at 722 MWp (CBS 2014). It is predicted that in the year 2020 an amount of 4 GWp will be installed in the Netherlands (KEMA 2012). With present annual growth rates, this may be a conservative estimate.

Since the top-down assessment values are difficult to rely upon these should be validated using

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Bottom-up Analysis of the Solar Photovoltaic Potential for a City in the Netherlands - A Working Model for Calculating the Potential using High Resolution LiDAR Data.
DOI: 10.5220/0005431401290135
In *Proceedings of the 4th International Conference on Smart Cities and Green ICT Systems* (SMARTGREENS-2015), pages 129-135
ISBN: 978-989-758-105-2

bottom-up assessments that now are possible, using tools such as “Solar Atlas”, in Dutch Zonatlas (Zonatlas), which are based on aerial photographs and solar irradiation. But determining the actual solar potential of BIPV using high-resolution data can be very challenging due to the complexity of the urban areas.

High resolution rooftop potential studies are relatively new and not much has been done in this area at rooftop level for estimating the technical and geographical potential for PV deployment. (Izquierdo et al. 2008) estimated the technical potential of roof integrated PV systems using easily available data and stratified-samples of Geographical Information Systems (GIS) maps at a regional level. Based on this work, PV solar energy potential estimations at municipal to regional level was conducted in Italy with the help of global solar radiation maps taken from the Joint Research Centre of the European Commission (Bergamasco and Asinari 2011). (Hofierka and Kaňuk 2009) proposed a methodology for PV potential estimation in urban areas based on the open-source solar radiation tool r.sun (developed by (Šúri and Hofierka 2004)) and 3-D city model in GIS. Furthermore, models to estimate solar potential on building rooftops using GIS and statistical approaches to create roof-top solar radiation maps were explored by (Karteris et al. 2013; Kodysh et al. 2013). (Redweik et al. 2013)developed a model to calculate the solar energy potential of the buildings taking into account both the roofs and the facades using high resolution LiDAR (Laser Imaging Detection And Ranging) data and applied the model to the campus of university of Lisbon. However, all the mentioned studies fall short in estimating the potential at individual rooftop level.

In the present study, we estimate the rooftop PV potential in Apeldoorn, a city in the Netherlands using high resolution LiDAR data and GIS techniques. Only roof integrated PV is addressed here. With the use of Solar Analyst (Fu and Paul M Rich 1999) of ArcGIS solar irradiation over large geographic areas is computed accounting for atmospheric effects, sun angle, elevation and effects of shadows by buildings, elevation and orientation. Classification of the solar irradiation map was done to differentiate between optimum and less optimum suitable sites. These were the basis of potential estimation, where further energy potential calculations are made taking into account the slope and orientation information. These estimations would help in looking at the trend of PV diffusion, create business opportunities and additionally provide an insight for policy implementations.

2 METHODOLOGY

The area chosen for the study was the city of Apeldoorn (52° 13′ N, 5° 57′ E), in the Gelderland province of the Netherlands. For locating the potential PV sites and for calculating the PV potential a digital elevation model (DEM) derived from LiDAR data was used. This was obtained from Actueel Hoogtebestand Nederlands (AHN) (Nederland 2013). This key input has a resolution of 50 cm (point spacing of 9 points per m^2, which is well suited for estimation of solar radiation at roof-tops. The study area chosen in shown in Figure 1. The city itself is at low elevation, while in the West one recognizes a hilly region called De Veluwe. Another important dataset was a vector file of the footprints of residential buildings in the study area. In this paper we focus on the residential sector. The recent building footprint layer was obtained from Basisregistratie Adressen en Gebouwen (BAG), which is a part of the government cadaster system.

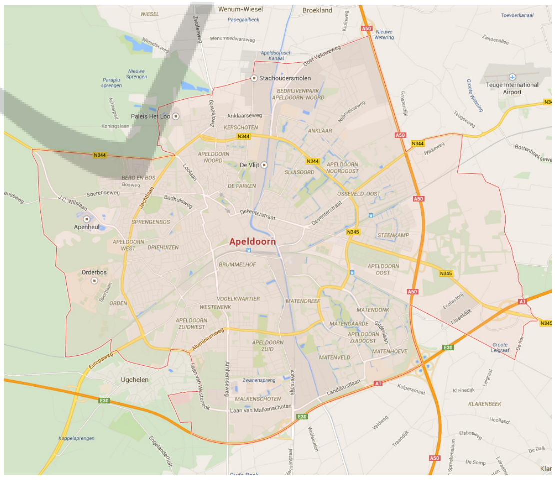

Figure 1: City of Apeldoorn which is taken as the study area in this research.

The estimation of solar potential in this study was calculated in two steps. First, suitable locations for roof-top PV were singled out, and then potential estimation calculations were performed based on GIS data analysis. We specified some requirements in order to characterize suitable locations; and performed all the calculations using ArcGIS.

The criteria chosen for locating suitable PV sites were solar irradiation, slope and orientation. This has been adopted from the work of (Chaves and Bahill 2010). The Area Solar Radiation Tool of the ArcGIS Spatial Analyst automatically performs the solar irradiation calculation based on the model by

(Fu and Paul M. Rich 1999). This model takes DEM as the main input and other parameters relating to slope, shade and transmissivity of the atmosphere and calculates the solar irradiance during the time specified and produces an output image having pixel values in units of Wh/m^2.

The other inputs for the model were slope and orientation, which were also created by the Spatial Analyst tool in ArcGIS.

All the three images were masked to show only residential buildings and were converted into binary raster images taking the following criteria:

- Feasible Slope: less than or equal to 38 degrees
- Feasible Solar Irradiation: greater than 70% of the annual maximum received in the area which has been taken at 600kWh/m^2 according to the modelled irradiance
- Feasible Orientation: (a) South facing and (b) other orientations.

South facing slopes have been considered as optimum while the other slopes have been taken as less optimum in this study. The binary rasters were then combined together to create a final binary image, which was then filtered to create a smooth and continuous image.

A raster to polygon tool was used to convert the suitable areas into a vector polygon layer. Attributes like area, potential capacity and power were then attached to these polygons. A value of 150Wp/m^2 has been taken as the PV power density that can be installed. Therefore, the final output has been classified as follows

- 0 : for unsuitable areas shown in red
- 1: partially suitable areas (with high solar irradiance and orientations other than south) shown in yellow and
- 2: optimally suited areas(high irradiation and south facing slopes) in green.

In addition, the production from the estimated capacity was determined using values determined by (van Sark et al. 2014). This study states that the annual production of a PV system in the Netherlands can be estimated at 875 kWh/kWp. Therefore, for optimum (south facing) oriented areas 950 kWh/kWp has been chosen and for other, less optimal orientations 750 kWh/kWp has been taken.

3 RESULTS

The results are explained in the following subsections. The first subsection shows the model inputs and in the second subsection binary outputs after the application of criteria are shown. The third subsection shows the final output, which is the result of a binary (AND) operation followed by a raster to polygon transformation and addition of attributes and finally the potential estimations.

3.1 Model Inputs

In this subsection the inputs taken in the model are displayed. Figure 2 shows the height map of the buildings. Figure 3 shows the annual solar radiation image in kWh/m^2. The area receives an annual maximum irradiation of 960 kWh/m^2 in a year according to the model-based calculations. Figure 4 shows the orientation image or the direction of the slope. Followed by a slope image where a distinction between flat and sloping roofs is vivid.

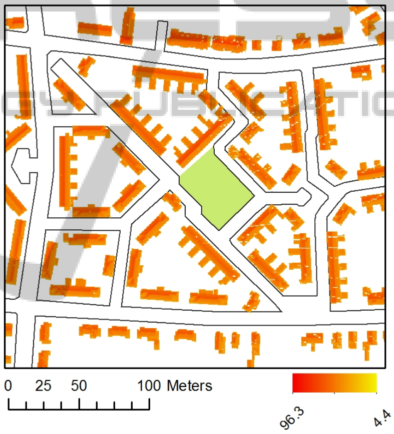

Figure 2: AHN height information derived for residential buildings. Height information is in meters.

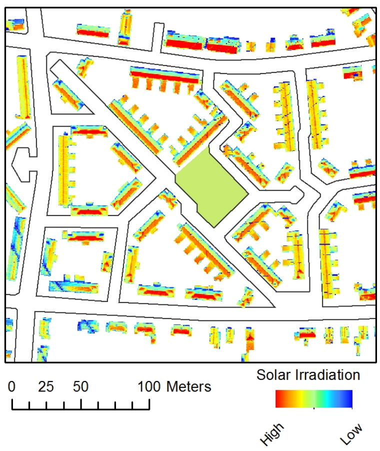

Figure 3: Solar Irradiation image derived for building by running the Solar Radiation tool. South facing slopes are seen to receive greater irradiation.

3.2 Binary Outputs

Binary outputs after applying the mentioned criteria for slope, solar irradiation and orientation have been determined and are presented here.

Figure 5 shows in green the optimum irradiation map of areas receiving greater than 600 kWh/m^2 per year. We see that most of the building rooftops are selected along with a few roads or empty areas. The right image in Figure 5 shows the feasible slope areas in green, which are 38° and below. The white areas show unfeasible areas, which we can identify mostly as facades or vegetation.

Images in Figure 6 are the optimum orientation map, which shows south facing slopes in green (left image) and other orientations image (right image).

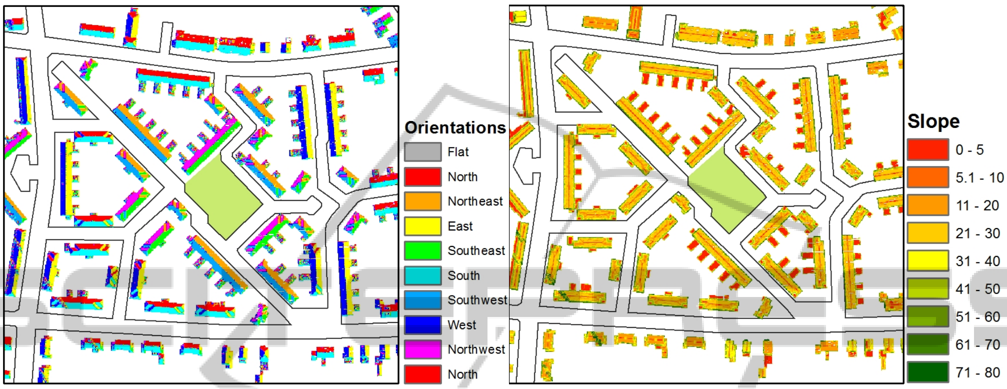

Figure 4: Left: Orientation image showing the direction of slope of the rooftops. Right: Slope image classified in classes to distinguish between flat and sloping roofs.

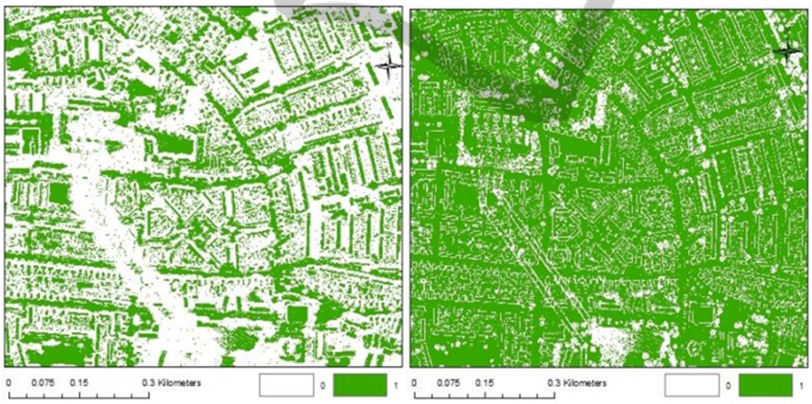

Figure 5: Optimum irradiation image (left) and feasible slope image (right).

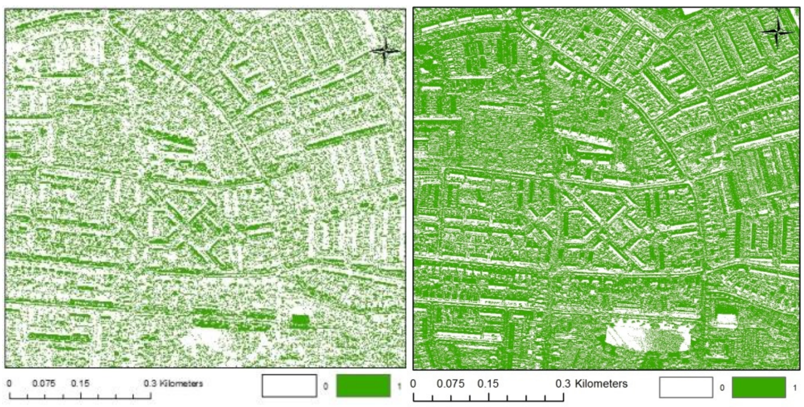

Figure 6: Optimum orientation image (left) showing south facing slopes and other orientations image (right).

Figure 7: Final output showing the geographic potential. Gridcode 0 shows unfeasible areas, 1 represents partially suitable area and 2 shows best suits areas for the deployment of PV.

3.3 Final Output

The final output is a polygon layer that shows 3 classes (Figure 7). Areas in green are optimally best-suited locations for PV. These areas receive maximum amount of solar irradiation and have an optimum slope and south orientation. South facing slopes in the Northern hemisphere receive maximum amount of solar irradiation.

The areas in yellow are partially optimum or the other orientations, which still receive about more than 70% of the average solar irradiation in the region. These areas are suitable for PV but may not show high energy yields, as they do not receive maximum solar irradiation throughout the year.

The red areas are categorised as totally unsuitable. These regions receive either minimum amount of solar radiation or have unfeasible slopes (facades or steep slopes) or are either shaded from trees or nearby buildings.

The final output presented below is the result of a smoothing filter on a raster, which was then converted into a polygon shapefile. These polygons were then intersected with the building information from BAG so that the final output has address information along with the building properties as shown in Figure 8.

Figure 9 shows the attribute table associated with the final map. Each record corresponds to an address and each address is further categorised based on the grid code, which is 0, 1 or 2.

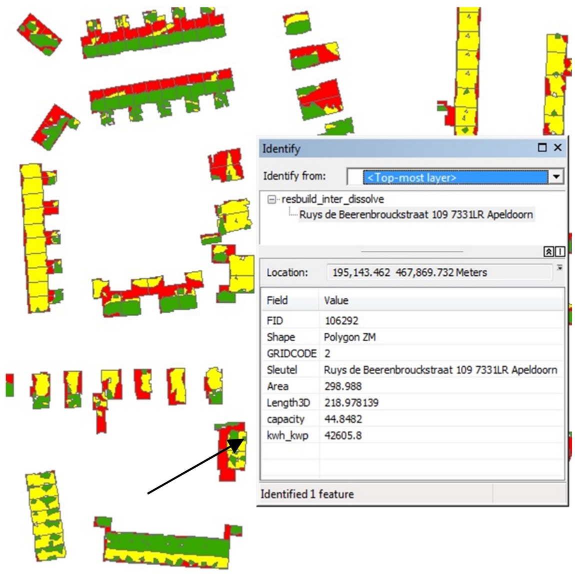

Figure 8: Final map with information on address, potential capacity and power.

Table

resbuild_inter_dissolve

FID	Shape	GRIDCODE	Address	Area	capacity kWp	Power_kwh
1	Polygon ZM	0	1e Beukenlaan 1 7313AH Apeldoorn	155.598	0	0
4138	Polygon ZM	1	1e Beukenlaan 1 7313AH Apeldoorn	6.69555	0.669555	502.166
7584	Polygon ZM	2	1e Beukenlaan 1 7313AH Apeldoorn	45.8384	6.87576	6531.97
2	Polygon ZM	0	1e Beukenlaan 1 A 7313AH Apeldoorn	6.93131	0	0
4138	Polygon ZM	1	1e Beukenlaan 1 A 7313AH Apeldoorn	77.6978	7.76978	5827.33
7584	Polygon ZM	2	1e Beukenlaan 1 A 7313AH Apeldoorn	106.567	15.9851	15185.8
3	Polygon ZM	0	1e Beukenlaan 10 7313AJ Apeldoorn	78.9644	0	0
4138	Polygon ZM	1	1e Beukenlaan 10 7313AJ Apeldoorn	24.3852	2.43852	1828.89
7584	Polygon ZM	2	1e Beukenlaan 10 7313AJ Apeldoorn	2.25	0.3375	320.625
4	Polygon ZM	0	1e Beukenlaan 11 7313AJ Apeldoorn	82.4278	0	0
4138	Polygon ZM	1	1e Beukenlaan 11 7313AJ Apeldoorn	5.88867	0.588867	441.65
7585	Polygon ZM	2	1e Beukenlaan 11 7313AJ Apeldoorn	18.8675	2.83013	2688.62
5	Polygon ZM	0	1e Beukenlaan 12 7313AJ Apeldoorn	49.6556	0	0
4139	Polygon ZM	1	1e Beukenlaan 12 7313AJ Apeldoorn	12.9069	1.29069	968.018
7585	Polygon ZM	2	1e Beukenlaan 12 7313AJ Apeldoorn	41.2643	6.18964	5880.16
6	Polygon ZM	0	1e Beukenlaan 13 7313AJ Apeldoorn	59.7151	0	0
7585	Polygon ZM	2	1e Beukenlaan 13 7313AJ Apeldoorn	48.0723	7.21084	6850.3
7	Polygon ZM	0	1e Beukenlaan 14 7313AJ Apeldoorn	82.7415	0	0
4139	Polygon ZM	1	1e Beukenlaan 14 7313AJ Apeldoorn	3.35988	0.335988	251.991
8	Polygon ZM	0	1e Beukenlaan 16 7313AJ Apeldoorn	72.0345	0	0
4139	Polygon ZM	1	1e Beukenlaan 16 7313AJ Apeldoorn	3.82378	0.382378	286.784
7585	Polygon ZM	2	1e Beukenlaan 16 7313AJ Apeldoorn	29.4144	4.41216	4191.55
9	Polygon ZM	0	1e Beukenlaan 17 7313AJ Apeldoorn	75.1865	0	0
7585	Polygon ZM	2	1e Beukenlaan 17 7313AJ Apeldoorn	29.5764	4.43646	4214.64
10	Polygon ZM	0	1e Beukenlaan 18 7313AJ Apeldoorn	72.7447	0	0
4139	Polygon ZM	1	1e Beukenlaan 18 7313AJ Apeldoorn	1.5	0.15	112.5
7585	Polygon ZM	2	1e Beukenlaan 18 7313AJ Apeldoorn	36.6479	5.49719	5222.33
11	Polygon ZM	0	1e Beukenlaan 2 7313AJ Apeldoorn	78.1161	0	0
4139	Polygon ZM	1	1e Beukenlaan 2 7313AJ Apeldoorn	74.6925	7.46925	5601.94
7585	Polygon ZM	2	1e Beukenlaan 2 7313AJ Apeldoorn	23.5895	3.53842	3361.5
12	Polygon ZM	0	1e Beukenlaan 20 7313AJ Apeldoorn	59.5123	0	0

Figure 9: Attribute table for the final output.

3.4 Potential Estimation

Potential estimations for the city of Apeldoorn have been calculated using the field calculator of ArcGIS for each of the final polygons as can been seen from the table in Figure 9. Figure 10 shows the rooftop area in relation to grid code. Total area is about 3.9 km^2. A constant power density of 150 Wp has been used to estimate the potential capacity per square meter. This value has been multiplied with the total area available. Potential estimation has not been performed for grid code values of 0.

The potential PV capacity for the city of Apeldoorn thus was estimated at 319.9 MWp for the residential buildings (Figure 11). This would mean a power production of 283.94 GWh. Note that the present PV capacity installed in the region is 3.4 MWp and the annual demand is around 230 GWh at the rate of 3500 kWh/yr per household.

Using an annual average household consumption, PV would be able to provide the annual energy demand of 65,730 households, which is more than 100% of the total households in Apeldoorn.

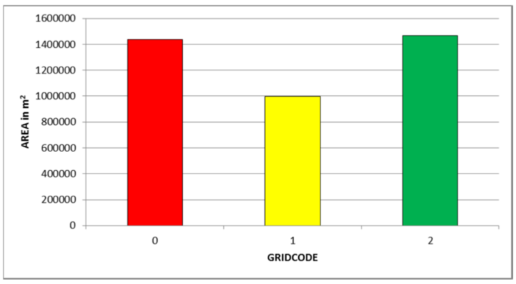

Figure 10: Graph showing rooftop area covered under each class after analysis. The total of these classes corresponds to the total roof area of residential buildings in Apeldoorn.

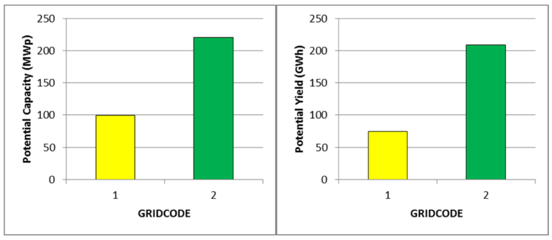

Figure 11: Potential capacity in MWp and expected yield in GWh of the optimally suitable areas (Grid code 2) and partially suited areas (Grid code 1).

4 CONCLUSIONS

In this paper a working model for the estimation of solar PV potential using high-resolution LiDAR data and GIS techniques has been presented. Detailed PV potential estimation studies require high-resolution height information models. The model presented in this paper shows great potential and is easy to implement. The calculations showed that the city of Apeldoorn has great PV potential in its residential sector. Based on an average electricity consumption of residential houses in Apeldoorn of 3500 kWh/yr, the potential electricity that could be generated would be able to cover the electricity demand of the city completely and even produce more.

The application of this methodology to a city has shown that this method could be deployed in the whole country for accurate bottom-up determination of PV potential. This method could also be applied to the whole of the Netherlands but proper extrapolation techniques have to be developed. This is currently under investigation.

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