Part A: Building-integrated photovoltaics (BIPV) - Irradiance and PV performance modelling
Energy in the Built Environment (GEO4-2522)

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Group 13

Question 1

Question 1.1:

1) We start with importing the UPOT data file from BlackBoard, "Irradiance_2015_UPOT.csv", specifying the appropriate index column and delimiter sign.
2) The data is resampled to create data steps of 5 minutes, taking the mean of all values that belong to the 5-minute intervals.
3) The time zone is localized to UTC and converted to CET.
4) Longitude and latitude are based on Utrecht, Science Park and are stated to be 5.16750 ° and 52.08777 ° respectively.
5) The pressure is assumed to be atmospheric pressure (101,325 Pa).
6) The solar position at the different timestamps is calculated by using the assumed pressure value and geographical coordinates, as well as the imported values for the air temperature as inputs.
7) After calculating the solar position, we eliminate all data entries where the elevation of the solar position is 0 or lower, since there is no irradiance at that time of the day.
8) The solar position data is used as input for the different models to model the DNI values at the different timestamps, which allows us to compare these modelled values to the measured ones from the UPOT file.
9) An exception to step 8) is the DIRINDEX model, in which additional inputs are necessary for the model. Namely, relative airmass and absolute airmass, which were retrieved from solar position data (apparent zenith) and the kastenyoung1989 model. Additionally, turbidity was required as an input which was calculated using the geographical coordinates specified in step 4).
10) Once the DNI values were calculated for the four models, NaN values were dropped for each of them to assess the remaining values in the error functions in the next question to find the best fitting model.

Question 1.2:

RSME:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}(y_t - x_t)^2}{T}} \qquad (1)$$

Where:

y_t = modelled value at timestep t

x_t = measured value at timestep t

This error function quadratically measures the average magnitude of error, which means this is particularly fitting when we consider outliers to be problematic and prefer more relatively small deviations from the measured values over a few relatively large deviations.

MBE:

$$\mathrm{MBE} = \mathrm{y}_t - x_t \tag{2}$$

This error function is unlike the others, as it is simply concerned with assessing whether the model has a negative or positive bias on average. Additionally, it has the downside of the negative and positive bias cancelling each other out on average, at the risk of portraying a seemingly more accurate model than it really is.

MAE:

$$MAE = \frac{\sum_{t=1}^{T} |y_t - x_t|}{T} \tag{3}$$

This error function is quite similar to the RMSE, only it linearly measures the average magnitude of error instead of quadratically.

R^2:

$$R^2 = 1 - \frac{\sum_t (x_t - y_t)^2}{\sum_t (x_t - \bar{y})^2} \tag{4}$$

Where:

$\bar{y}$ = the overall mean of the modelled values

This error function measures how well the modelled data would correlate with the measured data yet is expressed from a scale of 0 to 1.

For the four different error functions, the MBE function is not the best one to use since it is only considered with the direction of the bias, as well as the risk of cancelling out positive bias with negative bias values. Similarly, the R^2 is not optimal to use since the magnitude of the average bias remains unknown. The MAE and RMSE functions are quite similar, with the only exception being that the RMSE error function gives a penalty to large outliers more than the MAE would.

As our objective is to find the model that simulates the most realistic values, the model that has the least outliers is most preferable. Therefore, ultimately the RMSE function is most appropriate to assess the different models. The model with the lowest RMSE score will therefore be chosen for the subsequent questions.

Question 1.3:

The different models and how well they fit to the measured data can be found in Figure 1. As can be seen from this figure, the trends are similar across the different models, which indicates that (with the same amount of data points) the R^2 values are similar as well. For all models, the modelled values seem to fit the measured values quite well, displaying a high correlation.

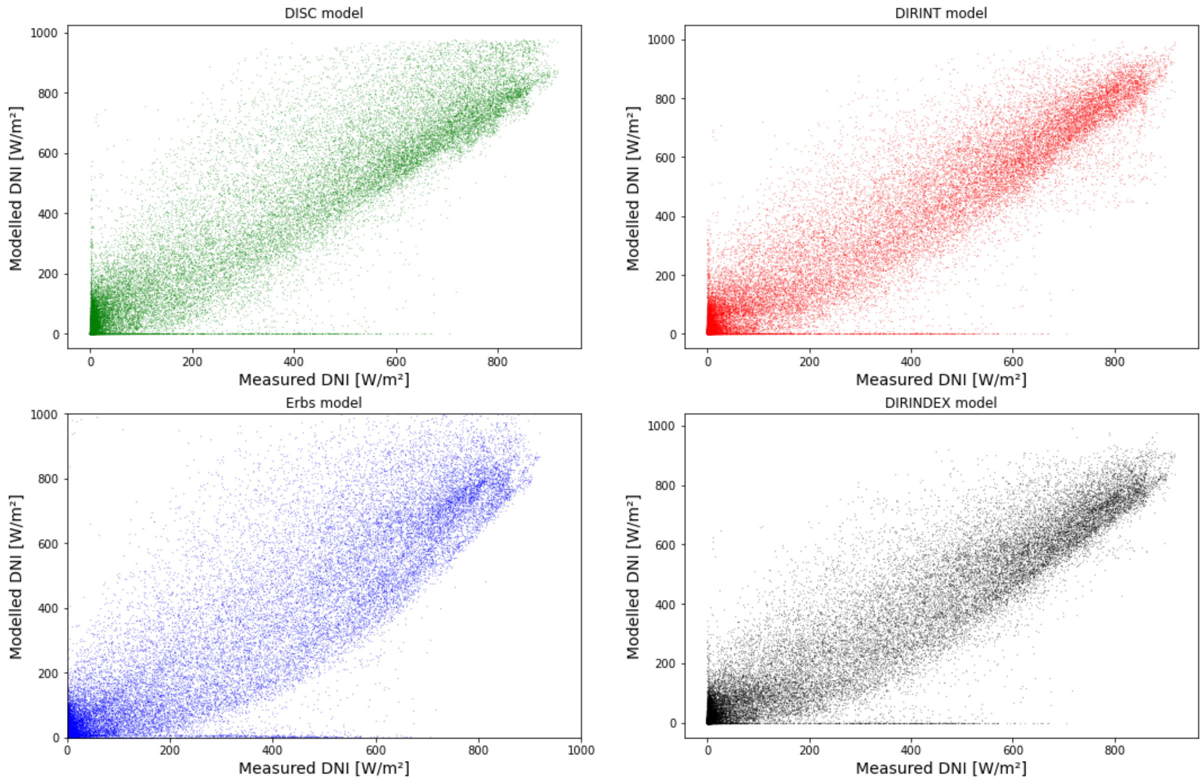

Figure 1: Scatter plots of modelled versus measured DNI values for the different models

Table 1: Errors for each of the four models.

	RMSE	MBE	MAE	R^2
DISC	100.37	17.92	55.36	0.86
DIRINT	88.33	4.9	48.24	0.89
DIRINDEX	89.45	-12.7	51.5	0.89
Erbs	106.7	-5.75	60.83	0.85

Table 1 presents the scores of the different models according to the different error functions. The model that results in the lowest RMSE value is the 'DIRINT' model. Going forward we will be using this model to answer the following questions.

Question 2

Question 2.1:

For this question, the KNMI data for the weather station of 'Hupsel' was selected. The data from the KNMI is provided in time intervals of hours, where the first hour represents the measures data from 00;00-01;00. Moreover, the observed temperature at 1.50 m height is measured in 0.1°C, the average windspeed measured in 0.1 m/s, and the GHI measured in J/cm^2.

Several steps were required to prepare the data for the analysis:

1) The global radiation has been converted into W/m^2 unit, the temperature into °C and the average windspeed into m/s.
2) Date and time columns were merged and used as timestamps to index the data.
3) To align the measured data with the real time in Hupsel, the data was localized at UTC and converted to the European time zone, CET.
4) Moreover, the provided data points from the KNMI data consider the cumulatively measured data (such as GHI) as the sum of the hourly measurements by the end of the timestamp. Therefore, the data points are manually shifted by 30 minutes earlier in time (e.g. 17:00 would become 16:30) in order to average out this cumulative data across the hour evenly and align the measured data with the real time in Hupsel.

Question 2.2:

For this question and subsequent questions, the standard has been adhered to that considers, for the Northern hemisphere, that the surface azimuth angle is 180° when facing south. The surface areas of the different buildings were calculated using the given dimensions in the assignment. For the surface areas of the roofs of building C and D, trigonometric functions were used. The slopes and tilts for the different surfaces of the buildings were determined by keeping in mind the previously mentioned standard for surface azimuth angle, and the tilts provided in the assignment. For the rooftops of building A and B, the tilt was assumed to be 0°, which would mean this is considered (for now) to be a flat surface.

Overall, building A has two façades that we consider, one facing South-West and one facing South-East. Building B has three façades that we consider, one facing West, one facing South, and one facing East. Additionally, we consider two separate sections of the rooftop of building C, one being orientated as North-facing and the other orientated as South-facing. Similarly, for building D, we consider two separate sections of its rooftop, one being orientated as Eastern-facing, and once being orientated as Western-facing. The different slopes and orientations for the buildings are shown in Table 2 in question 2.5, found below.

Question 2.3:

The longitude and latitude used for Hupsel are respectively 6.616657° and 52.0819672°. From the KNMI data the solar position, solar zenith and azimuth were calculated. Using these values the DNI and DHI where calculated. Using the tilt, surface azimuth, zenith, solar azimuth, the DNI, GHI and DHI, the incoming irradiance per surface is calculated in the plane of array (POA), which is divided in POA global, POA diffuse and POA direct.

Question 2.4:

The best tilt and orientation of the rooftops of Building A and B have been calculated by varying these configurations with certain intervals between the ranges specified in the assignment. The results of the calculations can be found in Table 2. The bar charts of the annual irradiance (POA Total) for building A and B can be found in Figure 2. As can be seen from Figure 2, the optimal configuration for the rooftop of building A is a South-Eastern orientation with a tilt of 30°. For building B the optimal tilt is 35 °, with a south orientation. From figure 2 it can also be observed, that for building A, an orientation of South-east scores overall better than the south-west orientation.

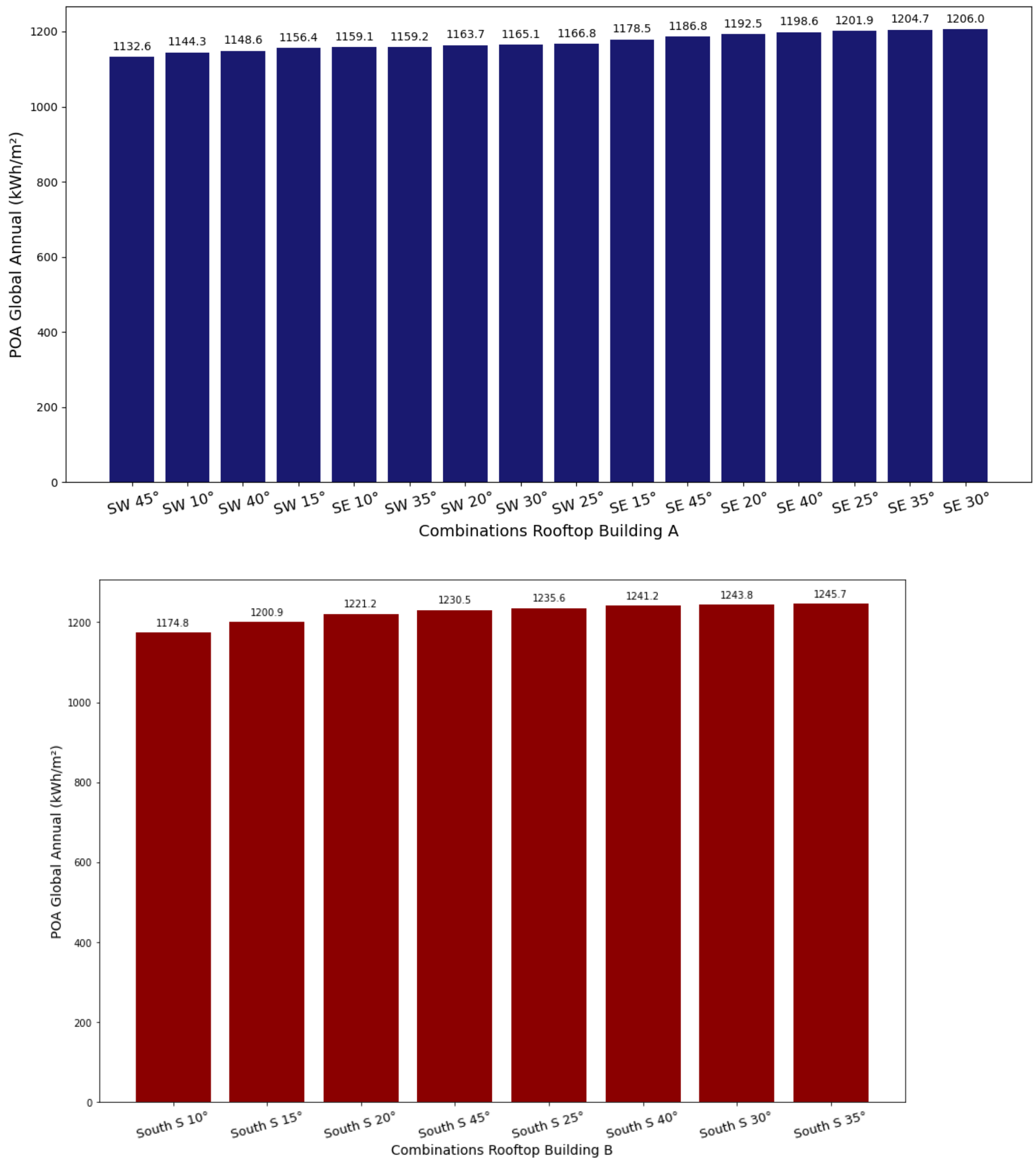

Figure 2: Annual irradiance sums of POA Total for Building A and B for different orientations.

Question 2.5:

The most optimal tilt combinations for rooftop A and B are given in Table 2. As established in question 2.4), a 30° angle facing South-East is the most optimal for the roof of building A. Similarly, it shows us that the most optimal tilt for the building of roof B is a 35° angle facing South.

Table 2: Tilts and orientations of the different surfaces

	Slope/tilt (°)	Orientation/surface azimuth (°)
Rooftop C (S)	40	180
Rooftop C (N)	40	0
Rooftop D (W)	40	270
Rooftop D (E)	40	90
Rooftop A (SW)	0	225
Rooftop B (S)	0	180
Façade A (SW)	90	225
Façade A (SE)	90	135
Façade B (W)	90	270
Façade B (E)	90	90
Façade B (S)	90	180
Rooftop A (SW, optimal)	**30**	**225**
Rooftop B (S, optimal)	**35**	**180**

The POA diffuse, POA direct and POA total values of all buildings are shown in Table 3.

Table 3: POA diffuse, direct and total for each building.

	Building A – façade SE	Building A – façade SW	Building A - roof	Building B – façade E	Building B – façade S	Building B – façade W
POA diffuse (kWh/m^2)	407.8	407.8	515.5	407.8	407.8	407.8
POA direct (kWh/m^2)	468.3	412.7	643.7	323.3	482.6	262.8
POA total (kWh/m^2)	876.1	820.6	1159.2	731.1	890.4	670.6

	Building B - roof	Building C – roof N	Building C – roof S	Building D – roof E	Building D – roof W
POA diffuse (kWh/m^2)	515.5	508.5	508.5	508.5	508.5
POA direct (kWh/m^2)	730.2	198.6	732.7	523	458.6
POA total (kWh/m^2)	1245.7	707.1	1241.2	1031.6	967.1

Question 2.6:

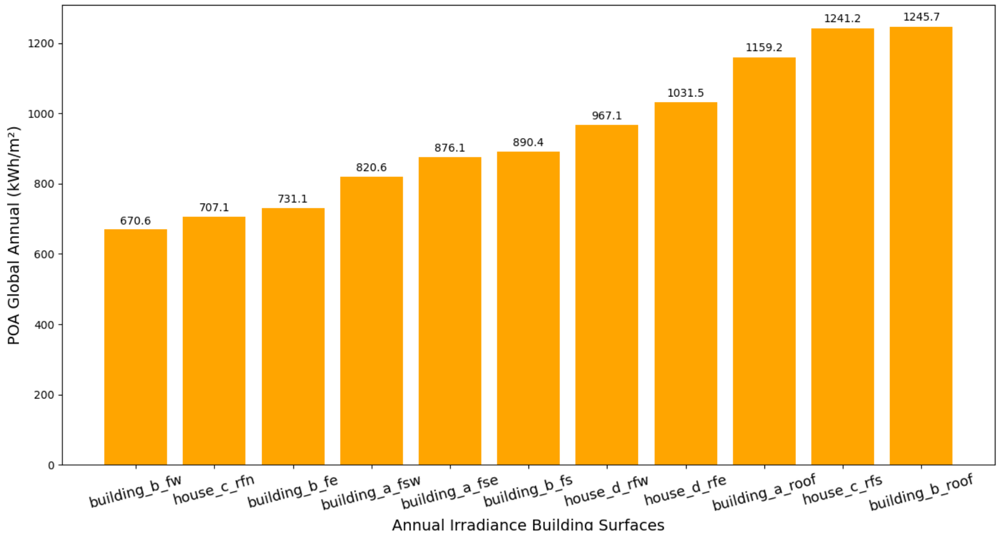

Figure 3: Annual irradiance of the different building surfaces from low to high

Figure 3 contains the sum of the total irradiance for each building surface in kWh/m^2 over one year. The surface of building B facing West has the lowest total irradiance with a value of 670.6 kWh/m^2 per year. The roof of building b obtains the highest yield (1245.7 kWh/m^2) per year. In addition, it can be observed that all the roofs, except for the roof of house C facing north, obtain the highest yield relative to facades.

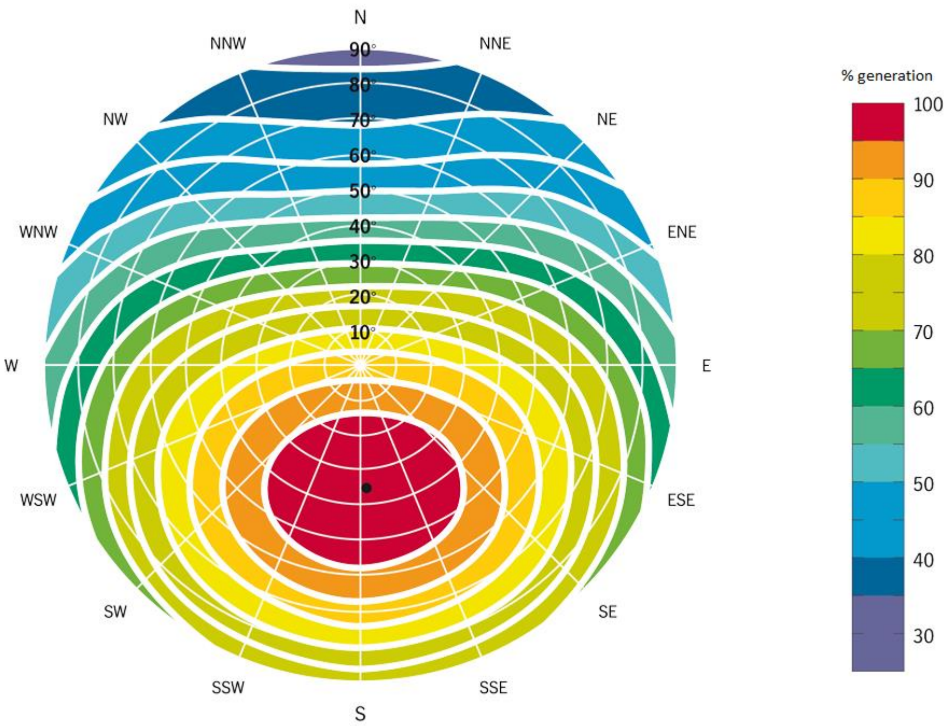

Figure 4: Optimal orientation and tilt for installation of PV modules in the Netherlands (InDuurzaam, n.d.)

Figure 4 depicts the optimal orientation and tilt for the installation of PV modules in the Netherlands. As can be seen in this figure, our results are seemingly in line with what is expected to be the most optimal placement of PV modules.

The yield of the PV installation highly depends on the tilt and orientation of the modules. All the roofs are either capable of optimizing this tilt and orientation, or are already oriented in roughly the optimal setting, therefore resulting they also generate the highest yield. Therefore, it can be concluded that for the Netherlands, the highest yield is obtained with a south-ward orientation. The optimal tilt varies between 30 and 35 (and could of course be between these values as well), depending on the orientation of the module.

Question 3

Question 3.1:

To determine the available roof and façade area where modules could be placed, the total surface area is multiplied with the percentage of available area per surface. For building A & B this is 30% for the facades and 50% for the rooftops, for buildings C&D this is 60% for the rooftops.

By dividing this calculated available area by the area of one PV module the number of modules per surface area is calculated for the three different module types. This number is rounded off downwards, since modules cannot be installed partly.

Lastly, the total installed capacity per surface per module type is calculated by multiplying the number of panels per surface with the peak capacity per module type provided by the module parameter data.

Table 4 depicts the available surface area for each different building surface and the number of modules with their corresponding installed capacity.

Table 4: The available module area, the number of modules and the total installed capacity per module per building surface

Building	Available area (m^2)	Number of hit modules	Number of cdte modules	Number of mono si modules	Capacity of hit (kWp)	Capacity of cdte (kWp)	Capacity of mono si (kWp)
Building A facade South East	1800	1428	2500	932	343	175	261
Building A facade South West	1500	1190	2083	777	286	146	218
Building A roof	1500	1190	2083	777	286	146	218
Building B facade East	270	214	375	139	514	263	389
Building B facade South	450	357	625	233	857	438	652
Building B facade West	270	214	375	139	514	263	389
Building B roof	750	595	1041	388	143	72.9	109
Building C rooftop North	140.1	111	194	72	26.6	13.6	20.2
Building C rooftop South	140.1	111	194	72	26.6	13.6	20.2

Building D rooftop East	140.1	111	194	72	26.6	13.6	20.2
Building D rooftop West	140.1	111	194	72	26.6	13.5	20.2

Question 3.2:
To calculate the DC performance, three variables are required: the effective irradiance, the cell temperature and certain module parameters.

The effective irradiance requires the POA global, POA diffuse, the absolute airmass of Hupsol, the angle of incidence (aoi) and some module parameters. Both the POA parameters are already known, the absolute airmass is calculated similar as in question 1, the aoi is calculated using the tilt, orientation, the solar zenith, and the azimuth and lastly, the module parameters are known and provided in the data sheet.

To determine the cell temperature, the POA global, the ambient temperature, wind speeds and the module parameters a, b and delta T are required. It is assumed that the values provided by the module parameter sheet are for open rack installation. Only the rooftops of A and B are suited for open rack installations, thus for these installations the above-mentioned module parameters are used. For all other installations, the close roof values are used provided by the pvlib library values which are defined as follows: a = -2.98, b=-0.0471 and delta T = 1.

All the above-mentioned variables and input values are used to determine the DC output per individual module per surface. To determine the total DC output, the individual DC performance is multiplied with the number of modules for that surface.

Question 3.3:
Figure 5 displays the annual yield in MWh per surface for the different modules for the different building. From figure 4, it can be observed that the HIT module has the best performance on all surfaces, followed by the Mono-Si module and the least performing module type is the CDTE. Moreover, it can be observed that the roof of building A has the highest annual yield. Table 4 depicts the precise annual values per surface per module.

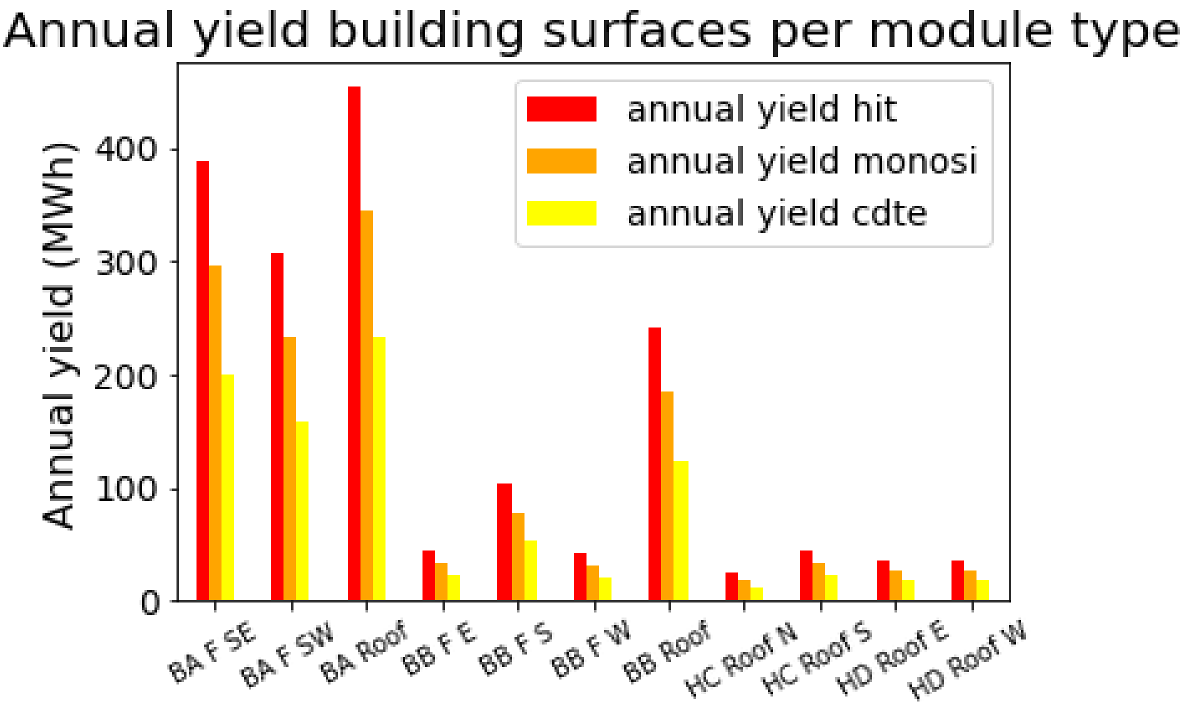

Figure 5: The annual yield per area of the different building surfaces for different module types

Table 5: Annual DC performance per module and per surface.

Building	HIT (MWh/year)	Mono Si (MWh/year)	CDTE (MWh/year)
Building A facade South East	389	296	200
Building A facade South West	308	234	158
Building A roof	454	345	234
Building B facade East	45.5	34.4	23.3
Building B facade South	103.3	78.6	52.8
Building B facade West	42.3	31.9	21.7
Building B roof	243	185	125
House C rooftop North	25.5	19.1	12.7
House C rooftop South	45.0	34.1	23.0
House D rooftop East	36.7	27.7	18.7
House D rooftop West	35.0	26.4	17.9

This difference in performance can be explained by analyzing the module parameters. Each module type has a different module area and peak performance. In these analyses the available area for all modules is almost the same (with a minor deviation due to rounding). Therefore, the main driver of performance is the performance of the modules per m^2. This can be calculated by dividing the maximum power output by the area per module. The HIT, mono so and CdTe module score 190.5, 145.1 and 97.2 Wp/m^2 respectively.

Question 3.4:

The energy yield per unit of façade area is calculated by dividing the total DC output by the available area for PV modules.

Table 6 displays the optimal module type, total installed capacity, the yield per m^2, the tilt and the orientation of the best performing modules installed on the different building surfaces. From table 5 It can be observed that the HIT module is the best performing module for all the different surfaces.

Table 6: Optimal module type, total installed capacity and tilt and orientation for the different building surfaces

Building	Best Module	Total capacity (kWp)	Yield Per m^2 (kWh/ m^2)	Tilt (°)	Orientation (°)
Building A facade South East	hit	343	64.9	90	135
Building A facade South West	hit	286	61.5	90	225
Building A roof	hit	286	151	35	225
Building B facade East	hit	51.4	50.6	90	270
Building B facade South	hit	85.7	68.9	90	180
Building B facade West	hit	51.4	47.0	90	90
Building B roof	hit	1143	162	35	180
Building C rooftop North	hit	26.6	109	40	0
Building C rooftop South	hit	26.6	193	40	180
Building D rooftop East	hit	26.6	157	40	270
Building D rooftop West	hit	26.5	150	40	90

Question 4

Question 4.1:

Using the formulas and constraints provided in the assignment document the AC power output is calculated. For the conversion of the DC power generated by the PV modules to AC power, a conversion efficiency is taken into account. This efficiency is not a static value, but rather depends on the amount of DC power generated at the time. There are three possible values (or value ranges) for the DC power taken into consideration in determining this efficiency, and therefore AC output:

1) The DC power is 0, in this case there is no efficiency value (as nothing is converted)

2) The DC power is higher than the rated DC power of the installed PV system, in this case the actual power production is limited by the capacity of the inverter (Paco). For this scenario, the nominal efficiency (η_{nom}) is used to convert to AC power. The nominal efficiency is set to be 96%.

3) The DC power is anywhere between 0 and the rated DC power of the installed PV system, in this case the conversion efficiency fluctuates depending on the magnitude of the DC power, and is expressed by the following equation:

$$\eta(P_{dc}) = -0.0162 \cdot \zeta - \frac{0.0059}{\zeta} + 0.9858 \tag{5}$$

Where:

$$\zeta = \frac{P_{dc}}{P_{dc0}}$$

$$P_{dc0} = \frac{P_{ac0}}{\eta_{nom}}$$

$$P_{ac0} = rated\ power\ of\ the\ inverter$$

Additionally, we assume the rated power of the inverter to be equal to the rated DC power of the PV system (as is mentioned in the assignment).

As for the inputs we used, the rated power of the inverter is set to the maximal power output of the module parameter, in case of the HIT module we have chosen before, this is 240 Wp. Using the provided nominal efficiency, the P_{dc0} can be calculated. Then using previously calculated module DC power output for P_{dc}, the hourly AC output can be calculated accordingly, while making sure the P_{ac} conditions that are described above are adhered to.

Question 4.2:

Figure 5 depicts the annual AC output per surface and Figure 6 for the total AC output of each building both Figures depict the results using the HIT PV module. When analyzing the difference of the annual AC output and DC output (Figure 4, HIT to Figure 5), it follows that the average deviation between DC and AC is 4.4%. Indicating, that the efficiency losses due to the inverter are approximately 4.4%.

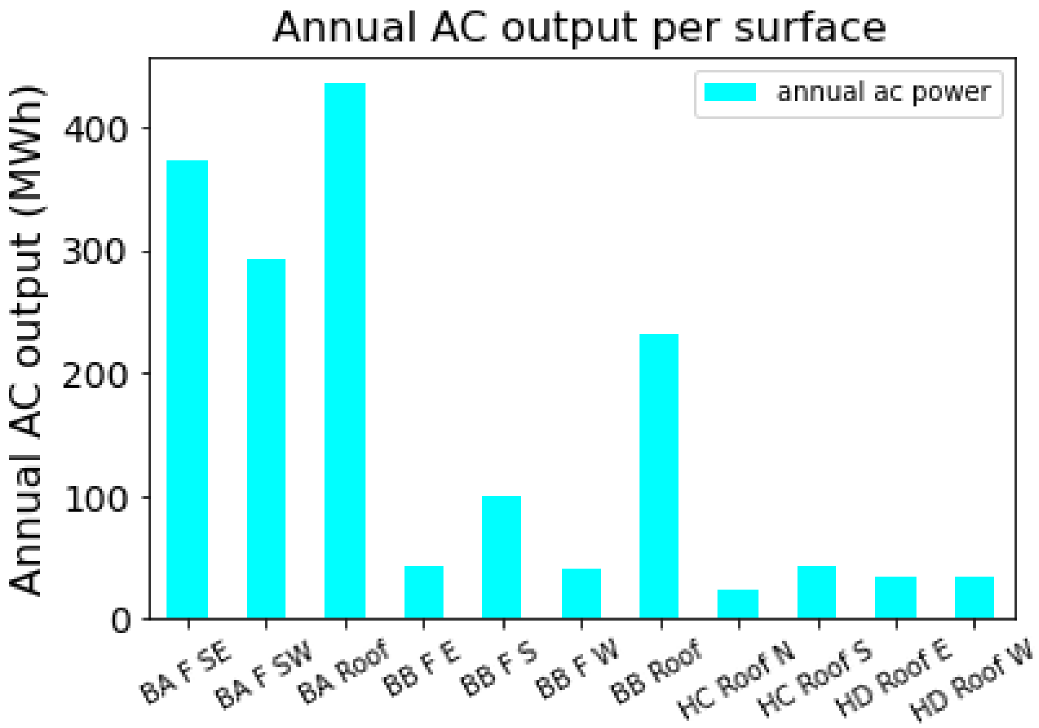

Figure 6: Annual AC output per surface

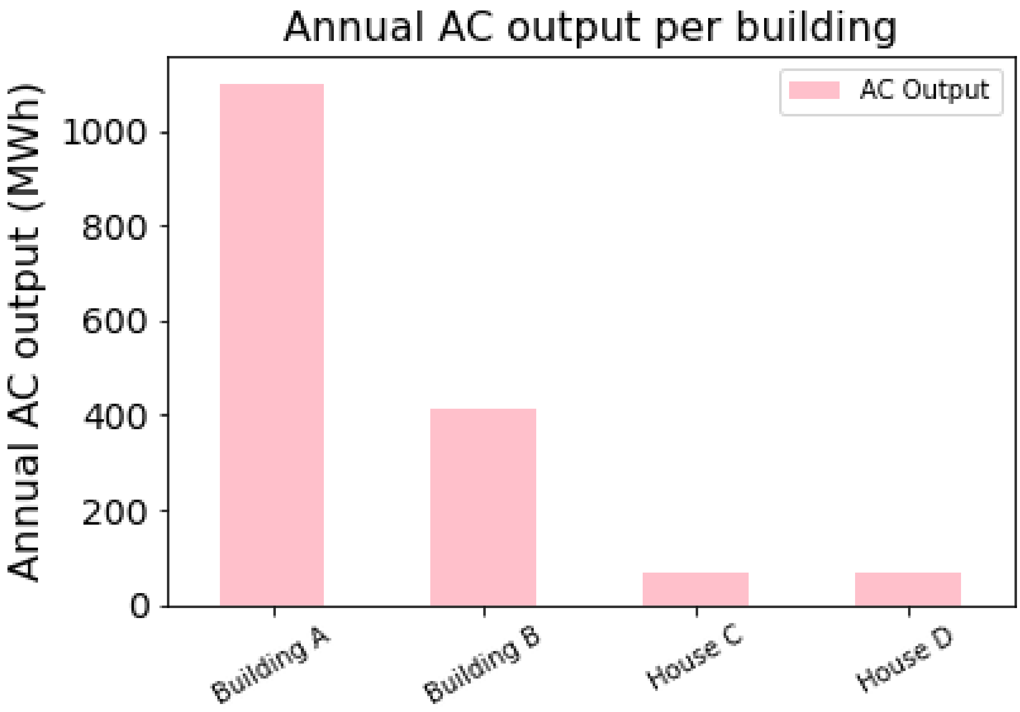

Figure 7: Annual AC output per building

From figure 6 it can be observed that building A has the highest annual AC output (1100 MWh), followed by building B (415 MWh), house C (67.5 MWh) and house D (68.7 MWh). Building A has the highest annual output, the cause for this being the significantly higher available surface area (2.75 times the area of building B), as shown table 3. Whereas building B has a higher yield per surface of the building. This can be concluded when looking at the yield per m^2 depicted in table 5, or by dividing the annual output of building A by building B, which is 2.65. Since 2.75 > 2.65, this implies that building B has a higher output per surface than building A.

House C and D are very similar in their annual AC output. House C has the most optimal roof (southward) and the least optimal roof (northward). This compensates for the two sub optimal orientations of building B, east and west.

Question 4.3:
For the selection of three different days, the following days were selected:

- *For a day in Spring, April 5th is chosen, which has irradiance hours from 07:00 till 19:00, and the highest GHI is noted at 330.*
- *For a day in Summer, July 4th is chosen, which has irradiance hours from 05:00 till 21:00, highest GHI is noted at 852.*
- *For a day in Autumn, November 7th is chosen, which has irradiance hours from 08:00 till 16:00, highest GHI is noted at 177.*

Figures 8 to 19 display the hourly AC outputs per building for different days, which are all grouped per building in seasonal order.

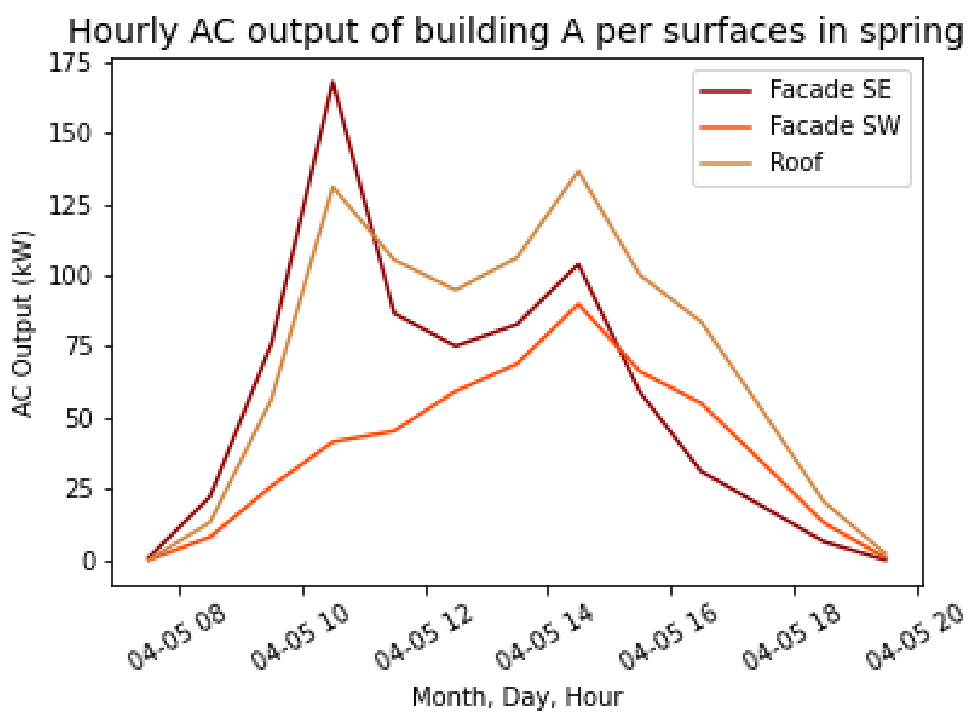

Figure 8: Hourly AC output of building A per surface in spring

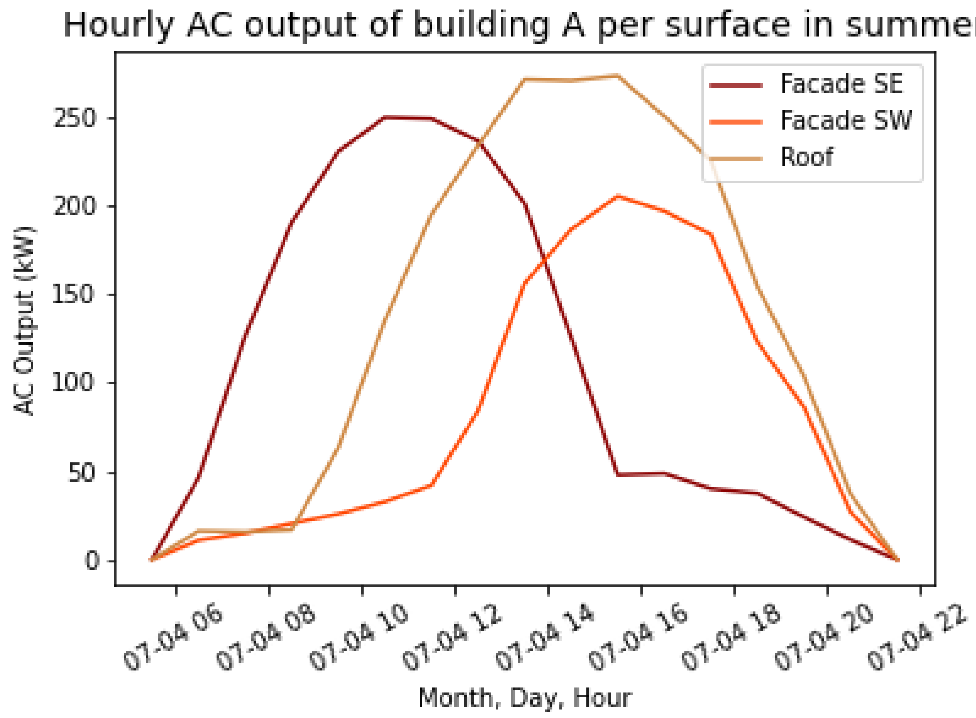

Figure 9: Hourly AC output of building A per surface in summer

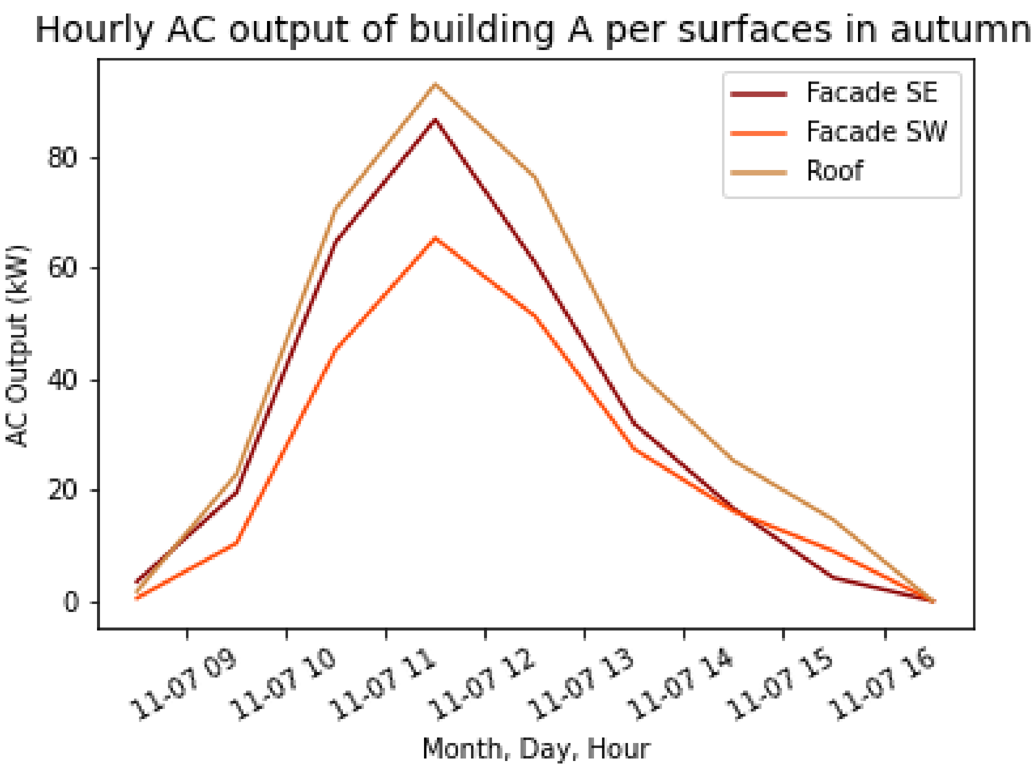

Figure 10: Hourly AC output of building A per surface in autumn

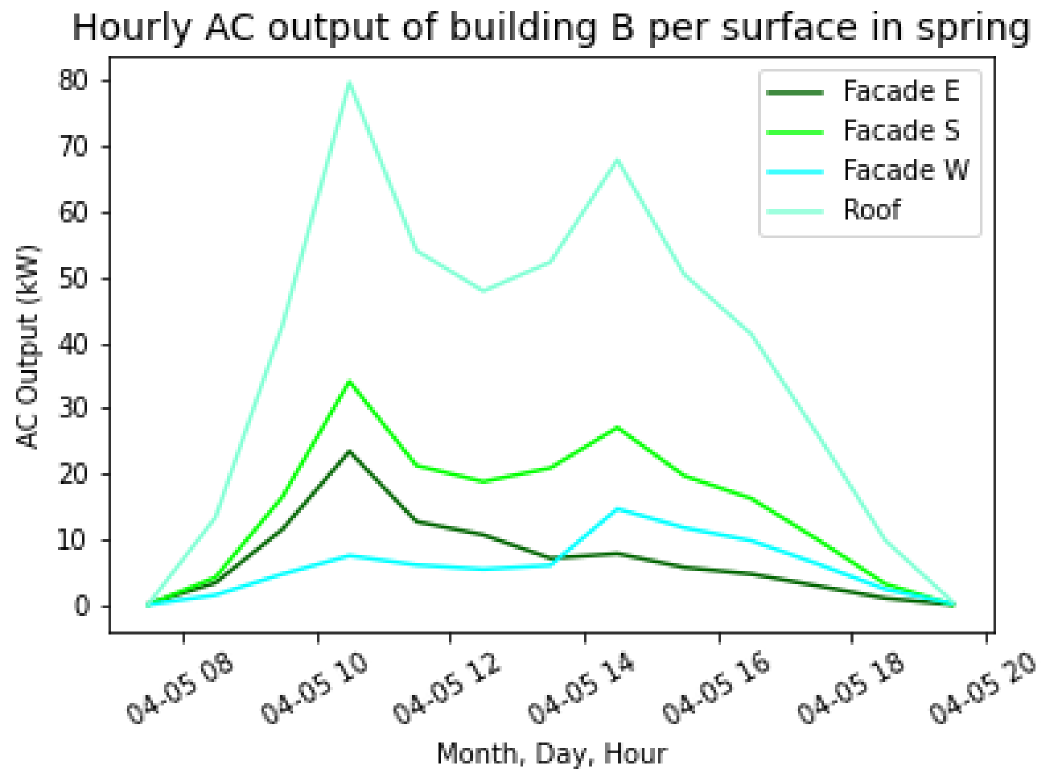

Figure 11: Hourly AC output of building B per surface in spring

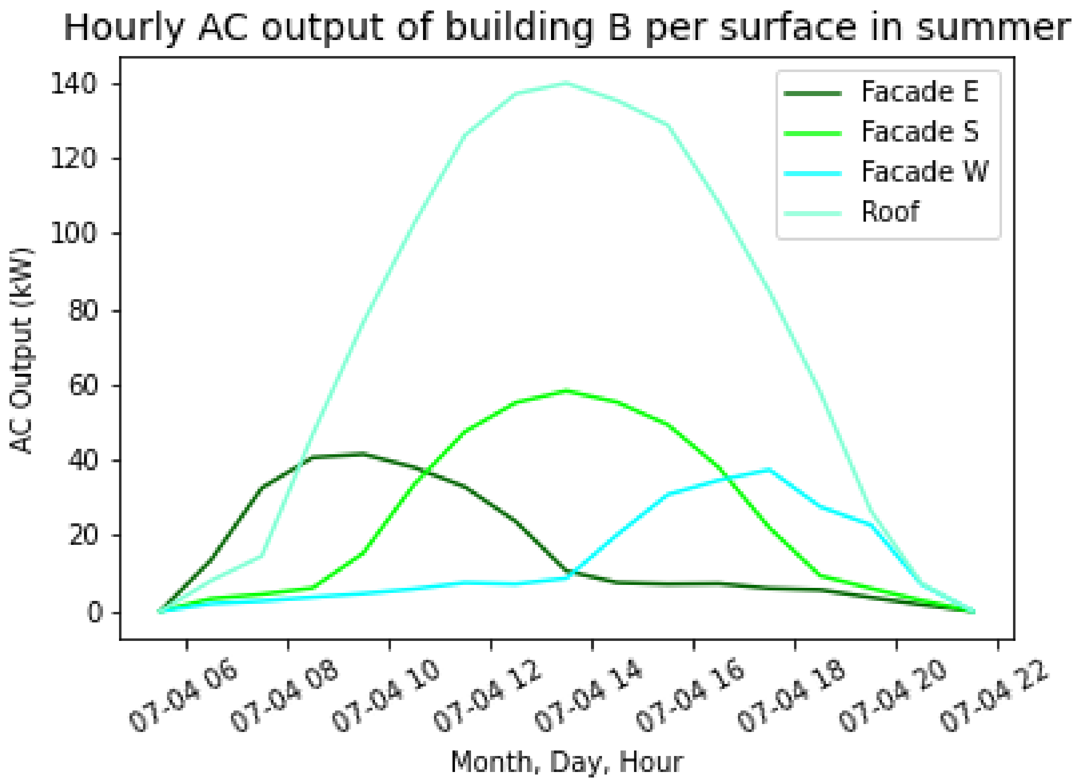

Figure 12: Hourly AC output of building B per surface in summer

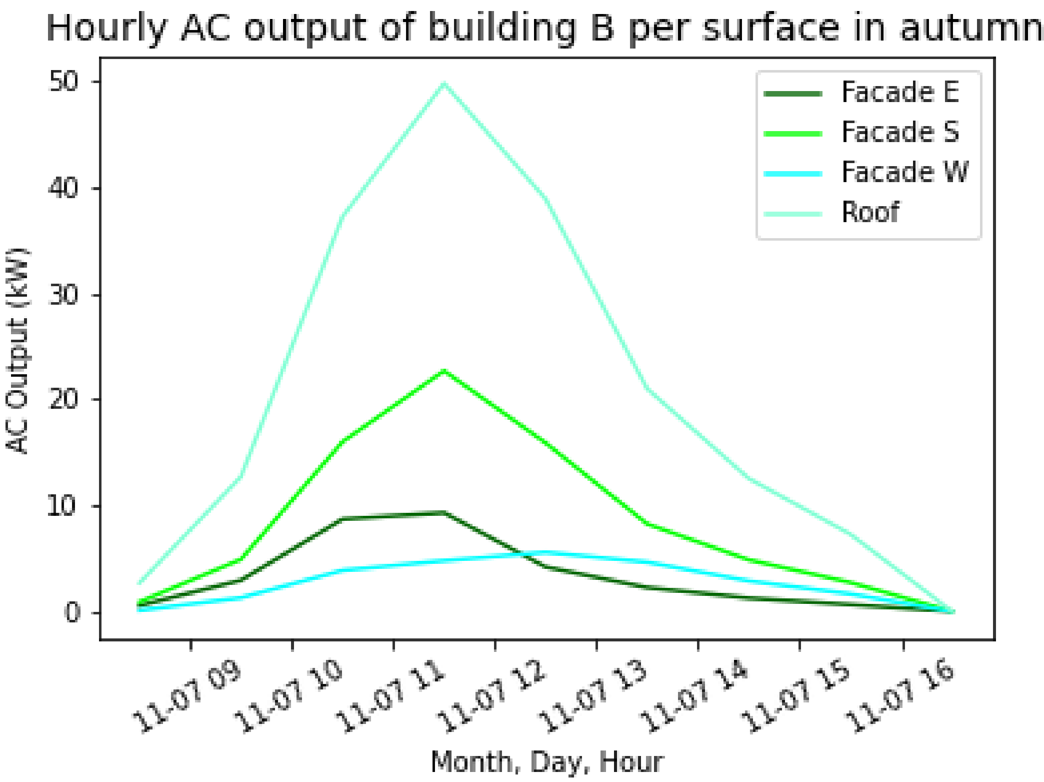

Figure 13: Hourly AC output of building B per surface in autumn

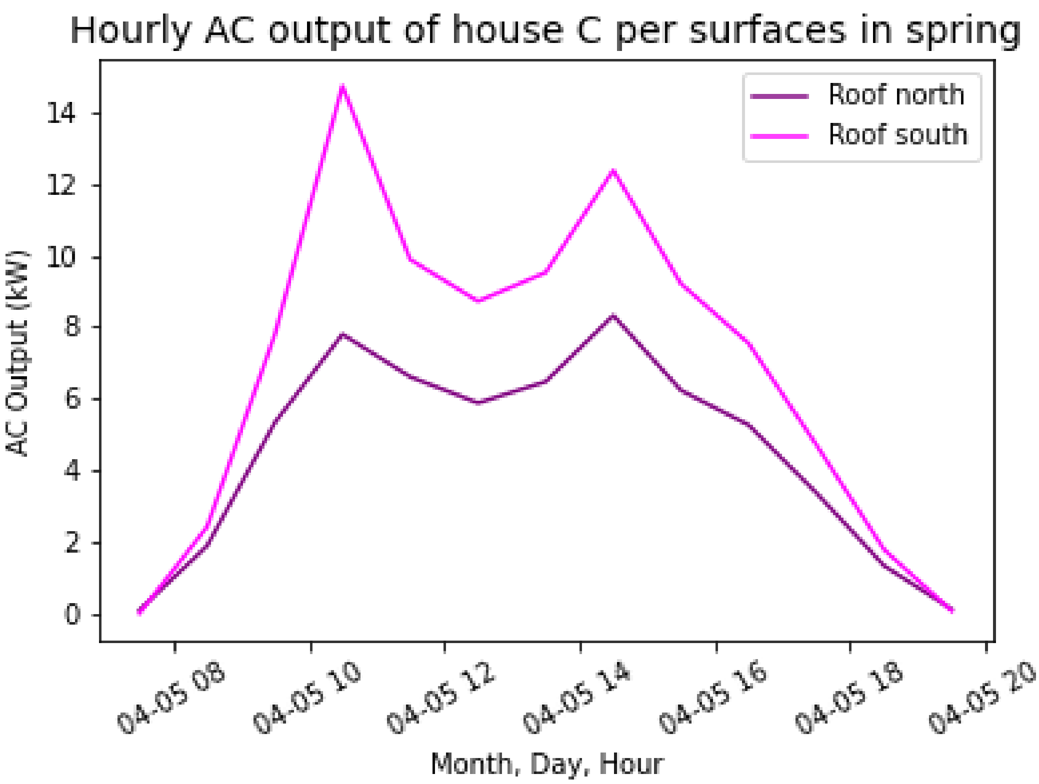

Figure 14: Hourly AC output of building C per surface in spring

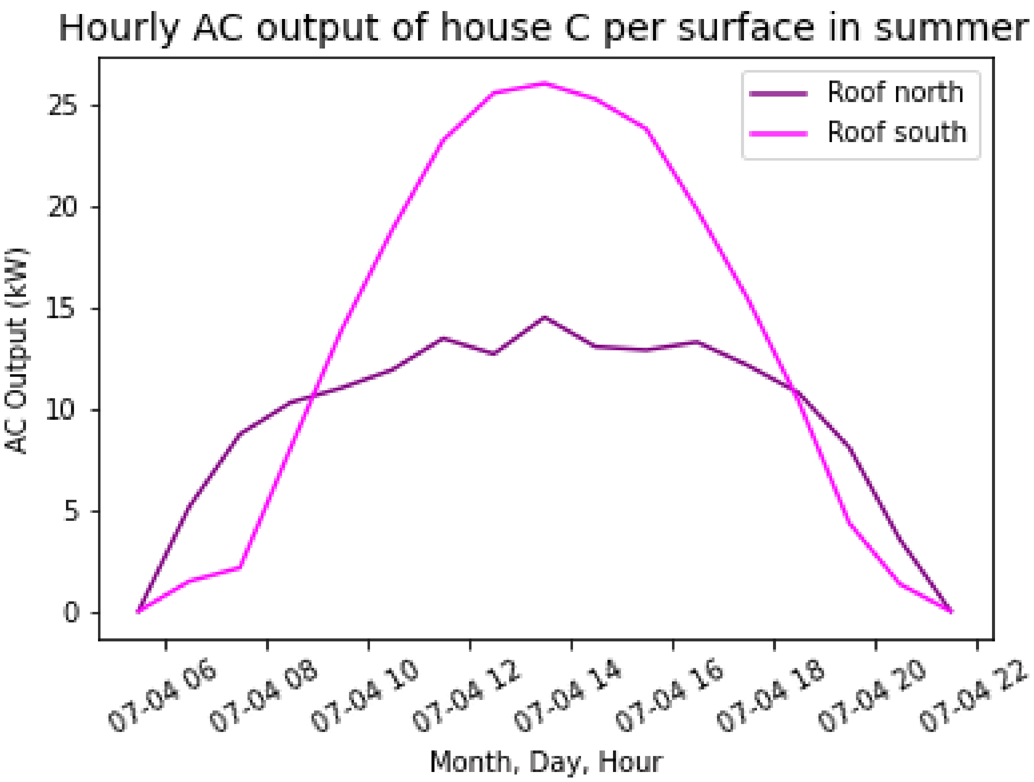

Figure 15: Hourly AC output of house C per surface in summer

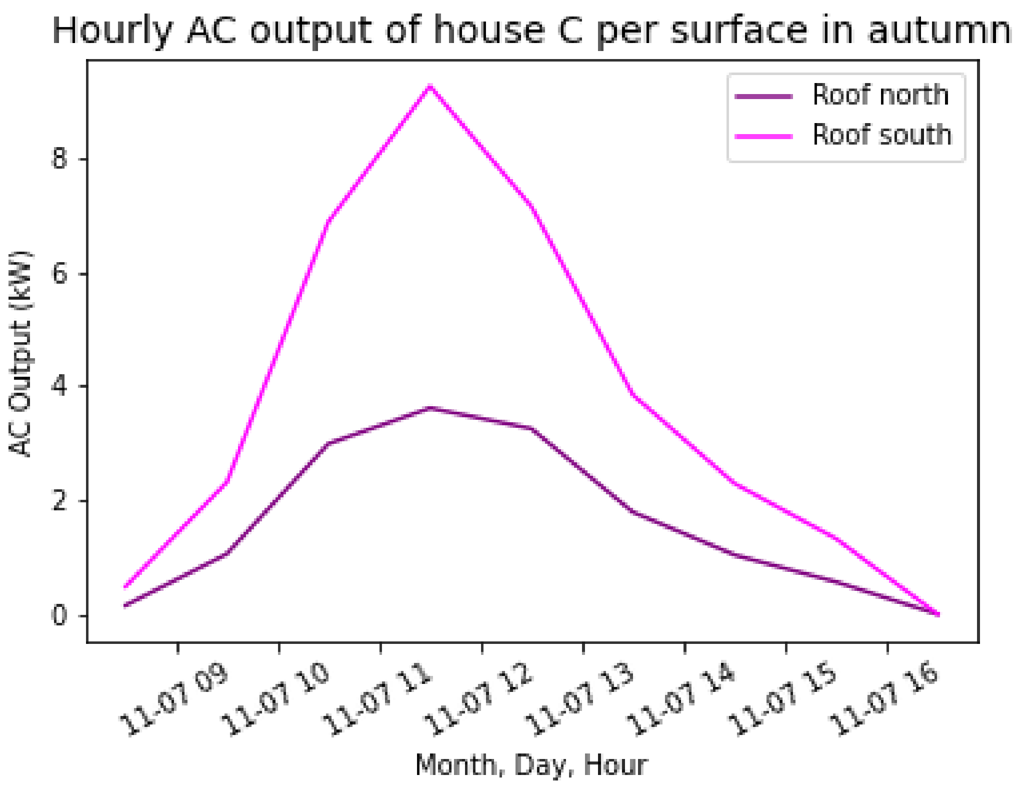

Figure 16: Hourly AC output of house C per surface in autumn

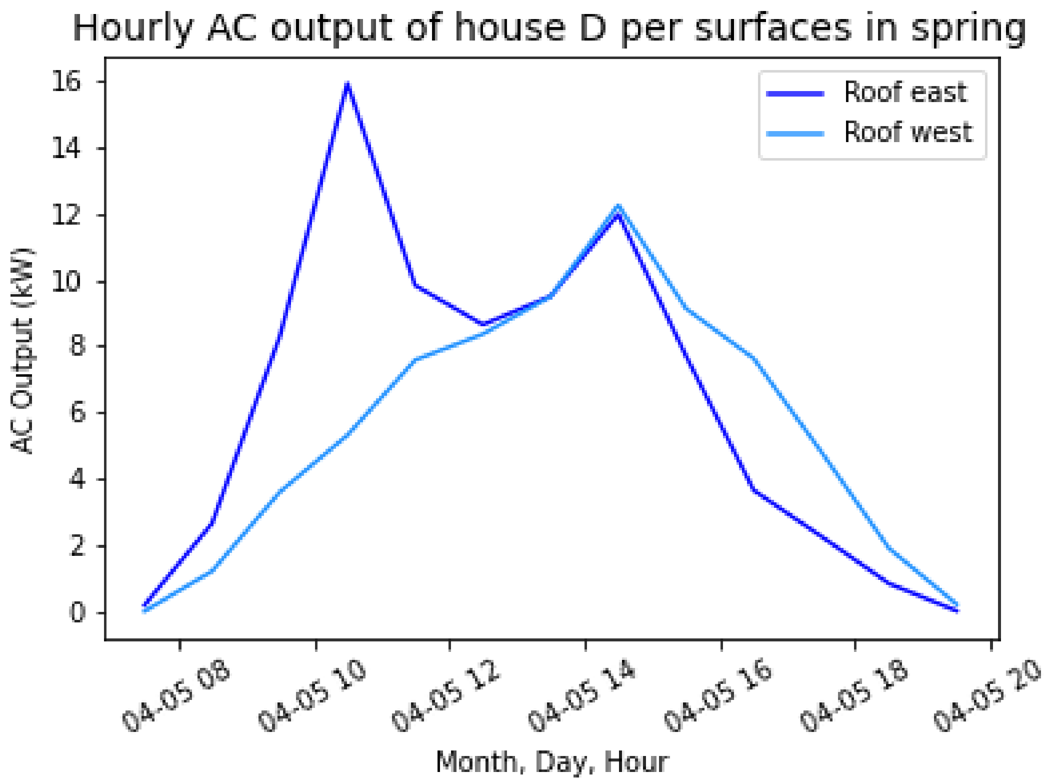

Figure 17: Hourly AC output of house D per surface in spring

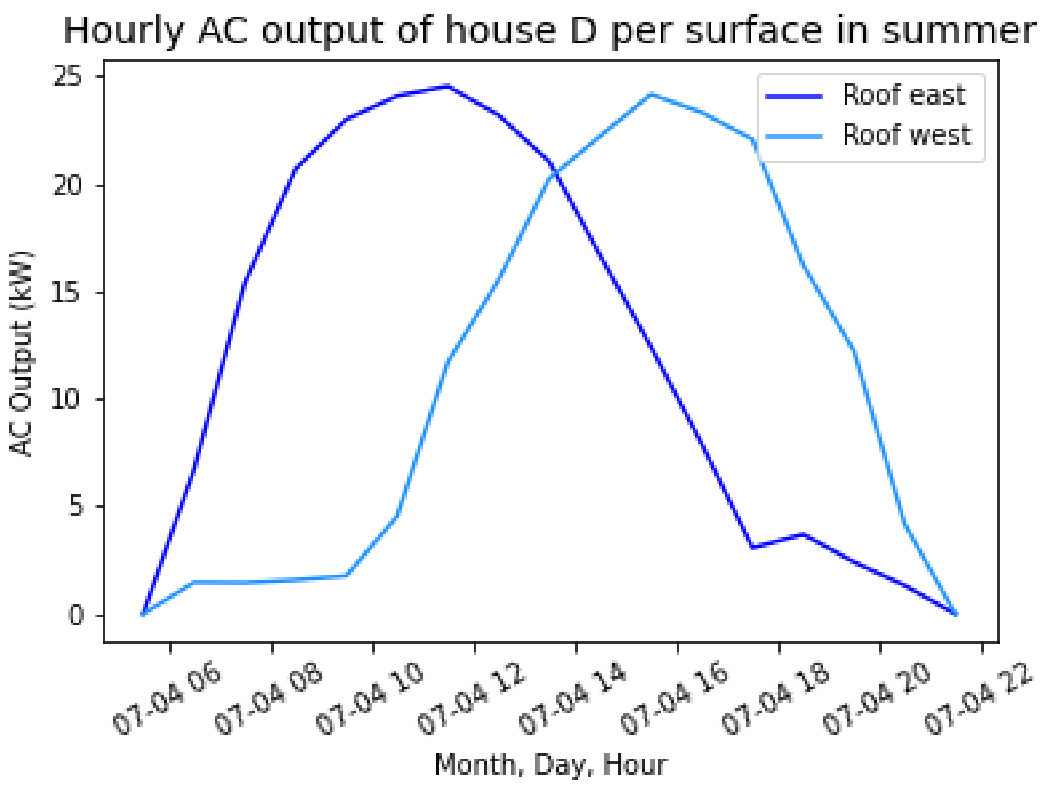

Figure 18: Hourly AC output of house D per surface in summer

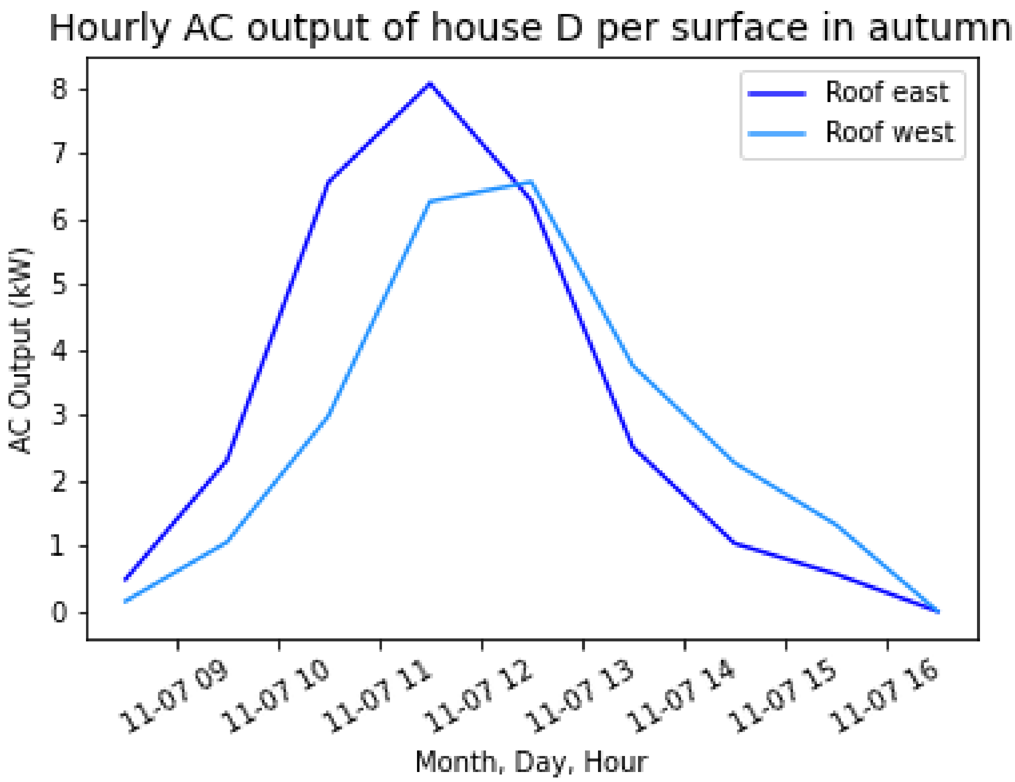

Figure 19: Hourly AC output of house D per surface in autumn

Question 4.4:
Regarding the impact of different orientation of facades, the following observations can be made.

The first observation that can be made from Figures 8 to 19, is that roof-oriented facades almost always have the highest output. Except for the South-East facing façade of building A during spring, which generates the same output as the roof throughout the morning.

The second observation that can be made from Figures 8 to 19, is that facades which have an eastward orientation produce more during the morning and South-West facades more during the afternoon. Rooftops show a pattern which lie in between. This is expected due to the sun rising in the East and setting in the west on a daily basis. This is reflected most accurately in the façades of building B (since it has a façade facing East, South, and West).

A third observation that can be made from Figure 14 to 16 is that the North facing roof almost always has a lower AC output then the South facing roof. Which is in line with wat you would expect from roofs facing North and South in the northern hemisphere.

Regarding the seasonal differences on the AC power production, the followings observations are made.

The first observation is, that during summer the daily power production is spread out over a longer period during summer than spring or autumn due to longer sunlight availability. Similarly, due to higher irradiance levels during summer, this period produces significantly more power than spring or autumn.

Another observation can be made from Figures 18 and 19. During summer East and West facing roofs have a clear different time of peak generation, whereas in autumn this peak occurs at almost the same time in the day.

A general and concluding observation regarding the orientation of facades and seasonal differences would be that there are clear differences to be observed. These differences could be utilized in building design to optimize electricity generation and demand within buildings. Thus, increasing self-consumption and self-sufficiency.

References

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