Delft University of Technology - Campus PV potential, analysis report

Fremouw, M.A.; Zhou, Y.; Nata Djaja, Puji

Publication date
2021

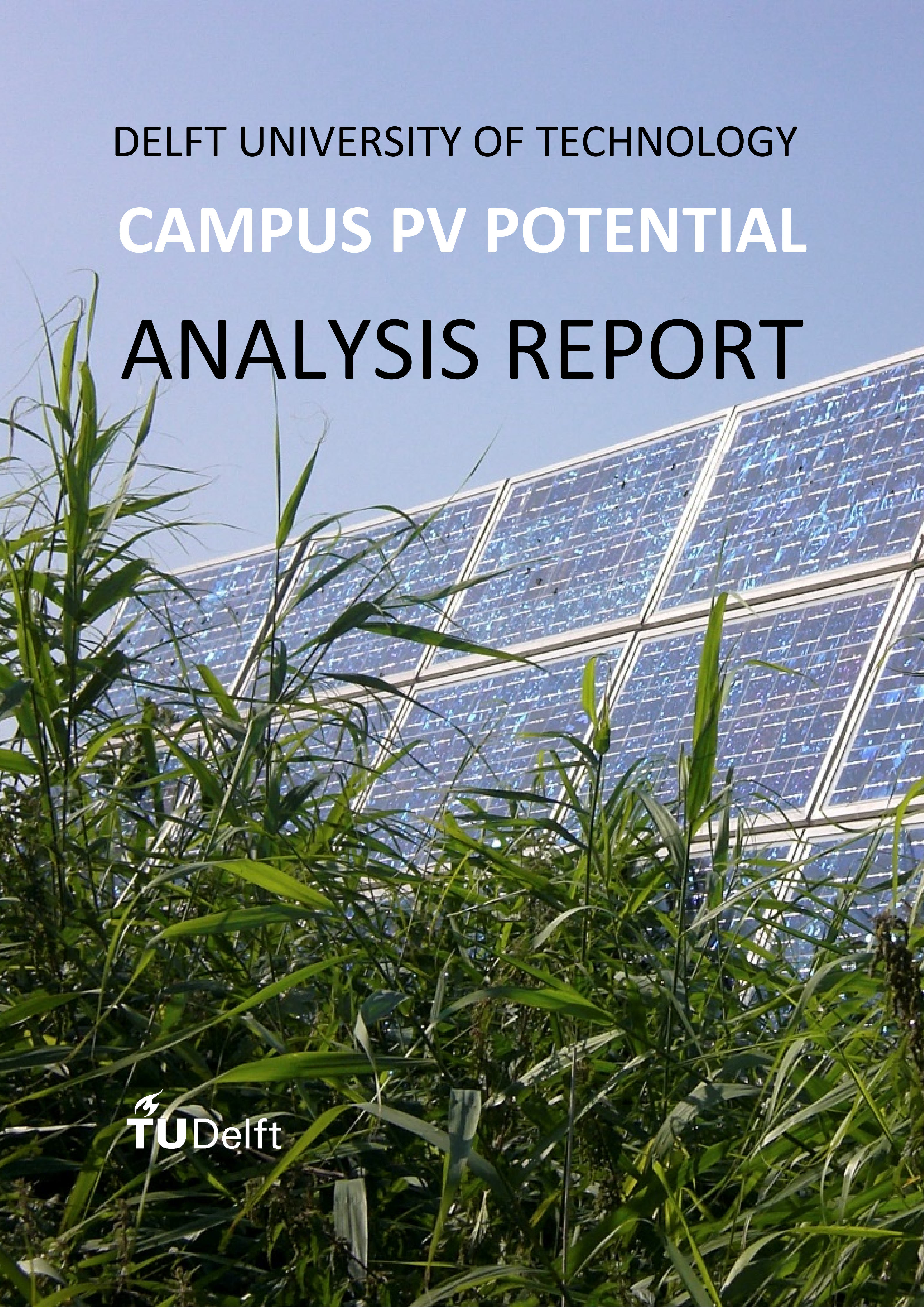
Document Version
Final published version

Citation (APA)
Fremouw, M. A., Zhou, Y., & Nata Djaja, P. (2021). *Delft University of Technology - Campus PV potential, analysis report*. Delft University of Technology.

DELFT UNIVERSITY OF TECHNOLOGY

CAMPUS PV POTENTIAL

ANALYSIS REPORT



TUDelft

Delft, March 2021

AUTHORS

- Michiel Fremouw MSc *
- Yilong Zhou MSc **
- Puji Nata Djaja BSc *

* Delft University of Technology, Faculty of Architecture and the Built Environment (ABE), department of Architectural Engineering + Technology (AE+T), chair of Climate Design and Sustainability (CD&S)

** Delft University of Technology, Faculty of Electrical Engineering, Mathematics & Computer Science (EEMCS), department Electrical Sustainable energy (ESE), Photovoltaic Materials and Devices (PVMD) group

Cover image: Michiel Fremouw

3D building images without a specific credit are taken from Google Earth.

Contents

List of abbreviations

Abbr.	Meaning	Category
3D	Three dimensional	geometry
3mE	Mechanical, Maritime and Materials Engineering (nl: WbMT)	Faculty
ABE	Architecture and the Built Environment (nl: BK)	faculty
AC	Alternating Current	energy
AHN3	Actueel Hoogtebestand Nederland (en: Current Digital Elevation Dataset Netherlands), third edition	dataset
AHN4	Actueel Hoogtebestand Nederland (en: Current Digital Elevation Dataset Netherlands), fourth edition	dataset
AS	Applied Sciences (nl: TN or TNW)	faculty
BK	Bouwkunde (en: ABE)	faculty
CD&S	Climate Design and Sustainability (chair at ABE)	organisation
CEG	Civil Engineering and Geosciences (nl: CiTG)	faculty
CHP	Combined Heat and Power (nl: WKC)	facility
CiTG	Civiele Techniek en Geowetenschappen (en: CEG)	faculty
CRE	Campus Real Estate (TUD)	organisation
DC	Direct current	energy
DUWO	Student housing corporation (no abbreviation)	organisation
E	East	orientation
EEMCS	Electrical Engineering, Mathematics and Computer Science (nl: EWI)	organisation
EKL	Else Kooij Laboratory	facility
ESE	Electrical Sustainable energy (EEMCS department)	organisation
ESP	Electrical Sustainable Power (EEMCS laboratory)	facility
EWI	Elektrotechniek, Wiskunde en Informatica (en: EEMCS)	faculty
FID	FeatureID (object identifier)	GIS
GIS	Geographic Information System	framework
kWh	kiloWatthour	unit (energy)
kWp	Kilowatt Peak	unit (power)
LIDAR	LIght Detection And Ranging	technology
m	meter	unit (distance)
m^2	square meter	unit (area)
MATLAB	Matrix Laboratory	software
N	North	orientation
NE	North East	orientation
NW	North West	orientation
PV	Photovoltaic	technology
PVMD	Photovoltaic Materials and Devices group	organisation
PVPMC	PV Performance Modelling Collective	organisation
RCE	Rijksdienst voor het Cultureel Erfgoed (en: Cultural Heritage Agency)	organisation
RID	Reactor Instituut Delft	facility
S	South	orientation

SE	South East	orientation
SNL	Sandia National Laboratories	organisation
SW	South West	orientation
TBM	Techniek, Bestuur & Management (en: TPM)	faculty
TN	Technische Natuurkunde (en: AS)	faculty
TNW	Technische Natuurwetenschappen (en: AS)	faculty
TPM	Technology, Policy and Management (nl: TBM)	faculty
TUD	Technische Universiteit Delft (en: Delft University of Technology)	organisation
VSSD	Vereniging voor Studie- en Studentenbelangen (en: Organisation for Study and Student Affairs)	organisation
W	West	orientation
WbMT	Werktuigbouwkunde, Maritieme Techniek & Technische Materiaalwetenschappen (en: 3mE)	faculty
WKC	Warmtekrachtcentrale (nl: CHP)	facility

List of figures

List of tables

1. Introduction

The Photovoltaic Materials and Devices (PVMD) group of the faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) at Delft University of Technology (TUD) has been developing a new calculation method to quickly establish PV potential in urban areas, based on AHN3[1] LIDAR data.

The chair of Climate Design and Sustainability (CD&S) at the faculty of Architecture and the Built Environment (ABE) has developed the method of Energy Potential Mapping, which includes PV potential, and has been involved in studies related to the transition to renewable energy of the built environment for over a decade.

In order to accelerate the energy transition of university building stock, the TUD Campus Real Estate (CRE) department has asked the PVMD group to apply their method to the campus, and the CD&S chair to both help validate the model, and identify the proverbial low hanging fruit at the university campus.

[1] https://www.ahn.nl/

2. Campus PV potential assessment

Assessing the PV potential of the campus was done in two stages. The first involved the PVMD 3D model, which calculated the technical potential of roofs and facades. The second stage involved an analysis by the CD&S chair of these results to further categorise building yields and both refine the maximum PV yield on campus, and identify the low hanging fruit.

Both stages developed concurrently and iteratively, with refinements from the analysis stage being fed back into the modelling stage and the refined results then used to update the analysis stage.

The Campus PV potential project will continue. The focus of this part is predominantly on the northern section of the campus (divided by the Kruithuisweg). Although a few specific buildings from the Campus South were included, the southern area in general will be studied in the second part.

2.1. PV potential calculation method

This section describes the steps that are followed in order to arrive at the potential PV yields for the campus. The source data is the AHN3 point cloud, which is transformed into a polygonal building model. For each of the buildings the irradiation per surface is calculated, after which the PV panel placement algorithm covers the available roof surfaces to get a more realistic PV potential.; the panel placements do not represent specific plans. A more detailed description of the calculation method is included in the simulation report.

- Building models: AHN3 point cloud -> mesh simplification -> manual refinement
- Generate a grid on the building surfaces with a density of 0.5m
- Implement a simplified skyline-based model (Sandia National Laboratories, 2015) to calculate annual solar irradiation for all surfaces: 75m buffer around the building bounding box is applied to generate a skyline
- Remove surfaces that have existing PV, green roofs and roof lights
- DC yield for roofs: apply selected panel configuration (portrait, landscape or dual tilt), the DC yield for each panel is averaged over 18 points.
    - Landscape configuration: the longest edge of the panel is parallel to the longest side of the surface segment
    - Portrait configuration: the longest edge of the panel is perpendicular to the longest side of the surface segment
    - Dual tilt configuration: shortest edge is aligned with the longest edge of the surface segment
- AC yield for roofs: implement SNL Model (Sandia National Laboratories, 2015)
- DC yield for facades: sum up the yield for each grid point (which represents $0.25m^2$)
- AC yield for facades: apply fixed percentage to DC yield

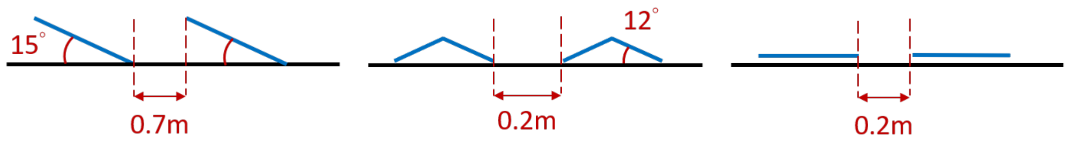


Figure 1 (left): Single tilt configuration (Portrait and Landscape orientations)

Figure 2 (centre): Dual tilt configuration

Figure 3 (right): Zero tilt configuration

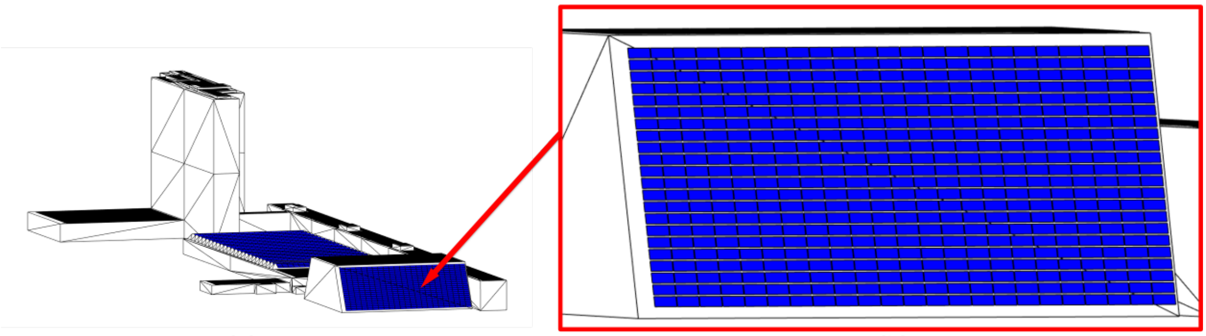
For the landscape and portrait orientations, the array configuration used is single tilt (Figure 1). The dual-tilt configuration (Figure 2) has panels set up back to back, which both results in a higher specific yield (because of fewer spaces between panels), and, if oriented north-south, a better yield spread over the day. For monuments, a special zero tilt configuration was applied, as these are more representative of what would pass the aesthetics committee (*'welstandscommissie'*, see also paragraph 2.4).

For the TUD campus, the buildings themselves are subsequently considered. Because there was no data available on the facades, the open/closed ratio of each facade surface was manually assessed to get an estimate of the facade potential, and applied on the simulation results.

2.2. Suitability

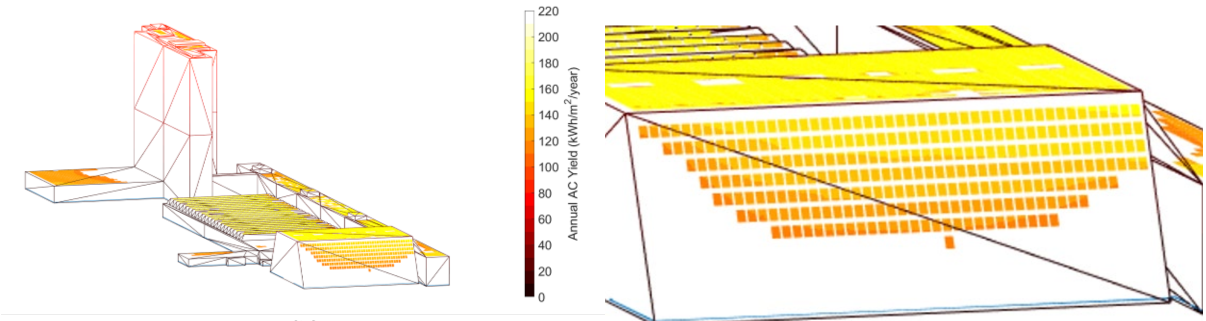
The model calculates solar irradiation first, then attempts panel placement on the roofs (for facades this is not applied) and calculates both the DC and the AC yields. The threshold value for economic feasibility has been set at 650 kWh/kWp (DC yield).

An example of this is the ESP lab's superstructure, one of the few exceptions where the PV placement module could be used on facade: Figure 4 shows a full fitting using an early iteration of the PV placement module. In Figure 2, a more economically realistic placement (away from the edges) is used, and the 650 kWh/kWp threshold is applied, removing panels on the lower area of the facade.



(a) **(b)**

Figure 4: Potential of the ESP lab's southern facade without considering economic feasibility



(b)

Figure 5: Potential of the ESP lab with both a more realistic placement of PV panels, as well as considering payback time

As a final step, in order to select the proverbial low-hanging fruit, a further selection was made of those roof surfaces where the specific yield exceeds 950 kWh/kWp.

As a result, the roof segments were classified based on the specific yield of the PV system mounted. Three categories were considered and each category was assigned with a color: 650~800 (red), 800~950 (yellow) and >950 kWh/kWp (green). The category for each roof surface is determined by the specific yield of the mounting configuration which delivers the highest total annual DC yield. The result is shown in Figure 5 providing information on which roof surfaces shall be prioritized for PV installation.

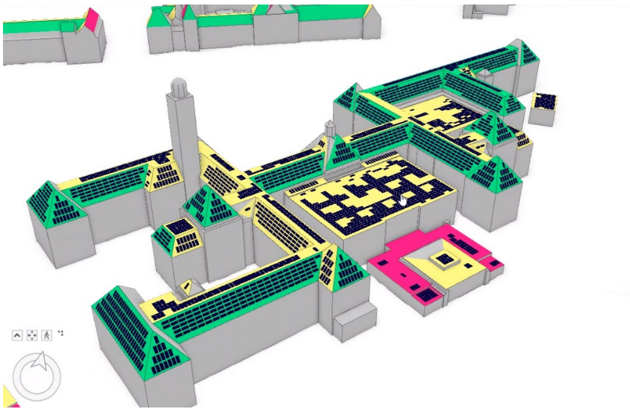


Figure 6: visual distinction of suitability in the 3D model. Note that the analytic considerations in this report were not incldued, this is purely yield.

In Figure 6 the colours were assigned as follows:

- Red = 650 to 800 kWh/kWp
- Yellow = 800-950 kWh/kWp
- Green = 950+ kWh/kWp

This visual model however only considers unfiltered technical yield. A further analysis was applied on these simulation results, see chapter 4.

For facades a similar, but modified approach was used. Because facade surfaces are not oriented ideally from a yield perspective and none of them reach that value, for these the basic economic threshold of 113 kWh/year (based on 650 kWh/kWp using the specific PV panel in the placement module) was used. This is also detailed in chapter 4.

As market prices for PV are expected to lower even further, this would over time increase the number of surfaces that are deemed economically viable. The analysis applied in this report should therefore be revisited in 3 to 5 years' time, as it is likely that more surfaces can at that moment be considered low-hanging fruit.

2.3. Mapping existing roof uses

The panel placement module considers existing uses of the campus roofs as follows:

- First the entire surface is filled with panels, according to a set grid.

- Then a skyline is generated for the surface considered (based on the highest points in the cloud).
- This will reveal if if any of the panels are shaded by the obstacle.

This works well with large obstacles, however others (like rooflights) are small and low in height. During skyline generation, these are too low to have an effect. Furthermore, their footprint is not included either.

Although some obstacles on roofs are tall enough to be part of the AHN3 model, others are not. Examples are existing PV arrays, green roofs, roof lights and smoke hatches. During an earlier iteration of the simulation model, the PV placement module was unable to distinguish some of the ID roof lights (which do not protrude much from the roof surface) and positioned PV panels on top of them.

Therefore, in order to be able to exclude these surfaces and make PV placement more realistic, these features have been mapped for the entire campus based on aerial photography commissioned in summer 2020. Where possible, the dataset has been updated with changes since that period, based on interviews with building managers. The resulting shapefile will be made available on the CRE ArcGIS portal for general use and to facilitate future updates. More on this can be found in section 3.4. Another possible improvement is to increase the resolution at which skyline generation is performed, however separate mapping is likely the most accurate.

Figure 7: example of existing roof uses: green denotes green roofs, yellow PV arrays, blue denotes roof lights. More on this map at paragraph 4.1.

Another category of roof obstructions are building installations. These are in most cases large enough to simply cast a shade and therefore exclude an area by virtue of locally lowering the available radiation. However, even though most of these shade providing obstacles are represented in the AHN3 point cloud, some are too low to be included in skyline generation. This could result in an overestimation of the maximum number of panels that can be fitted to the roof segment that's being considered. Roof surfaces with installations should therefore be subject to a detailed potential study.

2.4. Monuments and protected status

About 40% of the Campus North buildings is subject to a protected status: some buildings are outright monuments (for example the faculty of Architecture and the Built Environment), and some routes (for example the Jaffalaan / Prins Bernhardlaan area) are protected cityscapes, which means adjacent buildings are subject to aesthetics checks. An overview of the TUD campus and associated protected building statuses can be seen in Figure 11.

Applying PV panels to monuments is subject to strict regulations. In most cases, plans will have to pass the municipal aesthetics committee (*'welstandscommissie'*). As of last summer however, the possibilities for mounting PV on monuments without requiring a permit have increased, if they follow certain specifications (Figure 8). Surface areas that are out of public view already provided possibilities, however for those surfaces that are in public view, additional possibilities have opened up.

Figure 8: Cultural Heritage Agency: "more possibilities for solar panels on heritage" (Rijksdienst voor het Cultureel Erfgoed, 2020)

The City of Delft has already applied these regulations for a longer period of time (recently updated (Gemeente Delft, 2021)), as illustrated in Figure 9. In a phone interview, the municipal heritage department (*'monumentenzorg'*) conveys that they are available for advice on implementation.

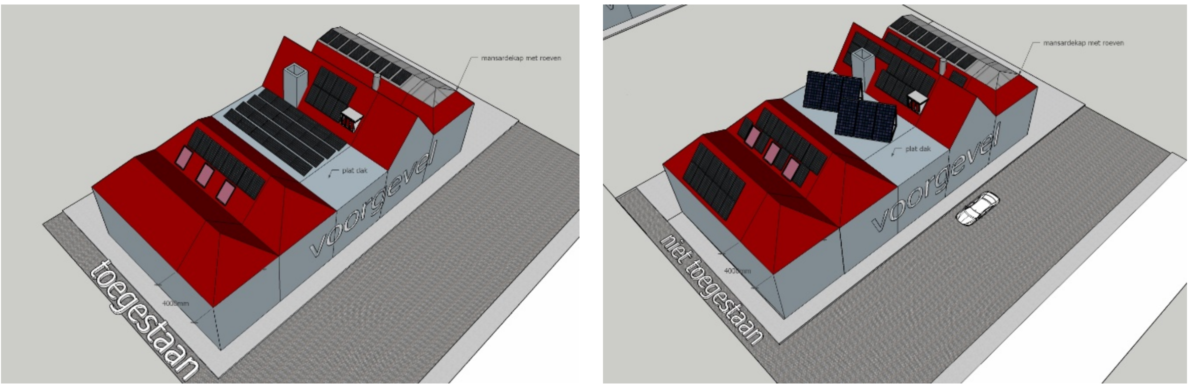


Figure 9: Aesthetics assessment for PV in Delft: on the left examples of permitted PV applications, on the right examples of prohibited ones (Gemeente Delft, 2020)

Even though following these rules might mean a building permit may not be required for specific situations, regulations still apply:

- The zoning plan (*'bestemmingsplan'*) may specify local regulations.
- Aesthetics (*'welstand'*) specifies *'reasonable requirements'*, for monuments these are specified in Figure 8.
- Building code (*'bouwbesluit'*): the technical and safety requirements specified here will always apply.
- Neighbourhood legislation (*'burenrecht'*): neighbours may still object, for example if the PV array results in hindrance due to glare (see also paragraph 3.7).
- In some cases an environmental permit (*'omgevingsvergunning'*) may be required. Figure 10 shows the decision tree that helps determine this.

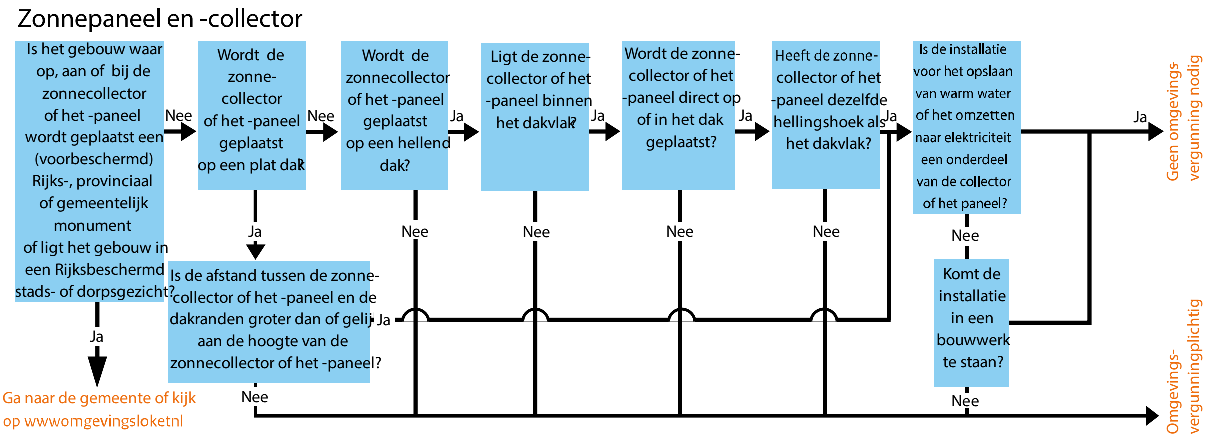


Figure 10: Decision tree for environmental permits ('omgevingsvergunningen') *(Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012)*

The website omgevingsloket.nl provides a permit check for corporate users[2], which can specify per address and per type of intervention, whether an environmental permit is required.

Even on individual buildings this may vary per project (for example flat or sloping roofs), and on the same surface different projects may be considered (for example integrated PV vs an external bracing structure), therefore it is advisable to perform this check when an outline of a project is defined.

[2] https://www.omgevingsloket.nl/Zakelijk/zakelijk/home?init=true

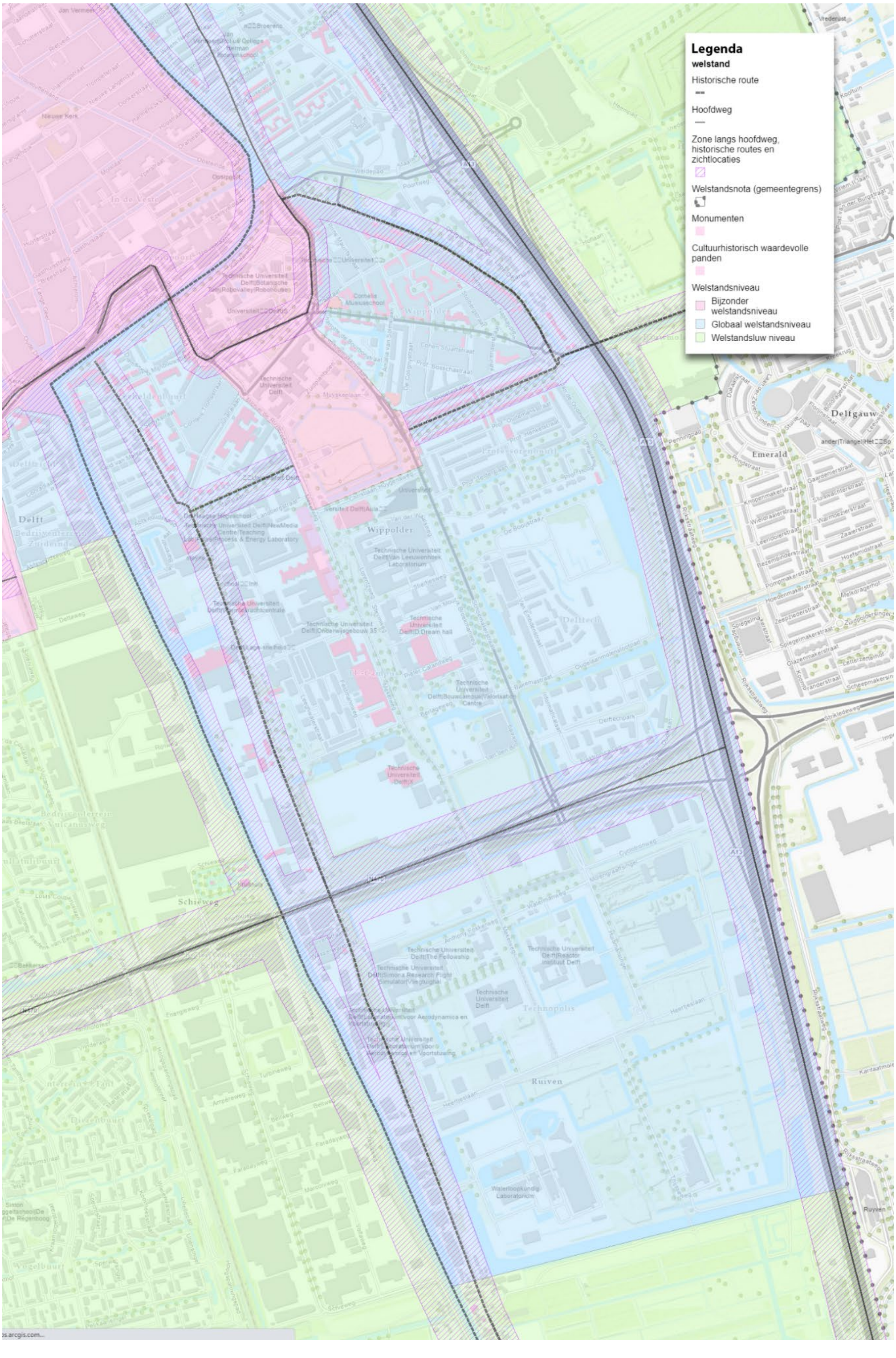


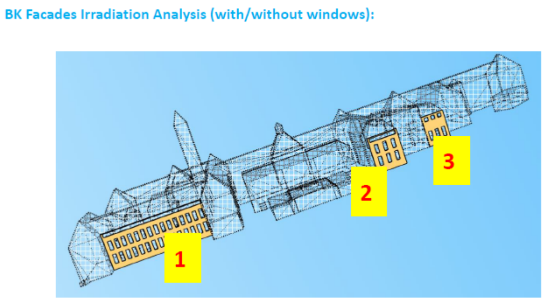
Figure 11: Aesthetic quality map ('welstandskaart'*) of the TU Delft campus. Solid pink denotes a building or area with a special status, hatched pink denotes a* 'beschermd stadsgezicht' *(protected cityscape) route. (Gemeente Delft, 2020)*

3. Analysis notes and modelling recommendations

During the course of this project, several issues were identified. This section details these, and provides solutions where possible. Furthermore, specific potential issues with PV placement on the campus are elaborated upon here.

3.1. Open / closed facades

Geodata on the facades on the TU Delft campus is not available. In order to get a better assessment of the available potential, an estimate was made of the open/closed ratio, so transparent and solid PV (with significantly varying yields) can be applied. For a small number of facade planes the open/closed geometry was drawn in order to validate yield accuracy improvement over the percentage estimate (Figure 12). However, as the panel placement algorithm was not applied to facades, and because of the time required to manually model these, the choice was made to apply visually estimated percentages for the majority of facades.



	Area (w) [m²]	Area (wo) [m²]	Irradiation (w) [MWh]	Irradiation (wo) [MWh]	Area Percentage [%]	Irradation Percentage [%]
Façade 1	350.8	226.4	682.0	441.3	64.71	64.52
Façade 2	88.1	53.8	211.0	156.4	74.12	61.06
Façade 3	83.6	62.7	151.0	120.5	79.80	75.04

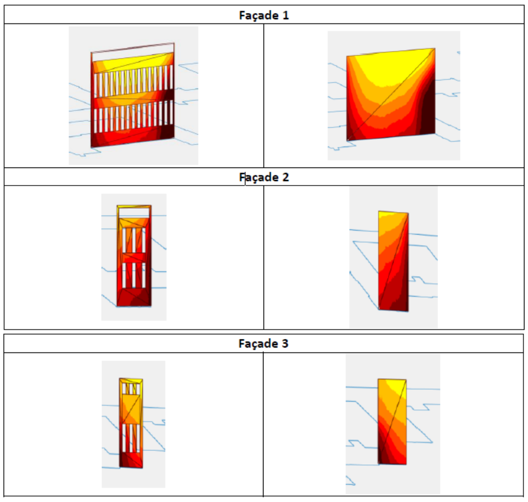


Figure 12: investigating the margin of error on open/closed percentage estimates vs actual geometry on assymetrically shaded surfaces

A future route to be pursued for facade potential could be automatic recognition of Google Street View imagery, which is also applied to 3D building models in Google Earth Pro for faster processing. APIs are available for accessing Google Maps data[3].

3.2. Negative slopes and spaces / apertures

The nature of the AHN3 model means facades outward leaning facades, or those where the roof or a building section also covers an open space, are not automatically mapped correctly.

This has consequences for several buildings, amongst which the Aula and the Central Library, as well as a few elevated walkways and other building apertures (for example the connection between the old TN building (22) and the adjacent buildings (20 (Aula), 97 and 104 (both used by TNO))). In order

[3] https://developers.google.com/maps/documentation/api-picker

to improve the accuracy of the results, or in case of the Aula and Library, get meaningful results in the first place, these surfaces will likely have to be modelled manually.

3.3. Curving slopes

Another category that at present requires special attention in the model are curving slopes. The distinction is made by considering the normal of each surface. If the normal's angle is 0 degrees compared to the ground it is considered a facade, anything else is designated a roof.

For a few buildings this is not accurate, for example buildings 46 (Figure 13) and the ESP lab at EWI (Figure 14). For these cases, manual adjustments need to be made.

Figure 13 curving slopes as roofs or facades in the PVMD 3D model

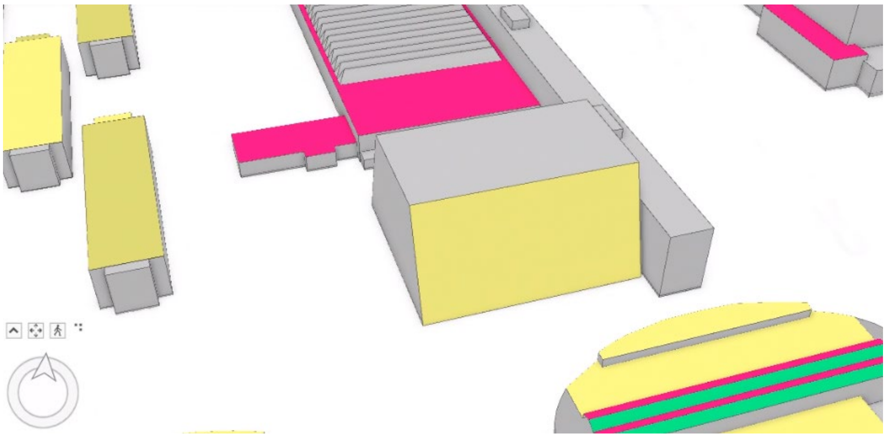


Figure 14: tilted slope as a roof on the ESP lab at EEMCS

3.4. Existing roof usage / obstacles

Slight elevations in the AHN3 model effectively disappear in the noise. Therefore, some roof lights, green roofs and existing PV installations therefore sometimes do not get detected. In order to alleviate this, a geodataset (Figure 15 and Figure 18) was created that contains existing obstacles of these nature, in order to increase the accuracy of the roof panel placement algorithm. As with the facades, image recognition of aerial photography might alleviate this issue.

The dataset created can be found on the CRE ArcGIS repository.

Figure 15: Existing PV arrays, green roofs and rooftops covering the TPM, ID and 3mE buildings

Panel placement on the main roof of the ID building may be optimized further. The roof lights are placed in lines with alternating mutual east-west distances, which means that the grid squares don't always align optimally, therefore potential yield may therefore be somewhat higher. A follow-up study on optimizing panel placement geometry on large roofs with roof lights is recommended.

3.5. Dataset accuracy and age

Multiple use of roofs is an active subject, therefore roof availability will change from year to year. For example, as the aerial photography dataset was recorded in the summer of 2020, several rooftop changes that happened afterward were not included. To a lesser extent, this also applies to ownership of campus buildings (both acquisition and sale), as well as construction of new buildings that were under way at that point. There were also minor mismatches between building footprints.

Finally, the AHN3 LIDAR data for Delft was recorded in 2014 (AHN, 2020) (Figure 16), therefore some new buildings were not included in the dataset. This includes building 58 (TNew), building 33 (Pulse) and others.

LIDAR data collection for the follow up AHN4 dataset is under way, and expected to be finished in 2022 (AHN, 2021). As data aquisition (i.e. LIDAR flights) happens in stages, the segment that covers Delft might however become available sooner (as early as this year).

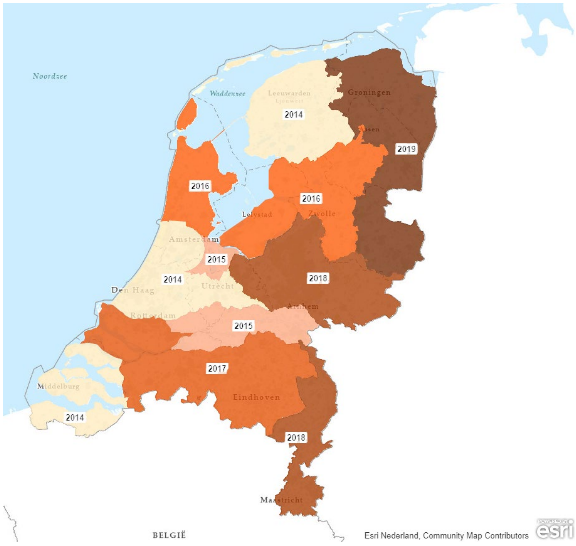


Figure 16: AHN3 dataset, ages per recording area (AHN, 2020)

3.6. Roof structure status

This remains an open subject, as support from the structures field was unavailable despite repeated attempts at acquisition. Geodata on roof and facade structures does not exist, which means an automated large scale first order assessment of an area will not be possible.

Furthermore, as structural safety regulations have evolved over time, and drawings of older buildings are not digitized and may be incomplete or inaccurate, both rooftops and facades will have to undergo a detailed structural analysis as part of a feasibility study.

3.7. Glare

Both low lying roofs and facades may cause glare towards other buildings if PV panels are applied to them. Care should therefore be taken to either suitably orient these, apply antireflective coating, or both.

For glass facades, glare may already exist, therefore anti-reflective coatings may eliminate an existing problem rather than add one.

Although detecting glare issues automatically will require additional research, this might be an interesting future feature to include in the 3D modelling method.

3.8. Skyline radiation radius and highrise

For the annual yield calculations only those buildings in a radius of 75m are considered. The only building of significance for this is EWI at 96m height, and only during limited hours of the day for affected buildings (EWI and CiTG, 3mE, TNW and Drebbelweg 5 (building 35)). Because of this and the spacing between these and the EWI highrise building, the quantitative effect should be limited.

For areas with dense highrise (>~75m) however, like the centre of Rotterdam and the Zuidas in Amsterdam, a sensitivity analysis is recommended to see what the effect is.

Figure 17: due to the wide spacing between buildings, the EWI highrise only has a limited effect on annual potential.

3.9. AC / DC

The simulation module provides PV potential both in AC and DC. Electronics and led lights require DC, therefore an efficacy increase of roughly 10% could be achieved by running part (either per building or campus wide parallel with AC) or whole of the campus electricity network in DC. In order to facilitate connecting to existing plans however, the AC yield values have been used in this report. The DC values are available directly from the model.

3.10. Peak shaving (diurnal yield distribution)

Although individually PV arrays may be ideally angled in one specific way in order to maximise annual yield, their impact on the electricity grid and alignment with campus electricity demand should be taken into account. It may therefore be better to also consider other orientations and east/west facing facades, so that the total hourly yield of the campus PV arrays is properly distributed over the day, rather than maximised for annual production.

It might be possible to apply diurnal curves on the calculated annual yield, effectively recreating hourly production for the different orientation options.

3.11. Trees and shading

A point of interest related to the previous paragraph is foliage. Because of the nature of the AHN3 model, the trees cast a year round full shade, even though almost all trees on campus are deciduous, and will therefore be far more transparent in winter.

The difference in yield between summer and winter is about sixfold during solar noon, so the effect on *total annual* yield will likely be very limited, however *winter peak* yield on those facades and roofs that receive tree shade may be better, than would initially expected based on these results. It is possible to automatically identify trees as such in AHN data (Meijer, Rip, van Benthem, Clement, & van der Sande, 2015) (WUR, 2014), which would allow these objects to be classed as semitransparent for part of the year. An existing data source that applies this method is the Bomenregister (“tree register”) (Geodan, 2015).

4. Campus PV potentials

The 3D model has irradiation values for most of the campus, however for the analysis CRE requested focus on the Campus North buildings. Some buildings were excluded from the study because they are being or have been sold, and therefore removed from TUD building stock. The area of focus is further described in paragraph 5.

Potential calculation is done in four stages (Martin, 2015):

1. determine the solar radiation incident on a surface considering the factors that influence it (physical potential)
2. identify available roof surface to place the appropriate PV systems (geographic potential);
3. estimate the potential power generation of a given technology in a view of the technical limitations and efficiency (technical potential)
4. the cost analysis with the installations and the energy generation (economic potential).

In the Campus PV project, stages 2 and 3 are combined. Stage 4, the economic potential, will be part of the follow-up second phase of this project.

Full campus physical potential: the total solar radiation received by the rooftops of the campus buildings considered is 100 GWh/a. Solar radiation received by their respective (south facing) facades is 55 GWh/a.

Full campus technical potential: Around 17% of this combined physical potential of 155 GWh/a, or about 26 GWh/a, can be converted into electricity, before geometry (windows, door and other obstacles) and technical restrictions (for example panel placement) are applied.

When including these restrictions for the buildings taken into consideration (as described in chapters 2 and 5), the technical potential is about **8.1 GWh/a** for the campus. This is higher than estimated in the CO_2 roadmap TU Delft (Blom & Dobbelsteen, 2019) which estimates 6 GWh/a for roofs and surfaces on the full campus, however this requires some elaboration: due to the detailed method applied to roofs, the new potential yield for roofs has a higher degree of confidence, whereas continuing insufficient data for facades means that the level of confidence for facade potential will be improved but still relatively low.

Total campus electricity demand (Blom & Dobbelsteen, 2019) is 82.3 GWh/a. Therefore, around 10% of the *current* electricity demand of the entire campus could potentially be supplied by the roofs and facades of the Campus North, reducing the carbon footprint by about **800 tons** of CO_2-equivalent.

4.1. Existing roof PV production

Table 1 lists production details for the existing roof PV arrays at TUD (including Campus South here), averaged over the years of 2017-2020, based on data received from CRE.

name	installed peak power [kWp]	average yield [kWh/year]	availability	notes
Building 23III	84.8	79,251	99.9%	
Building 26	22.8	21,570	99.9%	
Building 31	54.6	48,466	91.3%	Relatively low availability due to inverter issues
Building 32	121.4	114,463	99.8%	
Building 36 HD	68.4	64,394	97.1%	
Building 36 Sheds	133.6	124,536	98.7%	
Building 37	101.8	63,269	62.6%	average over 2019-2020 is expected to be more characteristic, 94822 kWh/year at 92.1% availability
Building 38	42.4	38,606	99.1%	
Building 58	135.2	134,852	99.0%	
Building 60	24.4	22,252	99.9%	
Building 61	130.4	118,670	98.0%	
Building 62	94.9	80,441	95.9%	grounding issue in 2016, not detected due to compounding network issues
Building 64	86.9	72,765	95.4%	array temporarily turned off in 2018 due to overheating issues with distribution boards
TOTAL	**1101.3**	**983,534**		

Table 1: existing PV arrays on campus, data averaged over 2016-2019 period

The areas that these PV arrays occupy have been mapped (see Figure 18) and excluded from the areas included in the roof potential calculations below (as described in paragraph 3.4).

The age and technical state of these arrays has not been studied, therefore some improvements may be gained from replacing existing modules by newer, higher efficiency ones, and applying denser placements (like the dual tilt configuration, as described in paragraph 2.1).

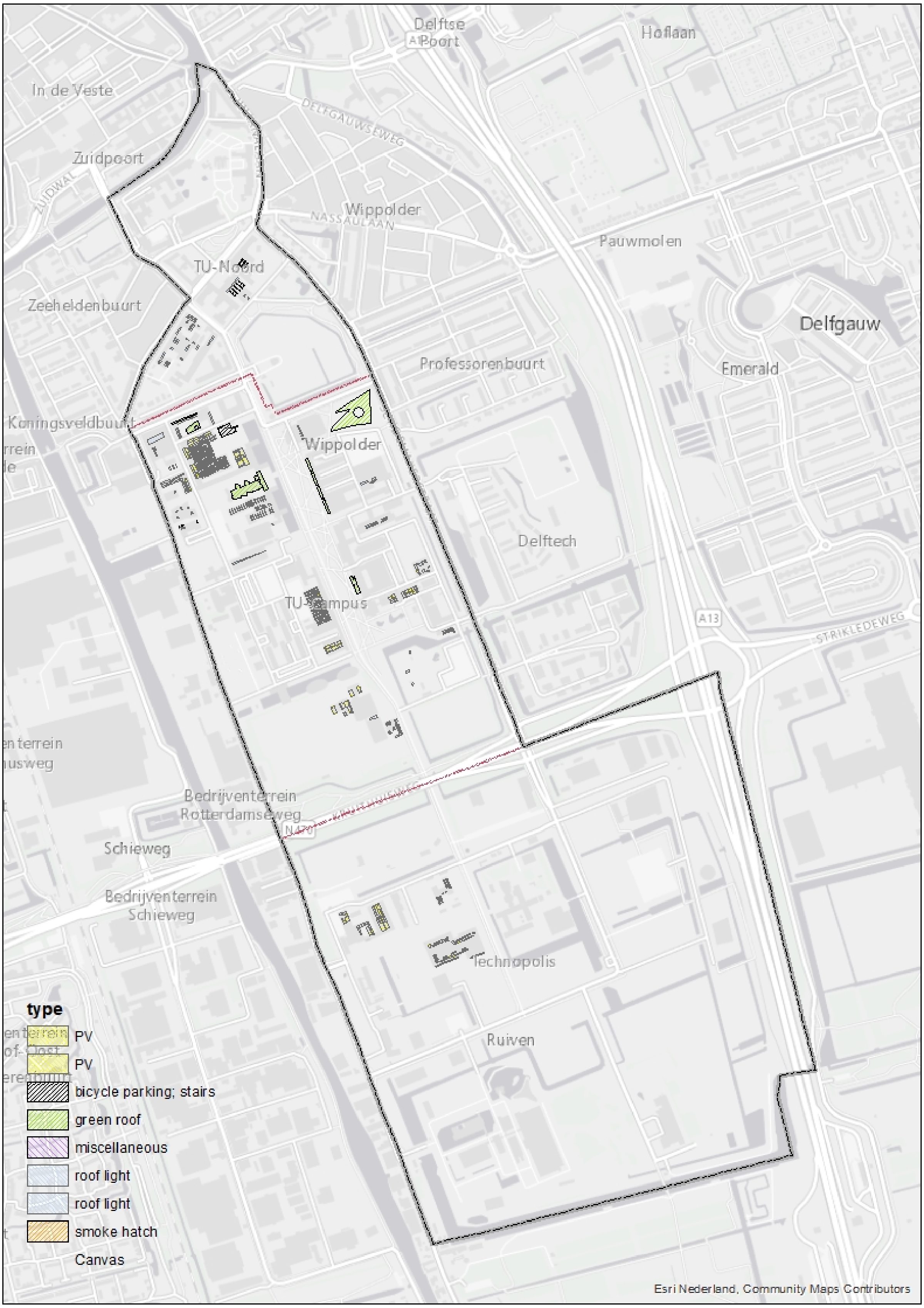


Figure 18: existing PV arrays, green roofs, roof lights and other low height obstacles at the TUD campus

4.2. Total roof potential

Total potential yield for the roofs, with a minimum specific yield of 650 kWh/kWp, is around **4.7 GWh/year**. This roof potential includes an additional refinement step in order to approximate technical yield: the PV panel placement module (as described in paragraph 2.1).

building #						YIELD CATEGORIES [MWh/a]				
	#	FID	best DC yield [MWh/a]	best AC yield [MWh/a]	max # modules	'low hanging fruit' [MWh/a]	'interesting' [MWh/a]	'other, non monument' [MWh/a]	'monument, partially visible' [MWh/a]	'monument, fully visible' [MWh/a]
ABE / BK	8	94	792.8	728.5	2,331	67.5	100.8	154.6	88.1	317.5
Aula	20	54	213.8	196.7	615	0	0	116	0	80.7
LIB	21	97	0	0	-			0		
AS / TN	22	43+44	689.2	632.7	2,143	608.7	0	24	0	0
CEG / CiTG	23	47+51+52+56	588.5	543.8	1,868	0	305.2	238.6	0	0
BCAMP	26	46+49	80.9	74.2	265	0	0	74.2	0	0
MATH	28	96	8.3	7.6	24			7.6		
ESA	30	60	109.3	100.3	338	0	50.4	49.9	0	0
TPM / TBM	31	57	30.6	28.1	91			28.1		
ID / IO	32	64	243	197.2	685	197.2				
3mE	34	74+75	567.4	521	1,822	0	228.1	292.9	0	0
DREB5	35	55	231	212.2	745	31.7	153.7	26.8	0	0
EEMCS / EWI	36	67	251.4	230.5	872	0	78.6	151.9	0	0
X-SPO	37	59	145.5	133.4	460	0	0	133.4	0	0
X-CUL	38	61	0	0	-	0	0	0	0	0
CHP / WKC	43	73	44.3	40.6	143	0	0	40.6	0	0
LSL / VSSD	45	76	25.8	23.8	88	0	0	23.8	0	0
RID	50	24	526.6	483.5	1,676	319.5	120	44	0	0
DC-RID	57	10	27.3	24.9	113			24.9		
AS / Tnew	60	7	38.5	35.2	127	0	0	35.2	0	0
L&E / L&M	61	4	24	22	82	0	0	22	0	0
AIRCR	62	1	39.3	36	164	0	0	36	0	0
AERO / LR	63	0	19.9	18.3	64			18.3		
SIMONA	66	8	106.6	97.9	335	97.9				
HSL	64	3	24.8	22.7	85			22.7		
P-ROTT	PG	-	334.7	307.5	812	307.5	0	0	0	0
TOTAL				**4,719**	**#####**	**1,630**	**1,037**	**1,566**	**88**	**398**

Table 2: Campus North buildings, roof yields and categories

Of this, 18 surfaces on seven buildings, amounting to about **1630 MWh,** are considered ***'low hanging fruit'*** (as described in paragraph 4.4), and a further 9 surfaces on seven (slightly different) buildings, or **1037 MWh,** are considered ***'interesting'*** (below the *'low hanging fruit'* threshold but having larger surfaces, therefore a high yield per project). These categories include surfaces on monumental buildings that no not have public visibility.

The other categories are monuments with partial (6 surfaces, 93 MWh) or full visibility (38 surfaces, 434 MWh) from public areas, and finally all others that do not fall into any of the previous categories (224 surfaces, 2,119 MWh).

category	threshold value	
'economic', minimum density	650	kWh/kWp
'interesting', minimum density	800	kWh/kWp
'interesting', minimum yield	50	MWh/a
'low hanging fruit', minimum density	950	kWh/kWp
'low hanging fruit', minimum yield	25	MWh/a

Table 3: roofs, thresholds per category

category	# surfaces	yield [MWh/a]
'low hanging fruit'	18	1,630
'interesting'	9	1,037
'other, non-monument'	224	1,566
'monument, partially visible'	6	88
'monument, fully visible'	38	398
TOTAL	295	**4,719**

Table 4: roofs, potential per category

These figures are about unused potential of the known campus: current roof usage, including existing PV arrays and green roofs, have been excluded. The simulation model however makes it possible to recalculate technical potential if roof surfaces become available again for repurposing, or if surfaces are being claimed for other uses. As mentioned in paragraph 3.5, the AHN4 dataset that covers Delft will be released in 2021 or 2022, and provide a new 3D snapshot of the campus buildings in existence at that moment. Furthermore, only surfaces with a minimum of 650 kWh/kWp are considered. If the price of PV panels goes down further, this threshold will also have to be adjusted, and more surfaces become available.

4.3. Total facade potential

Total potential yield for the facades, without any restrictions applied, is around **3.9 GWh/year**. However, as described in the modelling recommendations chapter, this campus facade potential has a high degree of uncertainty.

A quick summary: Due to the nature of the aerial LIDAR based AHN3 dataset, facade data is usually limited to extruding building footprints. Sloping facades, especially negative ones, as well as negative spaces (for example under walkways, or the Auditorium of the Aula) cannot be included.

Furthermore, without detailed data on facade geometry (walls and apertures), applying the PV placement module is not possible. In order to alleviate this inaccuracy, a basic open/closed percentage was applied to the facades under consideration, where the open (window) sections produce 10% of the yield of the closed (wall) areas, by using transparent PV (equating ~2% panel conversion efficiency, although technology development might increase this significantly).

It can be expected that monumental restrictions (requiring suitable aesthetics of the PV technology used, for example mimicking bricks) and unfavourable geometry (for example narrow walls between window sections) will bring this total down even more.

The DC yield threshold for promising facades was derived from the PV panel used in the simulation placement module:

- Economic threshold for specific power for roofs: 650 kWh/kWp
- Peak power of a PV panel: 0.365 kWp
- Annual DC yield for a PV panel: 650 * 0.365 = 237 kWh/a
- Annual DC yield per m^2 = 237 kWh / (2.066m * 0.997m) = **113 kWh**

4.4. Roofs with a high specific yield

From the list of roof surfaces, about 1,630 MWh/a is considered *'low hanging fruit'*, based on three categories:

- A minimum **specific yield** of **950 kWh/kWp** (low payback time)
- A minimum **AC yield** of **25 MWh/a** (minimum array size)
- No full or partial **monumental restrictions** (which would require a permit and extra time)

#	FID	roof index #	area [m2]	visibility (monuments)	**highest yield with type:**	**AC yield [MWh/a]**	no. of modules	specific Yield [kWh/kWp]
8	94	5	254.2	N	Portrait	29.9	92	967.7
8	94	36	528.5	N	Portrait	37.6	118	951.1
22	43+44	1	1283.6	n/a	Dual Tilt	133.8	448	989.2
22	43+44	2	1414.8	n/a	Dual Tilt	107.8	371	963.3
22	43+44	3	1292.1	n/a	Dual Tilt	104.2	353	983.6
22	43+44	4	1081.8	n/a	Dual Tilt	80.3	267	990.6
22	43+44	5	980.5	n/a	Dual Tilt	85	284	995.1
22	43+44	6	692.5	n/a	Dual Tilt	53.8	183	968.8
22	43+44	7	443.3	n/a	Dual Tilt	43.8	144	1008.4
32	64	1	5971.3	n/a	Dual Tilt	197.2	685	973.6
35	55	1	387.9	n/a	Landscape	31.7	94	1013.9
50	24	1	1913.9	n/a	Dual Tilt	136.7	459	993.1
50	24	2	766.3	n/a	Dual Tilt	74	247	995.9
50	24	4	593.4	n/a	Dual Tilt	57.8	196	987.5
50	24	6	595.3	n/a	Dual Tilt	51	175	973.2
66	8	1	1650.9	n/a	Dual Tilt	97.9	335	972.6
PG	-	1	1868.0		Dual Tilt	186.5	612	1005.1
PG	-	2	1159.0		Dual Tilt	121	200	989.5

Table 5: Roofs, low hanging fruit

A more detailed description of these surfaces can be found in the campus buildings section.

4.5. Additional roofs with a high total yield

From the remaining roofs, a second selection was made, focusing on larger roofs that did not meet the *'low hanging fruit'* thresholds. The following values were used:

- A minimum **specific yield** of **800 kWh/kWp** (low payback time)
- A minimum **AC yield** of **50 MWh/a** (minimum array size)
- No full or partial **monumental restrictions** (which would require a permit and extra time)

building					**CONFIGURATION SELECTION**			
#	FID	roof index #	area [m2]	visibility (monuments)	**highest yield with type:**	**AC yield [MWh/a]**	no. of modules	specific Yield [kWh/kWp]
8	94	35	1453.6	N	Portrait	100.8	343	880.1
23	47+51+52+56	3	4000.0	n/a	Portrait	305.2	1010	903.7
30	60	1	798.8	n/a	Portrait	50.4	166	906.2
34	74+75	27	2194.0	n/a	Landscape	137.8	489	841.3
34	74+75	28	1328.3	n/a	Portrait	90.3	305	882.9
35	55	2	2418.7	n/a	Dual Tilt	153.7	549	921.9
36	67	1	1352.5	n/a	Landscape	78.6	284	830.4
50	24	3	788.3	n/a	Dual Tilt	67.9	248	903.7
50	24	5	801.8	n/a	Dual Tilt	52.1	200	860.4

Table 6: Roofs, 'interesting' category – high yield, not featured in the 'low hanging fruit' section

4.6. Facade selection

For the facades the selection method was similar: the economic threshold of 650 kWh/kWp was translated into **113 kWh/m²** (as there is no PV panel placement, using kWp was not possible), as well as no monumental restrictions. The number of facades that reach this threshold is quite limited, see Table 7:

building #						**protection status**			10%	100%				
TUD	FID	Façade Index number	Area [m2]	Open Ratio [-]	Closed Ratio [-]	building = monument?	near city view?	surface visibility?	AC Yield (open) [MWh/a]	AC Yield (closed) [MWh/a]	AC yield density (open) [kWh/m²]	AC yield density (closed) [kWh/m²]	**total open/closed AC yield [MWh/a]**	**AC yield density [kWh/m^2]**
34	74+75	13	111.9	0.05	0.95	Y	N	N	0.1	12.9	12.2	121.5	**13.0**	**116.1**
36	67	5	873.8	0	1	?	N	N	0.0	105.2		120.4	**105.2**	**120.4**

Table 7: Facades, high specific yield average

This selection however considers complete facades, and combines the yield densities of both open and closed sections. In order to further identify potentially promising facades, an additional selection was based on the yield of purely the closed sections of each facade (Table 8), as well as large open

(Table 9) and closed (Table 10) areas. Facade #3 on the Mathematics building (28) features in both of these latter categories.

building #						protection status			10%	100%				
TUD	FID	Façade Index number	Area [m2]	Open Ratio [-]	Closed Ratio [-]	building = monument?	near city view?	surface visibility?	AC Yield (open) [MWh/a]	AC Yield (closed) [MWh/a]	AC yield density (open) [kWh/m²]	AC yield density (closed) [kWh/m²]	**total open/closed AC yield [MWh/a]**	**AC yield density [kWh/m^2]**
26	46+49	6	1049.4	0.6	0.4	N	N	N	7.3	48.4	11.5	115.2	**55.6**	**53.0**
32	64	3	556.5	0.4	0.6	N	N	N	2.7	40.4	12.1	121.1	**43.1**	**77.5**

Table 8: Facades, economic threshold, only considering closed surfaces

building #						protection status			10%	100%				
TUD	FID	Façade Index number	Area [m2]	Open Ratio [-]	Closed Ratio [-]	building = monument?	near city view?	surface visibility?	AC Yield (open) [MWh/a]	AC Yield (closed) [MWh/a]	AC yield density (open) [kWh/m²]	AC yield density (closed) [kWh/m²]	**total open/closed AC yield [MWh/a]**	**AC yield density [kWh/m^2]**
28	96	3	985.3	0.3	0.7	N	N	N	3.2	73.6	10.7	106.8	**76.8**	**77.9**
22	43+44	15	260	1	0	N	?	N	3.0	0.0	11.7		**3.0**	**11.7**

Table 9: Facades, large area, only considering open surfaces

building #						protection status			10%	100%				
TUD	FID	Façade Index number	Area [m2]	Open Ratio [-]	Closed Ratio [-]	building = monument?	near city view?	surface visibility?	AC Yield (open) [MWh/a]	AC Yield (closed) [MWh/a]	AC yield density (open) [kWh/m²]	AC yield density (closed) [kWh/m²]	**total open/closed AC yield [MWh/a]**	**AC yield density [kWh/m^2]**
8	94	5	523.2	0.35	0.65	Y	Y	Y	1.9	35.9	10.6	105.7	**37.9**	**72.4**
23	47+51+52+56	7	494	0.1	0.9	?	N	N	0.5	46.4	10.4	104.3	**46.9**	**94.9**
28	96	3	985.3	0.3	0.7	N	N	N	3.2	73.6	10.7	106.8	**76.8**	**77.9**
30	60	5	297.1	0.02	0.98	N	N	N	0.1	30.2	10.4	103.7	**30.2**	**101.8**
34	74+75	20	496.4	0	1	Y	N	N	0.0	54.7		110.2	**54.7**	**110.2**
38	61	2	289.3	0.1	0.9	N	N	N	0.3	28.3	10.9	108.5	**28.6**	**98.8**

Table 10: Facades, large area, only considering closed surfaces

Selecting potential facades is more complicated, both due to the more limited amount of data on their makeup, as well as the presence of windows and much higher visibility of PV (mounted or integrated), compared to roofs. The selection here should therefore only be used as an indication.

5. Campus buildings

This section describes specific cases for the buildings on the Campus North. Buildings 5/6, 12 and 15 are not included because of plans to sell these, and the buildings on the Campus South are part of the second phase that follows this study. The basis for the analysis are the results as described in the simulation report. Table 11 provides an overview.

	DESCRIPTIONS		11	17	MONUMENTS		
			open/closed?				
TUD #	name EN	status notes	percen-tage	geo-metry	monument status?	beschermd stadsgezicht?	roof PV angle
8	Architecture and the Built Environment (ABE)		y	some	Rijksmonument	x	flat
20	Aula Conference Centre	open/closed impossible from AHN3 data	-	-	Rijksmonument	x	flat
21	TU Delft Library	open/closed impossible from AHN3 data	-	-	Gebouw met prijswinnend ontwerp, eigendom TUD	x	flat
22	Applied Sciences		y	some	-	x	tilted
23	Civil Engineering and Geomatics (CEG)		y	n	Gemeentemonument	x	flat
26	Building Campus		y	some	-	x	tilted
28	Mathematics		y	n	-	x	tilted
30	Education & Student Affairs (ESA)		y	n	-	v	flat
31	Technology, Policy & Management (TPM)		y	n	-	v	flat
32	Industrial Design (ID)		y	some	-	x	tilted
34	3mE		y	n	Rijksmonument	x	flat
35	Education building Cornelis Drebbelweg 5		n	n	-	x	tilted
36	g, Mathematics and Computer Science (EEMCS)		y	some	Gemeentemonument	x	flat
37	Sports	recently rebuilt, AHN3 and streetview not up to date yet	-	-	-	x	tilted
38	Culture		n	n	-	x	tilted
43	Combined Heat and Power plant		y	n	Gemeentemonument	v	flat
45	Low Velocity Laboratory / VSSD / InHolland	too much shading	-	-	-	v	flat
50	Reactor Institute Delft	TU south, no priority	-	-	-	x	tilted
57	Data centre RID	TU south, no priority	-	-	-	x	tilted
58	Applied Sciences (AS-South)	TU south, no priority	-	-	-	x	tilted
60	Logistics & environment	TU south, no priority	-	-	-	x	tilted
61	Aircraft hall	TU south, no priority	-	-	-	x	tilted
62	Aerospace	TU south, no priority	-	-	-	x	tilted
63	SIMONA Research Flight Simulator	TU south, no priority	-	-	-	x	tilted
64	High Velocity Laboratory	TU south, no priority	-	-	-	x	tilted
66	The Fellowship	TU south, no priority	-	-	-	x	tilted

Table 11: overview of TUD campus buildings and modelling / protection properties

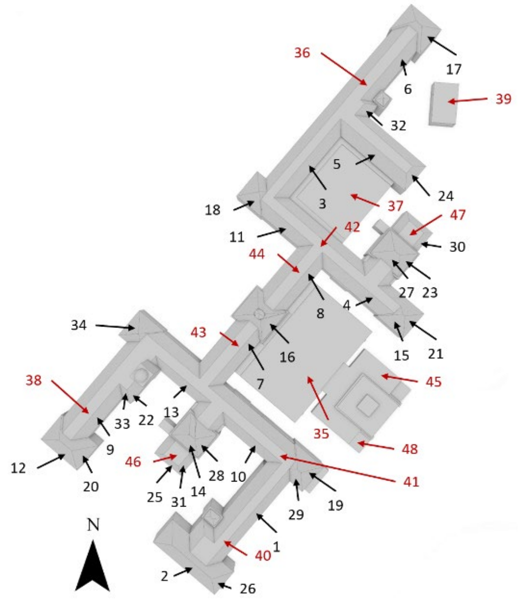
The buildings are considered partially independently from the larger study, in order to take into account specific circumstances. Therefore, although the simulation provides a solid background, different roof and facade surfaces may be in- or excluded in the analysis than purely based on the simulation results.

5.1. ABE / BK (building 8)

The ABE building (which hosts the CD&S chair, part of the writing team of this study) can provide up to 765 MWh/a from its roofs and up to 308 MWh/a from its facades. However, given its monumental status, these figures will likely be much lower in the economic analysis, as suitable and affordable PV products need to be applied in order to pass municipal aesthetics requirements (*'welstandseisen'*) for monuments.

Figure 19: ABE building (8) roof, roof lights and smoke hatches highlighted

The faculty of Architecture and the Built Environment is a national monument (*"Rijksmonument"*) and therefore subject to stricter limitations than other buildings. Surfaces in public view require a permit (and approval by the aesthetics commission, the *"welstandscommissie"*) and PV application would therefore take longer than other places. Thanks to changes in regulations however, there are a few areas (mostly the flat roofs) that do not require this permit, given specific conditions (see also paragraph 2.4). This would make the ABE building a promising pilot for historic building PV applications.



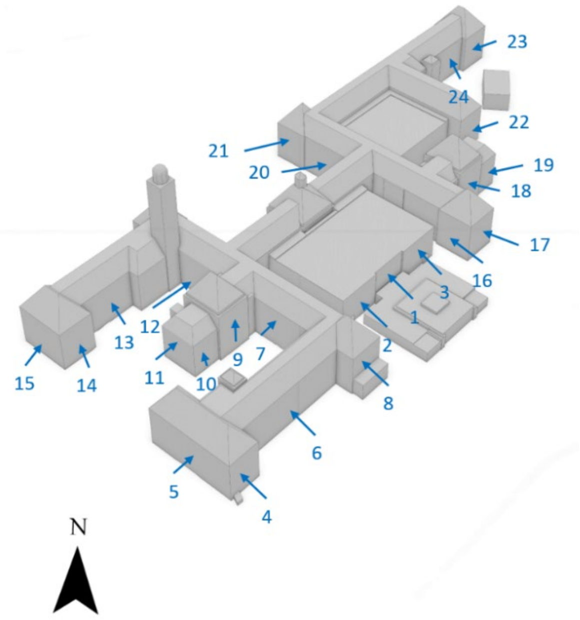


Figure 20 (left): Roof FIDs for building 8

Figure 21 (right): Facade FIDs for building 8

Two roof surfaces are considered low-hanging fruit based on their high specific yield and lack of visibility from public space (cfr monumental restrictions): roof 5 (30 MWh/a) and roof 36 (38 MWh/a), both highlighted on Figure 19.

Figure 22: Building 22 roof: steel beams and wood support structure [photo: Michiel Fremouw]

For roof 5, the yield will be lower than the PV module projects due to the monumental requirement of using strictly rectangular arrays (i.e. no sawtooth stacked edges), and for roof 36 there is a steel fall prevention wire running on top of the roof centre line, that needs to be taken into account (see Figure 23 and Figure 24). In both cases, the wooden roof structure (Figure 22) has a limited load capacity (van Kan, 2014), and therefore likely needs to be strengthened or bypassed with a separate support structure.

Figure 23 (left): Building 8, flat roof [photo: Michiel Fremouw]

Figure 24 (right): Building 8, fall prevention wire [photo: Michiel Fremouw]

Roof 35 (the Model Hall, or *"Maquettehal"*) is in the 'interesting' category due to a large surface (101 MWh/a between the smoke hatches and building services) and still a good specific yield (880 kWh/kWp). The loadbearing capacity of the roof support structure however was described in interviews as 'light', and therefore may need strengthening to support the additional weight. This needs to be investigated.

Finally, facades 5 and 15 (facing the Michiel de Ruyterweg) have a promising specific yield on their closed surfaces. These will however be challenging to utilise, as they are both part of a national monument (*"rijksmonument"*) and facing a protected cityscape area. This however also makes them interesting test cases.

Bouwpub

The Bouwpub building has a wooden roof structure and may require strengthening for PV to be feasible. Its potential is not part of the low-hanging fruit group, however still has a good specific yield of 857 kWh/kWp (and an AC yield of 16 MWh/a). Preventing glare towards both the faculty itself and the adjacent housing properties should be prevented by applying suitable panel orientation and anti-reflective coatings.

5.2. Aula (building 20)

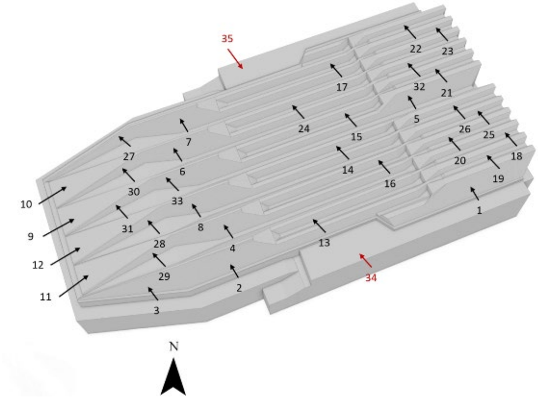
The Aula can provide up to 186.6 MWh/a from its south facing roofs (using the Landscape configuration).

As with several other buildings on campus, the shed roofs have favourably oriented southern slopes. As roof FIDs 4-8 (totalling 23 MWh/a) are not visible from public space, these could in combination be considered low-hanging fruit, given the design limitations mentioned in section 15. The relatively homogenous texture combined with the great distance from public space (ground floor) might make it possible to develop an integrated PV design that exceeds the yield mentioned above. A point of concern is the available loadbearing capacity of the wooden roof structure, which needs to be investigated (see below).

Due to the limitations of AHN3 based modelling and both negatively sloped facades and negative spaces below the building, facade potential cannot properly be established. Furthermore, as the building is a monument, facade renovations would require special attention to aesthetics in order to pass cultural heritage regulations.

Figure 25: Aula

Regarding loadbearing capacity, Van Kan (2014) suggests removing 15mm of rock ballast from those sections of roof where PV panels are placed. This likely refers to the flat roof sections on both sides, the shed roofs do not seem to be mentioned.



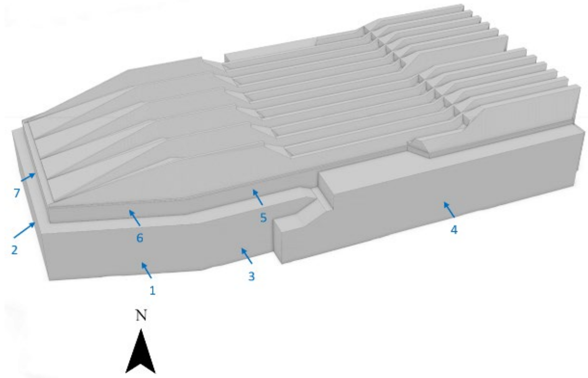


Figure 26 (left): Aula, roof FIDs

Figure 27 (right): Aula, facade FIDs

5.3. TU Library (building 21)

The Central Library has few potential options due to its negatively angled glass facades and green roof, and is therefore not considered part of the *'low-hanging fruit'*.

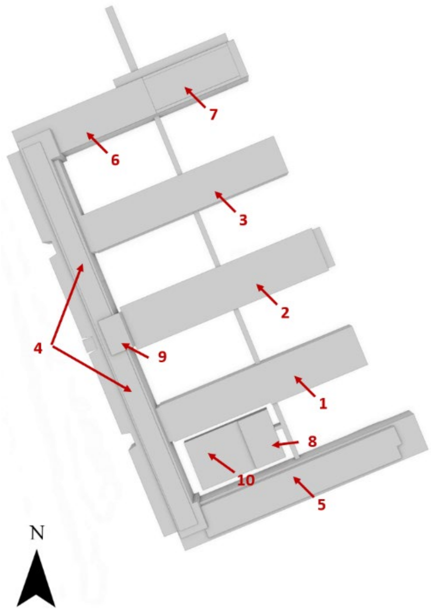
There is potential for PV technology demonstrators: examples are replacing the stepping stones with structural PV panels, and applying appropriately coloured, curved (or flexible) PV on the southern third of the cone.

Figure 28: Central Library

5.4. AS / TN (building 22)

The Applied Sciences building can provide up to 632.7 MWh/a from its roofs and up to 420 MWh/a from its facades. Although facade potential in this model at present carries a high level of uncertainty, the age of the AS building and its facade suggest (deep) renovation is required, at which point a BIPV facade could be considered, which could approach the potential mentioned.

Figure 29: AS building, roofs 7 and 9 highlighted



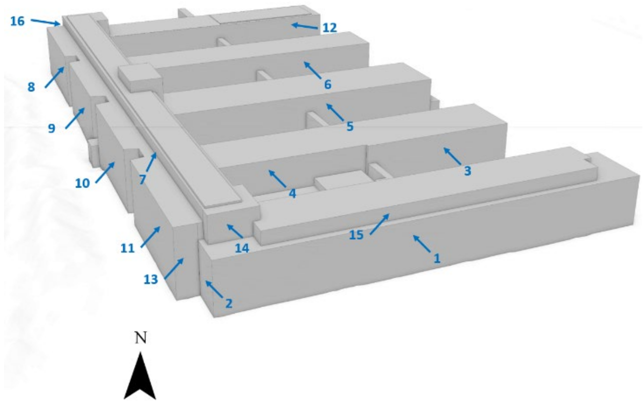


Figure 30 (left): AS building, roof FIDs

Figure 31 (right): AS building, facade FIDs

In general, the AS building provides significant opportunities. Although the main section is partially covered with a sedum roof, both the main section (FID 4) and the wings (FIDs 1-3 and 5-7) have ample space for medium to large PV arrays with a high specific yield. All these roofs are part of the low hanging fruit category, and add up to 609 MWh/a of PV potential, 13% of the roof PV potential of the campus as a whole.

The presence of walkways both between the wings and crossing the Stieltjesweg means the 3D model also contains a small amount of non-existing facade surface, which needs to be corrected for.

The south facing facade strip (FID 15) at the top of the southern wing is one of the two most promising vertical surfaces for transparent PV on campus, due to good orientation and limited obstructions.

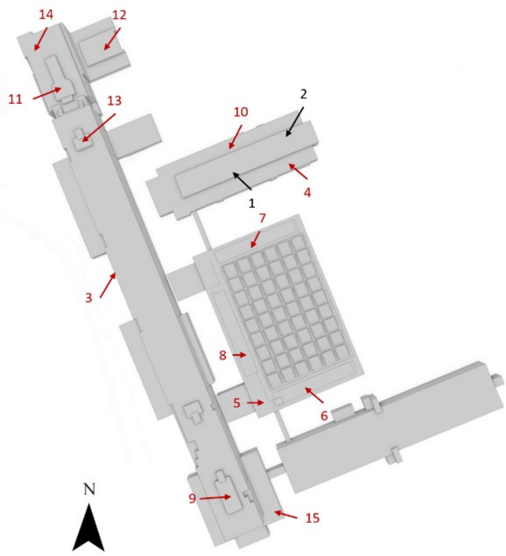
Figure 32: AS building (22), green roof

Although the report does not specify where exactly, Van Kan (2014) mentions ample loadbearing capacity for PV arrays *"at the indicated locations"*. Further study of the structural capacities of the roofs of building 22 is recommended, however this does suggest they will likely have sufficient strength.

5.5. CEG / CiTG (building 23)

The CEG building currently hosts an 84.8 kWp array on the Stevin III lab, which produces 79 MWh/a on average (see paragraph 4.1). The remaining available roof space can provide up to **515.4 MWh/a** from its roofs and up to **541 MWh/a** from its facades. The loadbearing capacity of the main roof, which has a wood construction, has to be investigated. Regarding facade capacity, the main section does not appear to be a monument (only the Stevin labs; see Figure 37), and its age suggests a deep renovation could be considered, at which point a BIPV equipped facade might approach the potential mentioned. The approach could be similar to those considered for the AS building (section 5.4).

Figure 33: CEG building with roof FID 1 and facade FID 7 highlighted



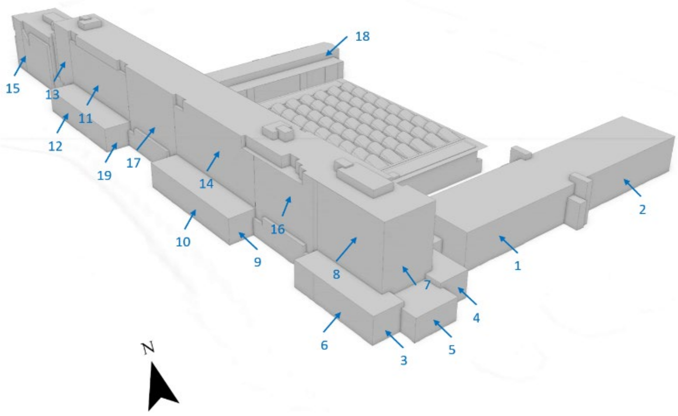


Figure 34 (left): CEG building, roof FIDs

Figure 35 (right): CEG building, facade FIDs

Facade wise, when considering only its closed sections, the facade with FID 7 (on the southern head of the main building) has a relatively high specific yield and an accompanying good yield of 46.4 MWh/a.

Figure 36: CEG building (23), existing PV and green roof

The Stevin I, II and III laboratories at the rear have a municipal monumental status (see Figure 37) and are therefore subject to more strict regulations (see paragraph 2.4). PV placement is not impossible however, as shown by the presence of a PV array on the southernmost Stevin III lab.

Only the loadbearing capacity of the Stevin I and II labs has been investigated (van Kan, 2014). In both cases, the roof is expected to have sufficient strength to carry PV arrays.

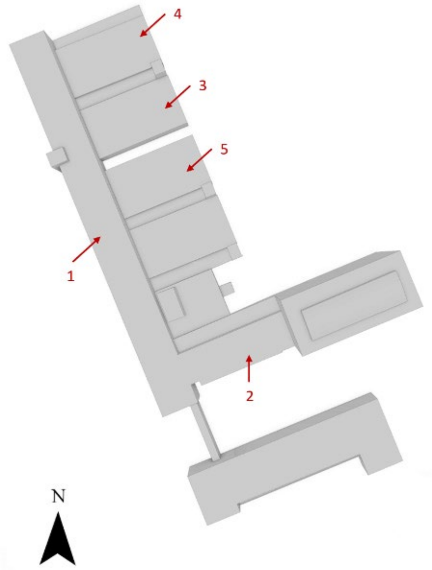
Figure 37: monumental status of the Stevin I, II and III labs – note that the main building does not appear to have a special status. (Gemeente Delft, 2020)

5.6. Bouwcampus (building 26)

The Bouwcampus currently hosts a 22.8 kWp array on its roof, which produces 21 MWh/a on average (see paragraph 4.1). The Bouwcampus building can additionally provide up to 74 MWh/a from its roofs and up to 172 MWh/a from its facades.

Figure 38: Bouwcampus

Although none of the surfaces reach the campus wide specified thresholds for low-hanging fruit (see sections 4.2 and 4.3), the facades with FID 4 (11.5 MWh/a) and 7 (31.3 MWh/a) are fairly interesting on this building, from both a specific and total yield perspective. Facade 6 finally can be considered interesting when looking only at its closed surface (115.2 kWh/m² and 48.4 MWh/a).



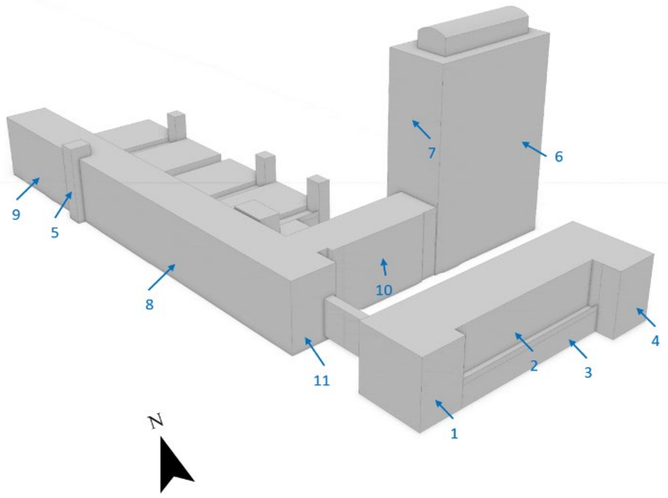


Figure 39 (left): Bouwcampus: roof segment IDs

Figure 40 (right): Bouwcampus: facade segment IDs

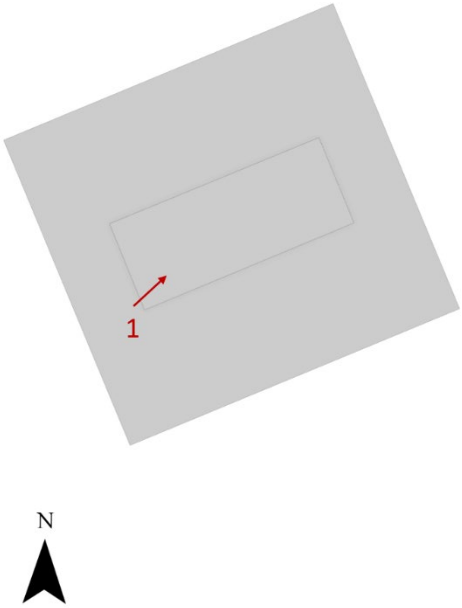
Figure 41: Bouwcampus (26), existing PV and roof lights

Van Kan (2014) indicates the roof *"at the locations specified"* is suitable for PV placement from a loadbearing capacity point of view. This likely refers to the PV array that already exists. As this is located on top of the annex, and the construction of the main building may differ, further study is therefore recommended.

5.7. Mathematics / Wiskunde (building 28)

The Mathematics (EEMCS) building has already been equipped with PV panels on its main roof, but can provide up to 7.6 MWh/a from its secondary roof and up to 152 MWh/a from its facades.

Figure 42: Wiskunde EWI / Mathematics EEMCS building



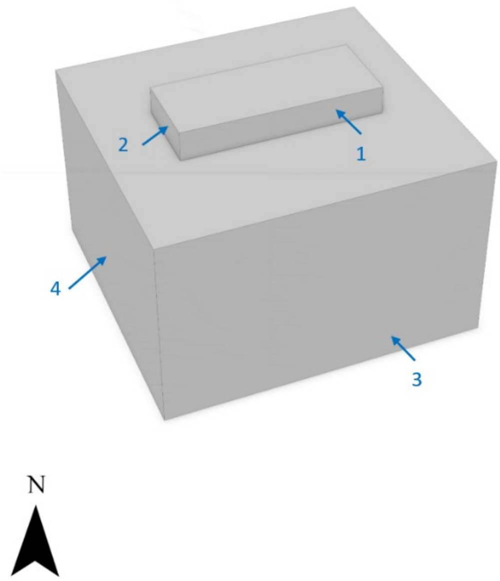


Figure 43 (left): Mathematics EEMCS roof FIDs

Figure 44 (right): Mathematics EEMCS facade FIDs

Figure 45: Mathematics building (28), existing PV

Although the remaining roof surface does not reach the campus wide specified thresholds for low-hanging fruit (see sections 4.2 and 4.3), none of the facades should be considered bad either, with FIDs 1 (9.8 MWh/a) and 2 (3.9 MWh/a) being the most favourable on this building, from a specific yield (and therefore payback time) perspective. Although the yield is modest, both of these facades are located on the sides of the technical structure on top of the roof. Therefore, PV placement would not cause interruptions for students and staff during construction, and there will not be glare issues afterward.

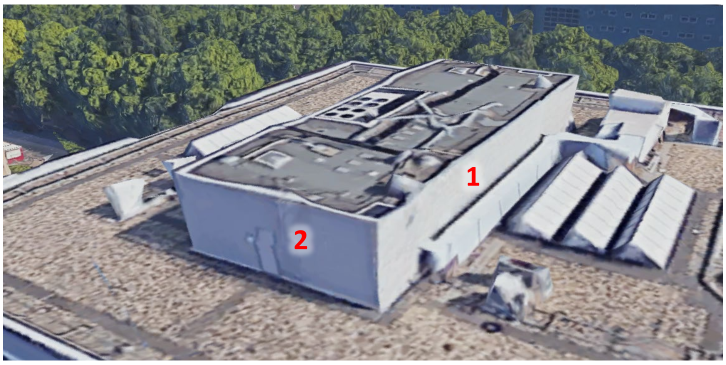


Figure 46: Mathematics EEMCS building, zoomed in on facades 1 and 2

Furthermore, the (main) facades with FID 3 (also featured in paragraph 4.6) and 4 could host movable PV on the blinds, as well as rows of (perhaps suitably coloured) PV panels in the rows between the windows, unlocking a further 138.7 MWh/a. Neither of these can be considered low-hanging fruit however, as the intervention may require significant design effort.

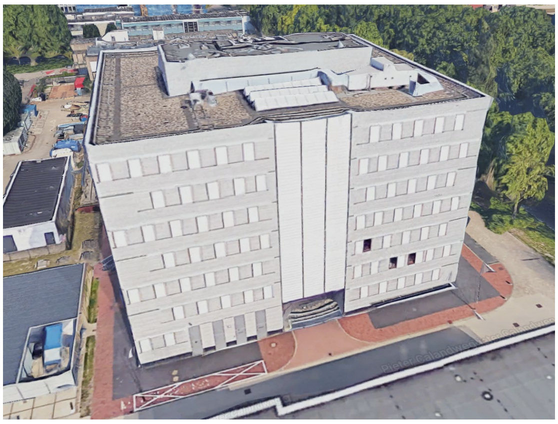


Figure 47 (left): Mathematics EEMCS, zoomed in on facade 3

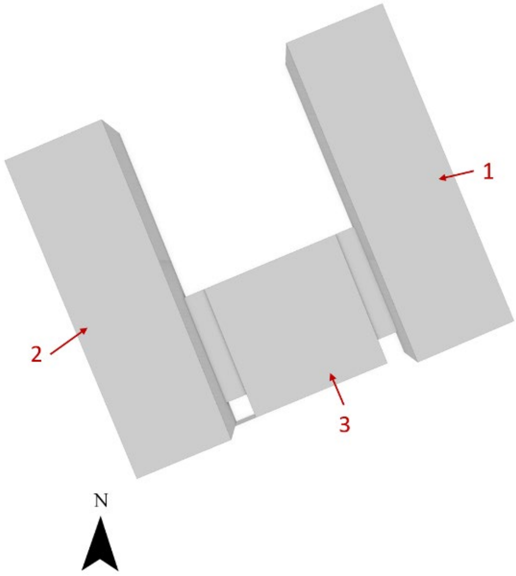
Figure 48 (right): Mathematics EEMCS, zoomed in on facade 4

5.8. ESA / O&S and CRE (building 30)

Building 30 can provide up to 100.3 MWh/a from its roofs and up to 139.5 MWh/a from its south oriented facades. The clean open/closed geometry of these facades, and in cases of facades 2 and 5 their mostly closed nature, means that this potential may have a lower degree of uncertainty than most. Building 30 has both interesting roofs and facades.

Figure 49: ESA / O&S and CRE building

Only the northern part of the building is part of the Jaffalaan protected heritage area, leaving the southern facades available for PV placement. Two facades are either close to or just over the threshold values defined for facade notability, FIDs 2 (27.2 MWh/a) and 5 (30.2 MWh/a).



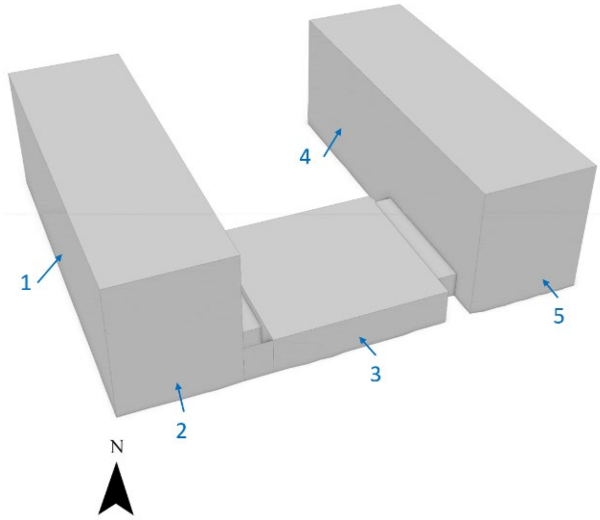


Figure 50 (left): ESA / O&S & CRE building, roof FIDs

Figure 51 (right): ESA / O&S & CRE building, facade FIDs

5.9. TPM / TBM (building 31)

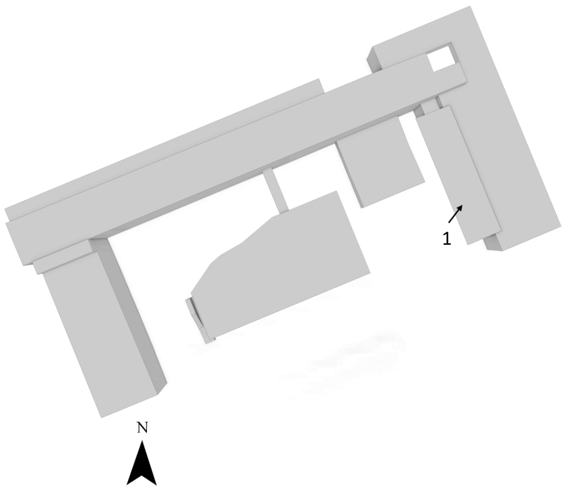
The TPM building currently hosts several arrays totalling 54.6 kWp on its roofs, which produce 48 MWh/a on average (see paragraph 4.1).

TPM has its roofs already almost completely covered by either PV arrays or sedum (Figure 53), therefore new PV potential is very limited.

Figure 52: TPM building

The facades could provide up to 140.5 MWh/a, however none of these reach the threshold values for specific yield or total yield to be considered low-hanging fruit.

Figure 53: TPM building (31), existing PV and green roofs



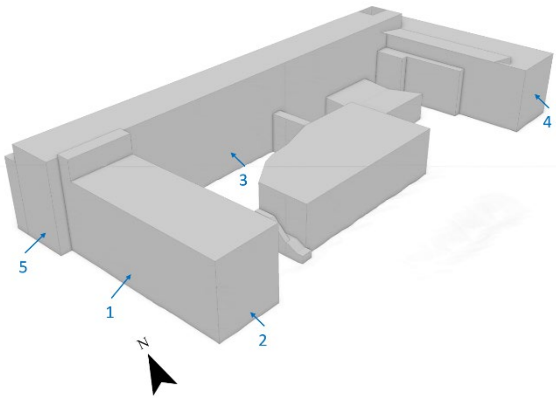


Figure 54 (left): TPM building, roof FIDs

Figure 55 (right): TPM building, facade FIDs

Although the canopy structure (roof FID 1, Figure 56) could provide an additional 28.1 MWh/a using Landscape oriented PV panels, or 2.8 MWh/a using transparent PV, the loadbearing capacity of the canopy would require further study for either of these options. An example of a solution is the semi-transparent PV roof structure of Rotterdam Central Station (Simons, 2011).

Figure 56: TPM building, canopy

5.10. ID / IO (building 32)

The ID building has already been equipped with PV panels on its roofs on the northern and western rims, but can provide about 197.2 MWh/a from its main roof (using the dual tilt configuration positioned between the roof lights), and up to 215.6 MWh/a from its facades if fully utilised.

Figure 57: ID building, facade FIDs 3 and 4 highlighted

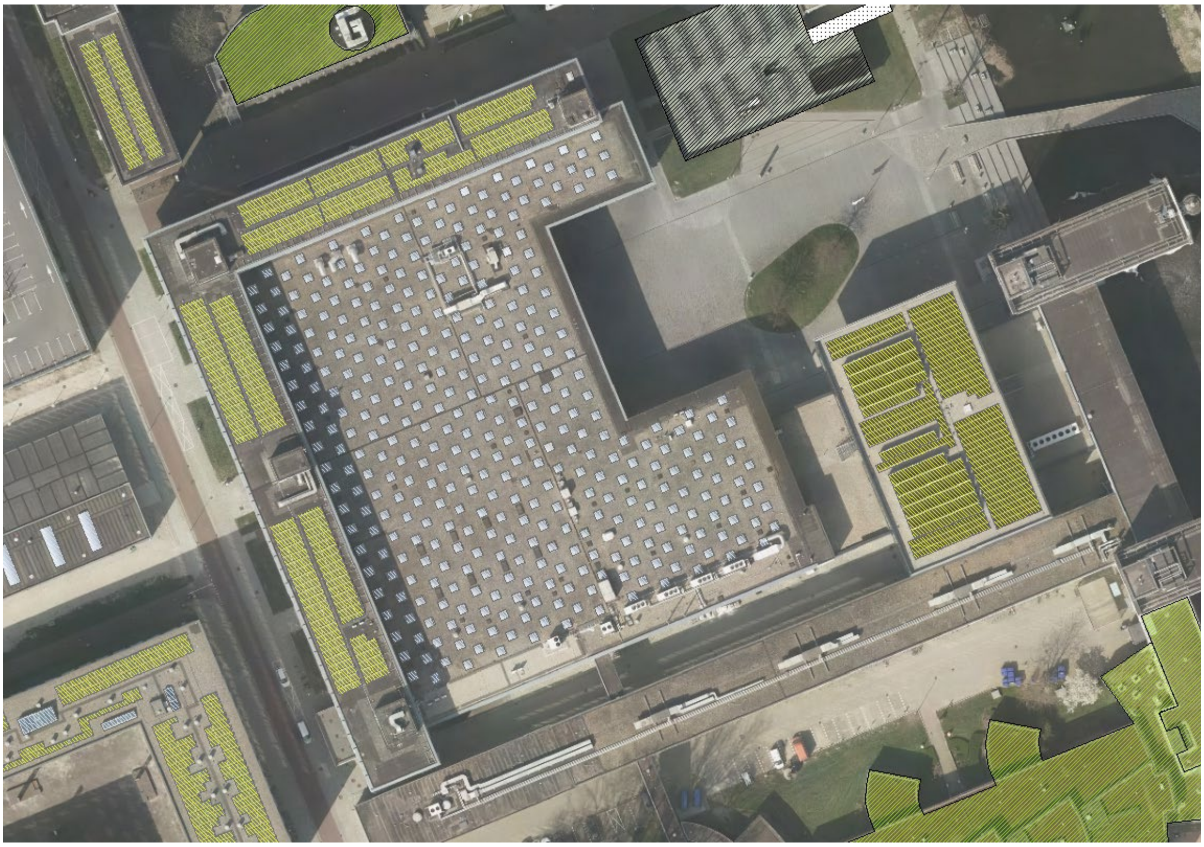
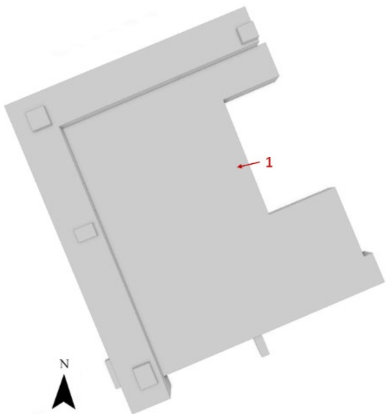


Figure 58: existing PV and roof lights on the ID building (32)

The largest roof (FID 1) of the ID building is dotted with roof lights, however it should be possible to place lines of PV in between, provided they are flush with the surface, so as to not remove light from the main hall (which would need compensating with artificial light and incur additional electricity use). Its high potential yield (197.2 MWh/a) and excellent specific yield (973.6 kWh/kWp) make it part of the low hanging fruit selection from a technical perspective. The loadbearing capacity of this roof however needs investigating however, as well as how to mount these panels.



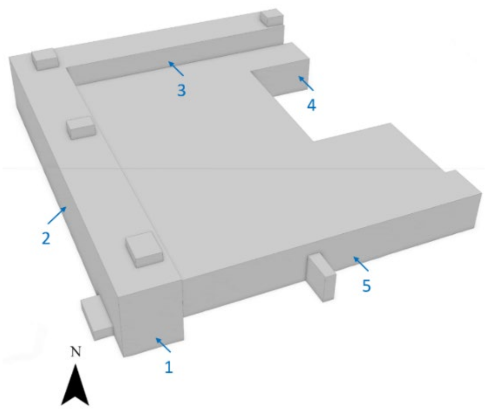


Figure 59 (left): ID building, roof FID

Figure 60 (right): ID building, facade FIDs

Although none of the facades reach the specified minimums of both specific yield and total yield to be considered low-hanging fruit on the campus, the facade with FID 3 has a high AC specific yield for its walls, and may therefore host single lines of PV panels.

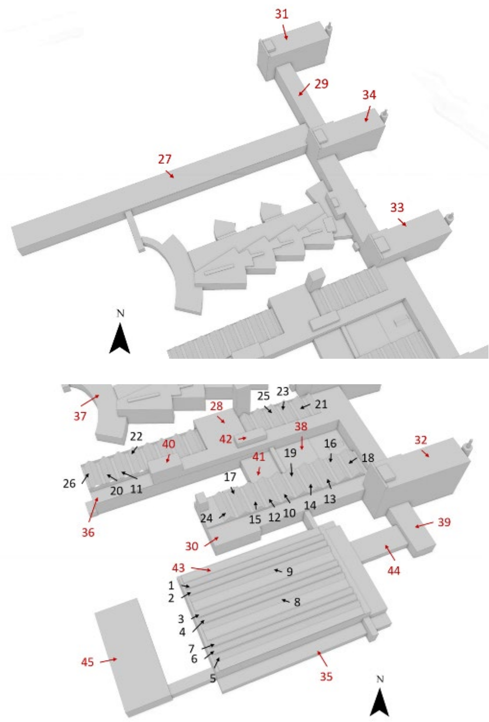
Van Kan (2014) indicates the roof *“at the elevated sections”* is suitable for PV placement from a loadbearing capacity point of view. This refers to the PV array that already exists. The hall roof will therefore require further study in order to assess its strength.

5.11. 3mE (building 34)

The 3mE building features a large green roof on its lecture rooms and entrance area (Figure 62), which are therefore at present excluded from PV generation. Furthermore, the oldest sections of the building have a municipal monument status, and therefore plans for these sections would be subject to approval by the municipal aesthetics committee.

Figure 61: 3mE building (roofs 1-9 and facades 13 and 20 highlighted)

Figure 62: green roofs on the 3mE building (34)



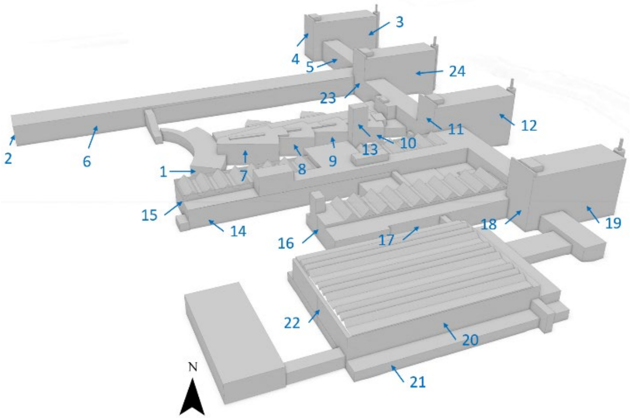


Figure 63 (left): 3mE building, roof FIDs

Figure 64 (right): 3mE building, facade FIDs

Potential yield from the roofs, excluding the sedum areas, is estimated to be 597.5 MWh/a. The tilted roofs on the southern section (Figure 65) are very favourably angled for PV, not part of the monumental sections, and could, when fully covered, potentially provide 76.5 MWh/a (Landscape configuration). From a specific and total yield perspective, these roofs combined should be considered low-hanging fruit. Roofs 27 and 28 are of the ‘interesting’ category, having good specific yield (841 and 882 kWh/kWp) and yield (138 and 90 MWh/a). Research on the loadbearing capacity of building 34s roof structures is recommended.

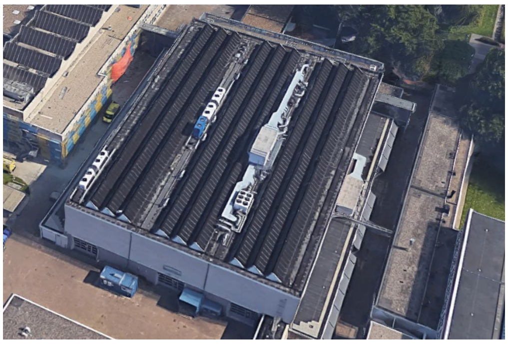


Figure 65 (left): 3mE building, lecture rooms

Figure 66 (right): 3mE building, southern roof

Potential facade yield is estimated at 582.1 MWh/a, however, this figure is expected to have a relatively low level of accuracy. Apart from partially being a municipal monument, the lecture room facades have overhanging features and mutual shading (see Figure 65). Although these features reduce solar heat load on the underlying lecture rooms, they would for the same reason render the facade PV potential calculation results of the 3D model inaccurate (see also section 3.2).

The facade with FID 13 (13 MWh/a) is interesting from a specific yield perspective (low payback time), and FID 20 (54.7 MWh/a) is interesting when only considering its closed sections.

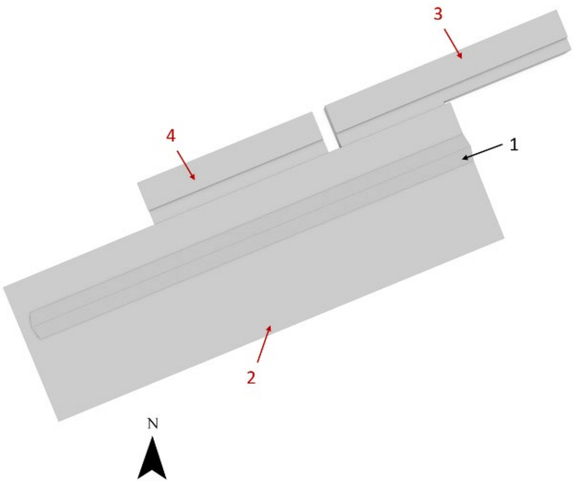
When considering structural strength, van Kan (2014) refers to *“wings 6 and 7”* as having sufficient loadbearing capacity *“at the locations specified”*, and therefore being suitable for PV placement, although it is not clear which areas these refer to. It is also mentioned that wings 4 and 9 were built at the same time, so they are expected to be suitable as well.

Figure 67: Part of the 3mE building has a monumental status (Gemeente Delft, 2020)

5.12. Drebbelweg 5 (building 35)

Building 35 can provide up to 212.2 MWh/a from its roofs and up to 52.6 MWh/a from its facades.

Figure 68: Building 35



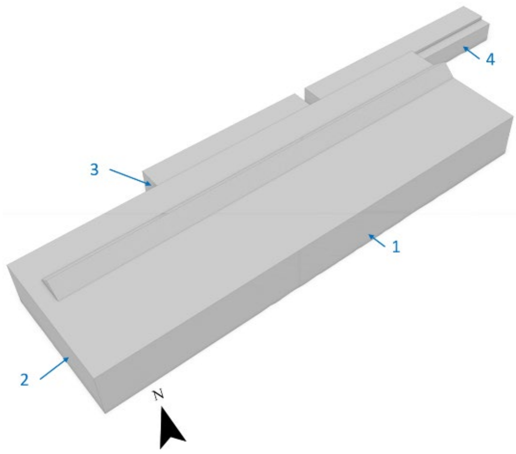


Figure 69 (left): building 35, roof FIDs

Figure 70 (right): building 35, facade FIDs

The main roof houses a shed roof light along its length (roof FID 1), the back of which is favourably angled for PV, and part of the low hanging fruit group. Provided the PV panels are placed high up to avoid shading from the ventilation systems on the adjacent roof (FID 2), this roof could additionally provide 31.7 MWh/a. FID 2 is close to low-hanging fruit (at 153 MWh/a and 921 kWh/kWp), although the large quantity of building installations on this roof requires careful positioning.

Due to shading from trees and a large number of windows, the facades of building 35 have an unfavourable specific yield, and should therefore be considered low priority.

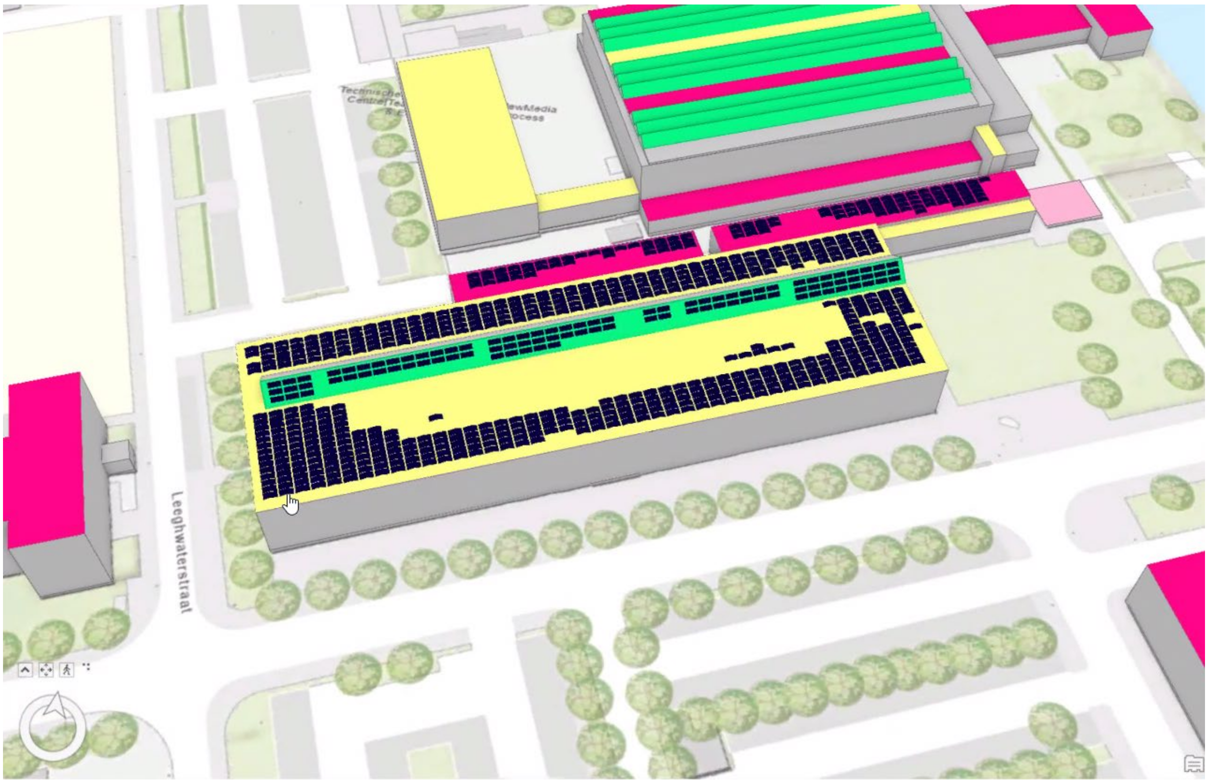


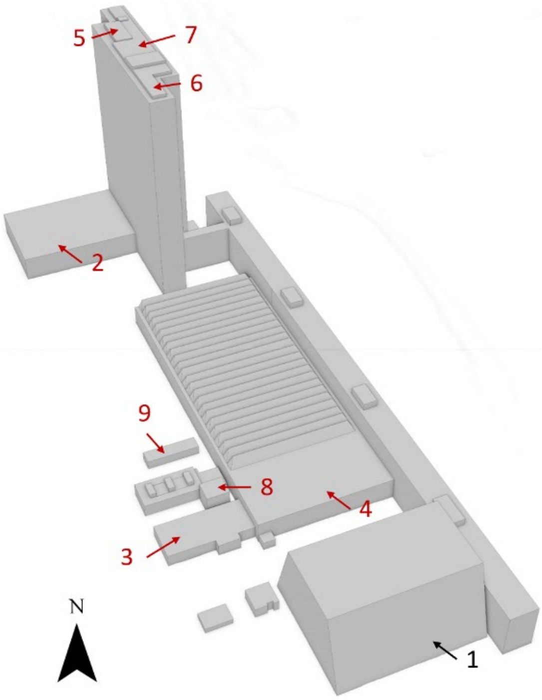
Figure 71: Building 35, possible PV panel placement

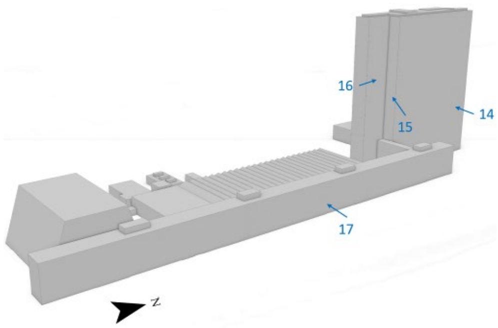
Van Kan (2014) indicates the roof *"at the locations specified"* is suitable for PV placement from a loadbearing capacity point of view, given 15mm of ballast is removed. This likely refers to the flat areas. If so, further study on the strength of the shed roof is recommended.

5.13. EEMCS / EWI (building 36)

The EEMCS building hosts the PVMD group (and part of the writing team of this study), as well as several existing PV arrays (on the ESP and the EKL labs, totalling 202 kWp and 198 MWh/a, see also paragraph 4.1) and a green roof (as of 2020, Figure 75), but can additionally provide up to 230.5 MWh/a from its remaining available roof space and 434.7 MWh/a from its facades (however, this may be much more, depending on how the highrise facades are utilised, see below). Its status as a municipal monument, as well as the presence of an unusual facade structure, mean that this estimate has a high level of uncertainty, and is partially dependent on future renovation plans and designs.

Figure 72: EEMCS building, ESP lab side roof (1) and lecture room roof (2) highlighted





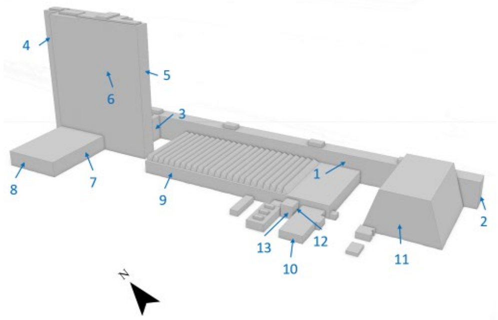


Figure 73 (left): EEMCS building, roof FIDs

Figure 74 (upper right): EEMCS building, facade FIDs from east

Figure 75 (lower right): EEMCS building, facade FIDs from west

Figure 76: EEMCS building (36), existing PV and green roof

Although none of the yields are above the thresholds to be considered particularly low-hanging fruit, two surfaces have a potentially high total yield: the ESP lab southern facade (classified as a roof here with FID 1, 78.6 MWh/a in the Landscape configuration) and the lecture rooms roof (FID 2, 105.4 MWh/a in the Portrait configuration).

Highrise

The highrise portion of the EWI building has an enormous amount of facade surface, which could host building integrated PV. If the climate facade is retained in its current appearance, transparent PV could be applied across the height of both east and west facades at a yield of approximately 100.8 MWh/a. Alternatively, appropriately coloured PV elements could be applied to the closed surfaces within the shaft (albeit with reduced performance during summer, as the temperature inside the climate facade will have risen sharply).

To give an idea of the enormous potential of this surface, the fully closed yield for the east and west facades combined is estimated to be about 1 GWh/a. This yield would however imply removing all windows, therefore a more reasonable maximum would be about half that (i.e. 50% windows), resulting in 500 MWh/a.

The highrise rooftop may host a small number of PV panels at a very high specific yield (up to roughly 19.6 MWh/a), however care should be taken that these do not interfere with the existing radar facilities (NREL, 2017).

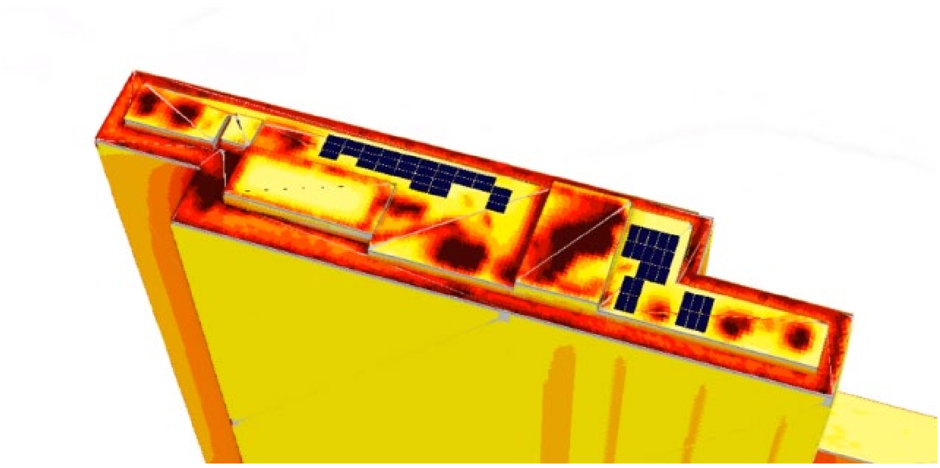


Figure 77: possible panel placements on the EEMCS highrise rooftop

Lecture rooms (west)

The lowrise that protrudes from the highrise section on the western side has a large, flat roof (FID 2) that may be suitable for PV arrays. Although limited to indirect radiation in the morning due to the presence of the highrise section, it may provide peak power in the afternoon. The specific yield is fairly good at 761 kWh/kWp, however the total yield is a significant 105.4 MWh/a.

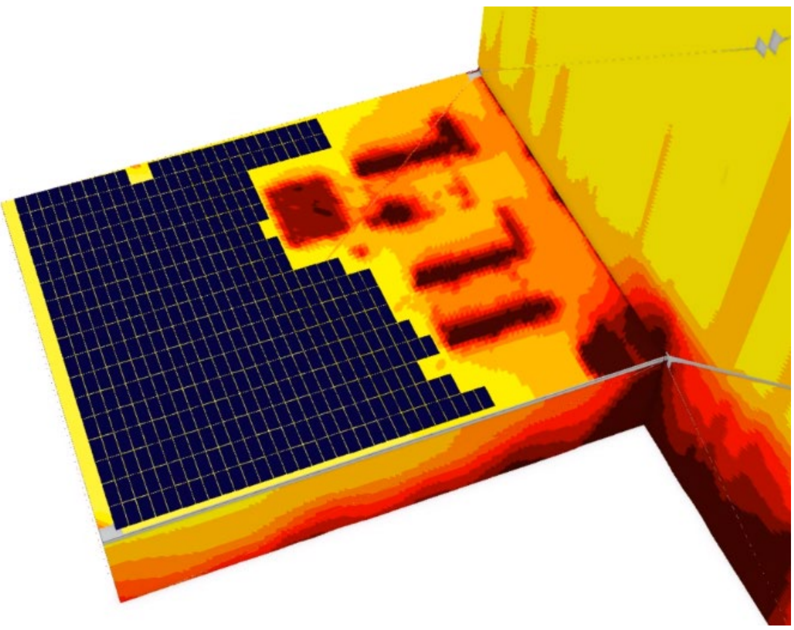


Figure 78: possible PV panel placements on the EEMCS lecture room rooftop

Lowrise east

The elongated lowrise of the EEMCS complex has the same facade layout as the highrise structure and may provide similar opportunities, however with the same uncertainties as described above.

Its roof was partially covered by a diagonally oriented PV array, however this was replaced in 2020 by a green roof over the entire length of the building, and is therefore currently unavailable to hosting PV.

Else Kooij Laboratory

The favourably oriented south facing sloped roofs of the EKL halls currently host a 133.6 kWp PV array, producing 124.5 MWh/a.

The largely closed western facade (FID 9) is less optimal from a specific yield (and therefore payback time) perspective, however could provide a significant amount of energy (62.3 MWh/a).

ESP lab

The roof of the ESP lab (Figure 78) is already largely covered with an existing PV array.

The lab has a south facing sloped facade (roof FID 1, for modelling reasons listed amongst the roofs in the overview) with promising yield (105.4 MWh/a). However, care should be taken however to prevent glare into the adjacent student housing at the Balthasar van der Polweg during certain times of the day and year, for example by using anti-reflective coatings.

This applies to the east facing facade as well (seen in Figure 78), which could provide peak power during the morning hours, and can provide an estimated yield of 19.4 MWh/a. The presence of the lowrise roof in front of this facade may facilitate construction and maintenance.

Figure 79: EEMCS ESP lab, seen from SE

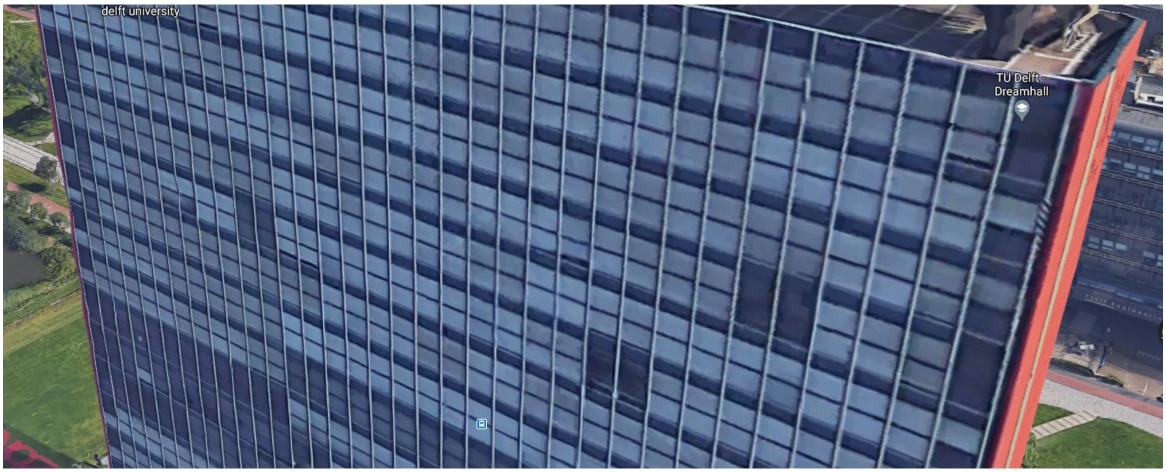


Figure 80: EEMCS building, highrise facade

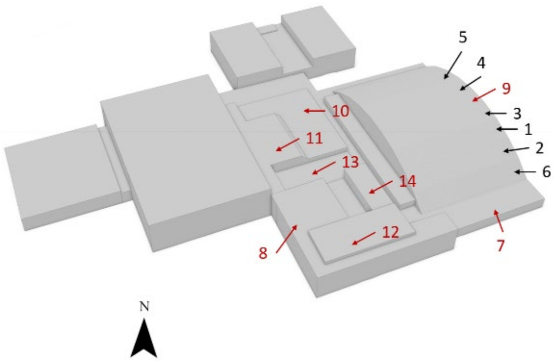
The outer shell of the climate facade is all glass, however the secondary facade is partially closed. Depending on how the building is renovated, either these closed strips, or features mimicking them, could be used for PV placement.

Van Kan (2014) indicates the roof at *"the low halls (wing 3)"* is suitable for PV placement from a loadbearing capacity point of view. This likely refers to the existing PV array on EKL. Furthermore, the roof of the ESP lab ("wing 4") was also approved, also a PV array that was realised afterward.

5.13.1.X Delft (buildings 37 and 38)

Due to the recent renovation, the sports section of X Delft was outdated in the AHN3 dataset, therefore the information on the geometry of building 37 is incomplete. Most of the roofs however already host existing PV arrays (totalling 144.2 kWp and 102 MWh/a, see Figure 83 and paragraph 4.1), therefore the potential for new PV is expected to be relatively low. The curved roof of the sports hall (roof IDs 1-6 and 9) may be suitable, however this strongly depends on the additional load bearing capacity of its roof structure, and the tall trees to the east may prevent sufficient specific yield on the eastern edge.

Figure 81: X Delft



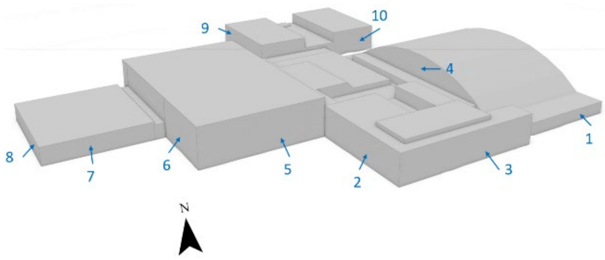


Figure 82 (left): X Delft, building 37, roof FIDs

Figure 83 (right): X Delft, building 37, facade FIDs

Van Kan (2014) indicates the roof *"of the gym halls"* is suitable for PV placement from a loadbearing capacity point of view. This likely refers to the current PV arrays. The curved roof of the large gym hall has a different structure, and therefore needs separate assessment.

Figure 84: X Delft, existing PV

The former culture section of X Delft (building 38) features an existing 42.4 kWp PV array that produces 38.9 MWh/a, but still has some limited additional space for roof PV. Although no monumental restrictions apply, if facade PV is to be pursued, suitably red coloured PV panels should be applied in order to preserve the aesthetics of the building. In that case, the facades with FID 2 (28.6 MWh/a) and 3 (7.1 MWh/a) are the most suitable for PV placement.

Figure 85: X Delft, building 38

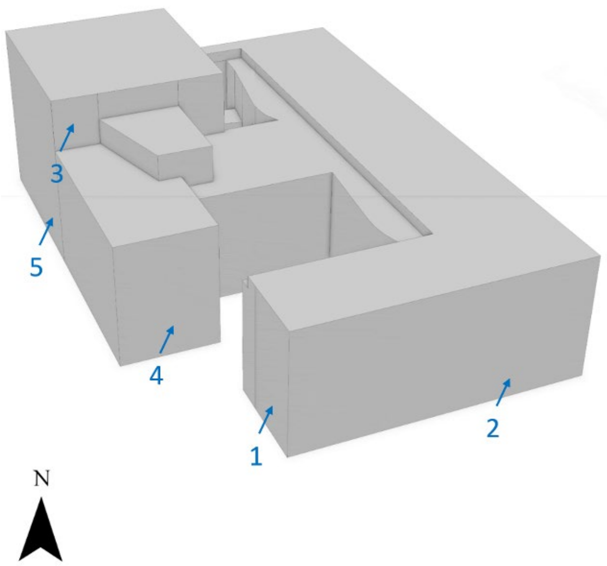


Figure 86: X Delft, building 38, facade FIDs

5.14. CHP / WKC building (building 43)

Although the campus power plant is a municipal monument, and therefore has stricter rules in regards to PV placement, it both features a few reasonably to highly suitable surfaces, and of all the buildings on campus, has the unique property of having specifically been built for energy production.

Suitably coloured PV panels are recommended to improve the chances of approval, and PV on the lower roofs should feature an anti-glare coating due to the Hogeschool InHolland Delft building to the North.

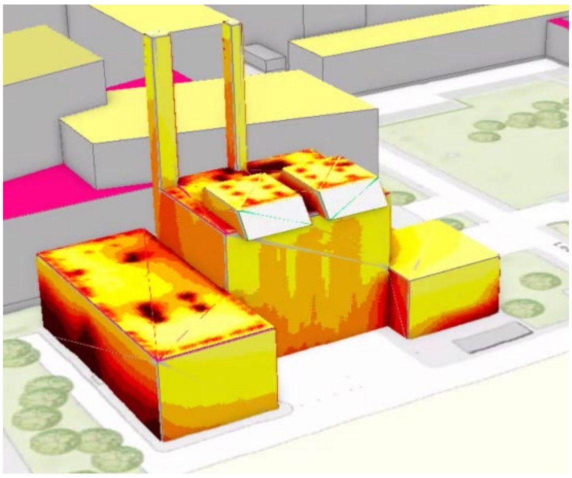
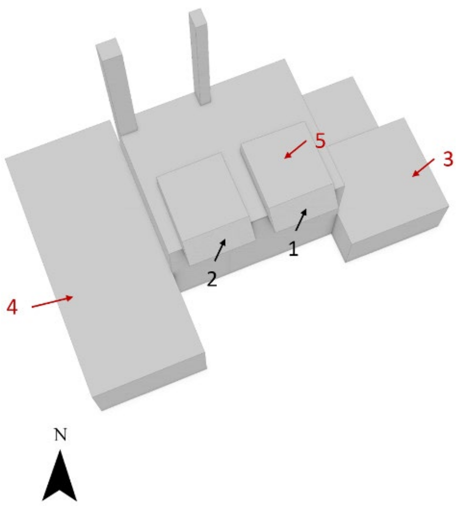


Figure 87 (left): CHP building

Figure 88 (right): CHP building, irradiation map

The CHP building already features two small solar trackers (placed by the PVMD group) on the south west facade. These however are for research purposes, not electricity production.

Although the two south facing sloped roofs (FIDs 1 and 2, 8.5 MWh/a combined) are relatively small in total yield, they are very well oriented and therefore have high specific yields of 1055 and 1071 kWh/kWp (and an expected short payback time). These could also be used as testing locations for high yield panels.



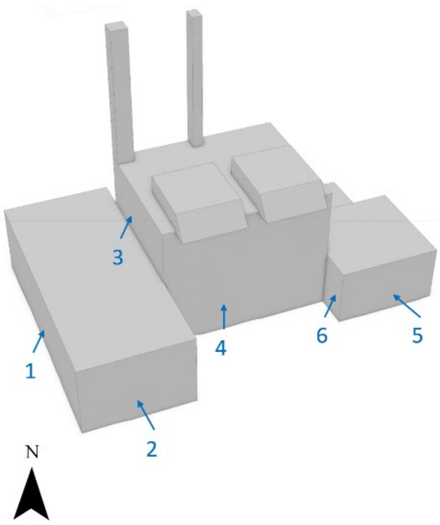


Figure 89 (left): CHP building, roof FIDs

Figure 90 (right): CHP building, facade FIDs

5.15. Lage Snelheden Laboratorium / VSSD / Inholland (building 45)

Building 45 is at present considered unsuitable for PV placement, due to the shade cast by large trees directly to the south. Total roof yield for the entire building would be 22.3 MWh/a, facade total yield is even less (at a very unfavourable density of 41.4 kWh/m^2/year).

Figure 91: Building 45

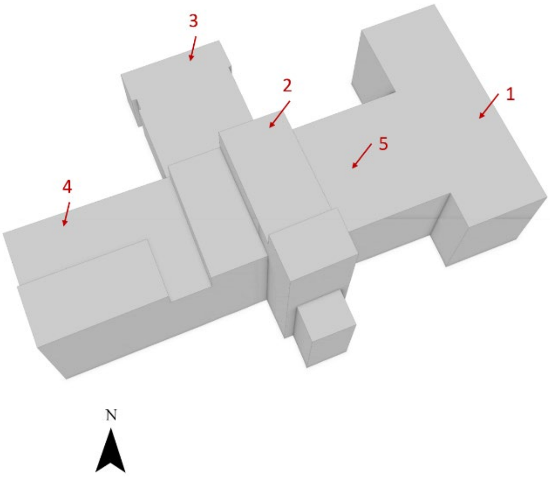


Figure 92 (left): Building 45, roof FIDs

5.16. Other buildings on campus

Several buildings on campus, not owned by TU Delft, are additionally deemed suitable for PV placement (both roofs and facades). These include a number of buildings owned by student housing corporation DUWO (for example the roofs of the Korvezeestraat complex, the facades of the PhD buildings at Leeghwaterstraat and roof sections of the Balthasar van der Polweg buildings), and commercial buildings with available roof space at TU South.

In addition to addressing its own buildings, TU Delft could seek cooperation with these building owners in order to meet its sustainability targets, for example by:

- University owned rooftop PV panels
- Facade leasing
- Purchasing their electricity

5.16.1. Higher risk building assessments

PV arrays carry with them a normally virtually negligible risk with them that is associated with electronics, higher voltages and temperatures (Verbond van Verzekeraars, 2020). However, for certain buildings with inherent functional safety concerns (like for example the RID), an additional risk assessment may be required. The outcome may have consequences for general feasibility of a location, but could also simply require additional fire compartments and other precautions to alleviate this.

5.16.2. Parking garages

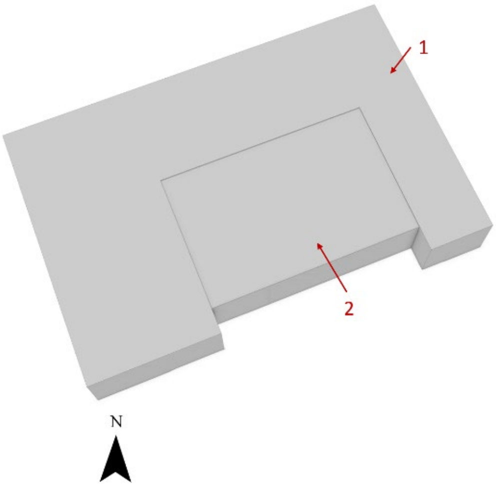
The TUD campus features two completed parking garages (P TNW, P-Sports) and one under construction (P-Rotterdamseweg, in front of the CHP/WKC building (43)). P-Sports has a temporary nature and may suffer from tree shade, and was therefore not included. As neither of the structures exists in the AHN3 dataset (which was recorded during 2014), a separate model had to be constructed (Zhou & Calcabrini, 2021). As this stage of the study focuses on the Campus North, P-Rotterdamseweg (Figure 92) has been included.

Figure 93: Rotterdamseweg parking garage, artist's impressions

As the loadbearing construction is dimensioned for (moving) vehicles, there is sufficient capacity to add a light superstructure on top, a solar carport.

This would only require a support structure to be built that covers the top layer, which means regular PV panels can be used. Depending on the nature of the superstructure, vehicles and people would additionally be provided with cover from both rain and high sun at this level.

Alternatively, applying so-called *'solar road'* panels to the parking spaces themselves could be considered (which would only incur a reduction in production if the garage is filled to capacity, assuming parking can be prioritised to first fill up the lower levels). Solar road technology does not appear to have finished the development stage though, so at this moment, this second option may not be available.



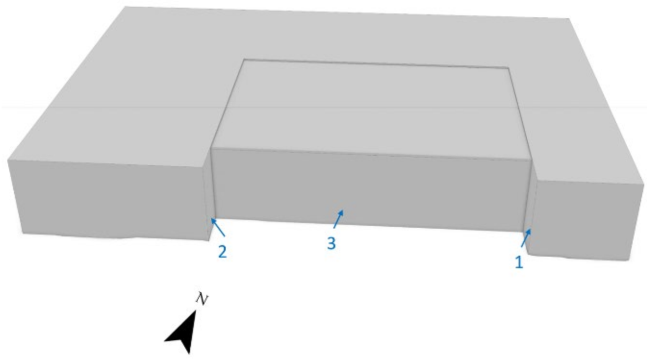


Figure 94: Rotterdamseweg parking garage, roof FIDs

Figure 95: Rotterdamseweg parking garage, facade FIDs

The closed sections of the facades (Figure 92) are currently planned to be covered with vegetation (Oostelbos Van den Berg, 2020). Therefore, in the PV study (Zhou & Calcabrini, 2021), the PV potential of these sections is considered as an alternative in select areas.

6. Conclusions & recommendations

This study has investigated the PV potential of TU Delft's building stock, with a focus on the Campus North. The AHN3 based approach allowed for initially casting a wide net, and both provided a total potential figure more accurate than previous studies, and easy access to the multilayer model for staff and students to explore themselves.

The study has produced two reports: the first one on the 3D building simulation itself, and this second one on the analysis of the results. Apart from the model improvement recommendations made in chapter 3, this report mainly dives into providing further analysis and insight into the results, both total (chapter 4) and per building (chapter 5).

Technical potential is about **8.1 GWh/a** for the campus. Current campus electricity demand is 82.3 GWh/a. Therefore, around 10% of the *current* electricity demand of the entire campus could potentially be supplied by the roofs and facades of the Campus North, reducing the carbon footprint by about **800 tons** of CO_2-equivalent.

The potentials described here are not final. Technological advancements may bring new technologies and products, facilitating usage of some surfaces, or unlocking others. If panel cost is reduced sufficiently, even north facing shed roofs and facades may become economically feasible, at which point the campus potential described in this report will increase. Therefore, both simulation and analysis should be revisited in a few years.

Developing a DC grid should also be investigated, which could increase yield by an additional ~10%.

Among the other avenues of development are BIPV, fixed and flexible solar shading (example), and for monuments, coloured or printed PV (example). Developing PV solutions for the EEMCS highrise facades could add as much as a GWh/a to the total mentioned above. In all of these cases, the TU Delft campus buildings themselves can play a role in development as a living lab.

However, this does not mean that increasing meaningful production should be postponed until these technologies become available at a production scale. This report should therefore be seen as a call to action. As far as campus prioritisation is concerned, the low hanging fruit as identified is expected to provide a significantly *shorter* than average payback time, and should therefore be explored as soon as possible. A **campus PV working group** with a broad background should be established, that follows up this study with **actions**.

Renovation plans for the campus should of course be included in prioritisation. Especially where strengthening of roofs or facade integration is required, a renovation window provides an excellent opportunity to make campus building stock PV ready, or downright equip them.

In the longer term, replacement of existing arrays should also be considered, for example with denser layouts (like dual tilt) and/or higher efficiency panels. This will increase production even further.

This study also exclusively focuses on buildings, however, there are also other surfaces to consider:

- Brownfields: using semi mobile arrays that can be moved to other areas when construction projects start
- Water surfaces: water quality deterioration needs to be prevented though
- Buildings on campus not owned by TU Delft: for example DUWO, TNO, HHS, InHolland Delft etc

- Neighbouring areas with huge roof surfaces (the Ruyven industrial park in the east, unused roofs at the Delftech park and the northernmost section of the Schieoevers Noord area, which is not slated for redevelopment (Gemeente Delft, 2017))

None of these options exclude one another, therefore they can and should all be explored simultaneously.

Therefore, as a final note: **let's start building**!

References

AHN. (2020). *Inwinjaren AHN2 en AHN3*. Opgehaald van AHN: https://hwh.maps.arcgis.com/apps/CompareAnalysis/index.html?appid=b2d67e3a99cf47759d34b19476476889

AHN. (2021). *AHN 4*. Retrieved from https://www.ahn.nl/ahn-4

Blom, T., & Dobbelsteen, A. v. (2019). *CO2-roadmap TU Delft.* Delft: TU Delft.

Gemeente Delft. (2017). *Conceptnotitie reikwijdte en detailniveau Schieoevers Noord.* Delft: Gemeente Delft.

Gemeente Delft. (2020). *Welstandseisen zonnepanelen*. Retrieved from Gemeente Delft: https://www.delft.nl/wonen/bouwen/verbouwen/zonnepanelen-en-zonnecollectoren/welstandseisen-zonnepanelen

Gemeente Delft. (2021). *Uitvoeringsrichtlijnen Monumenten Delft (UMD) 2021.* Delft: Gemeente Delft.

Geodan. (2015). *Alle bomen in Nederland op de kaart*. Retrieved from Bomenregister: http://boomregister.nl/overzichtskaart-van-de-bomen-in-nederland/

Martin, A. M. (2015). Applying LIDAR datasets and GIS based model to evaluate solar potential over roofs: a review. *AIMS Energy*.

Meijer, M., Rip, F., van Benthem, R., Clement, J., & van der Sande, C. (2015). *Boomkronen afleiden uit het Actueel Hoogtebestand Nederland.* Wageningen: Alterra Wageningen UR.

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2012). *Zonnecollectoren en zonnepanelen.* den Haag: Rijksoverheid.

NREL. (2017). *Electro-Magnetic Interference from Solar Photovoltaic Arrays.* Denver, CO, USA: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy17osti/67440.pdf

Oostelbos Van den Berg. (2020). *Parkeergebouw Rotterdamseweg in Delft.* Reeuwijk: Oostelbos Van den Berg. Retrieved from https://www.oostelbosvandenberg.nl/media/uploads/2020/11/19043-Parkeergebouw-Rotterdamseweg-in-Delft.pdf

Rijksdienst voor het Cultureel Erfgoed. (2020). *Elektriciteit opwekken bij monumenten of historische gebouwen*. Retrieved from Rijksdienst voor het Cultureel Erfgoed: https://www.cultureelerfgoed.nl/onderwerpen/duurzaamheid/installaties/elektriciteit-opwekken

Sandia National Laboratories. (2015). *PV LIB Matlab help: pvl_SAMLibraryReader_SNLInverters*. Retrieved from PV Performance Modeling Collective: https://pvpmc.sandia.gov/PVLIB_Matlab_Help/html/pvl_SAMLibraryReader_SNLInverters_help.html

Simons, W. (2011). *Eerste zonnepaneel op dak Rotterdam CS*. Retrieved from Platform Duurzame Huisvesting: https://www.platformduurzamehuisvesting.nl/2011/06/22/eerste-zonnepaneel-op-dak-rotterdam-cs/

van Kan, D. (2014). *Inventarisatie haalbaarheid plaatsing zonnecollectoren.* Amersfoort: Arcadis.

Verbond van Verzekeraars. (2020). *Preventiebrochure PV-installaties - Technische informatie voor verzekeringsprofessionals.* den Haag, NL: Verbond van Verzekeraars.

WUR. (2014). *Open Boomdata*. Retrieved from Wageningen University and Research: https://www.wur.nl/nl/Onderzoek-Resultaten/Onderzoeksprojecten-LNV/Expertisegebieden/kennisonline/Open-boomdata-als-basis-voor-webdiensten.htm

Zhou, Y., & Calcabrini, A. (2021). *Simulation of PV Facades of the Parking garage at Rotterdamsweg.*