D4.23.1. Monitoring report on the Middelburg PV installations

This document has been elaborated by KU Leuven for Middelburg

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Executive summary

This report describes the monitored data from two PV systems built within SOLARISE in Middelburg on listed historical buildings, with the largest system (117 kW at Zeeland Archives) providing the largest CO_2 savings for Middelburg, with the Zeeland Concert Hall at 22.8 kW providing a proportionally smaller contribution. Despite the challenges encountered in building the systems, it is expected that at least 1233 tonnes of CO_2 savings can be obtained from both PV systems over a 25-year lifespan. With appropriate monitoring and care, PV systems are expected to last up to 35 or 40 years, in which case the CO_2 savings would continue to accrue.

The table below summarises the expected energy yield and CO_2 savings results.

Site	Estimated annual PV production (PVsyst)	25-year average annual PV production	25-year total PV generation estimate	25-year annual generation (kWh/kWp) estimate	CO_2 savings over 25 years
Zeeland Archives	104.8 ± 8.4 MWh	95.3 MWh	2381.2 MWh	811.0	1035.8 tonnes CO_2
Zeeland Concert Hall	20.0 ± 1.6 MWh	18.2 MWh	454.4 MWh	798.2	197.7 tonnes CO_2
Total	**124.8 ± 10 MWh**	**113.5 MWh**	**2835.6 MWh**	**808.9**	**1233.5 tonnes CO_2**

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1. Context and historical development

The historic city of Middelburg exemplifies the challenge that well-preserved towns and cities with a rich heritage face, namely reducing CO_2 emissions whilst ensuring that those solutions respect the heritage and aesthetics that are so highly valued.

Through the participation of Middelburg in the Solarise project, three demonstration pilots were made possible on historical and/or listed buildings, of which two were implemented with PV modules, and the third with an innovative hot water heat exchange system on slate roofs. This report covers the two PV systems built during the Solarise project in Middelburg:

1. Zeeland Archives (Zeeuws Archief)
2. Zeeland Concert Hall

2. Sites

2.1. Zeeland Archives (Zeeuws Archief)

The Zeeland Archives building which hosts the 117 kW PV array is strictly speaking not a historic or listed building, as it was recently built in 2000, adjacent to the historic and listed building from 1316, which was extensively remodeled and completed in 1765. However, due to Dutch legislation, any new building (or extension) which is permanently affixed to an historic building, e.g. via a permanent connecting hallway, automatically inherits the classification from the older building, and with it, restrictions on modifications.

Installing a PV system on the Zeeland Archives was therefore not as easy as would be expected. From an aesthetic standpoint, the PV array to be hosted on the Zeeland Archives building needed to have minimal visual impact and best resemble the prior roof design, particularly as the roof faces a courtyard which is easily accessible to the public, as shown in Figure 2.

Figure 1: Zeeland Archives PV system viewed from the adjacent courtyard

Given the aesthetic requirements for the PV modules, custom-built black PV modules with black frames were selected by the installer, with each module having a nominal power of 150 Wp and a smaller footprint of 1.2 m by 0.75 m (0.9 m²). By contrast, “standard” commercial PV modules can now be purchased with power ratings of up to 600 W at sizes above 2 m², and a lower cost per W,

albeit significantly less well suited for historic or listed buildings when the modules can be easily seen. The attentive reader may also notice two areas in Figure 1 which are darker than the surrounding PV modules, which was a requirement by Zeeland Archives, for space for the heating and ventilation inlet and outlet, to ensure that the materials stored at the Zeeland Archives are kept at optimal conditions.

The complexity of the project resulted in challenges in obtaining sufficient interest from the market, as many installers were daunted by the site, as well as potential liability and insurance requirements. While the details will be particular to each site, there is a commonality and (usually) relative simplicity of PV systems, which suggest that innovative approaches to insurance as well as risk mitigation for all parties involved can unlock large rooftop spaces (roofs of large listed buildings such as churches, museums, etc) for PV systems, even if these happen to be on listed buildings.

The characteristics of the PV system are listed below. As the roof is oriented East, the PV array sees the highest production in the morning, dropping off in the late afternoon.

Tilt angle	Orientation (° clockwise from N)	PV modules	PV DC power	PV AC power	Inverter
25°	90° (E)	München Solar 150 Wp 28 cells (All Black), custom-made	117.45 kWp	110 kVA	Sungrow 110

2.2. Zeeland Concert Hall

The Zeeland Concert Hall was purchased and remodelled in 1896, and is famous in The Netherlands for its acoustic quality. The City of Middelburg as owner wished to further reduce CO_2 emissions of its assets, and elected to install a PV system on the roof and install a battery in the building for increased self-sufficiency. Due to safety considerations and a lack of experience by the fire marshals with lithium-ion battery systems, the battery system suffered a delay in installation. This report will therefore only focus on the PV system performance, noting that the battery is expected to significantly increase the self-sufficiency of the building, particularly as many activities such as concerts occur in the evenings after sunset.

The orientation of the PV array (due West) is optimised for peak production in the afternoon and evening, which aligns well with the activities within the building.

Tilt angle	Orientation (° clockwise from N)	PV modules	PV DC power	PV AC power	Inverter
40°	270° (W)	Jinko Solar 345 Wp	22.77 kWp	22 kVA	Sungrow 20 KTL

3. Monitoring results and CO_2 savings

3.1. Zeeland Archives (Zeeuws Archief)

As the PV system at the Zeeland Archives was completed in December 2021 (full operation from 14 December), less than 1 full year of data was available to be analysed, a PVsyst model was created to compare the performance, and extrapolate for the future.

Figure 2 shows the performance of the PV system at Zeeland Archives, from 1 January 2022 to 18 October 2022. The PV system appears to be operating roughly according to the expectations for a median year, with a measured cumulative yield by 18 October 2022 of 95.5 MWh (expected: 99.7 ±

8.0 MWh, i.e. -4.2% underperformance which is well within the uncertainty range of the PVsyst model (± 8%)), noting that the comparison is between a long-term average yield expectation (PVsyst) and the actual year 2022 for the installation. The data suggest that a month-long data outage occurred, from 25 August to 29 September 2022, which was confirmed by Zeeland Archives, which is shown in Figure 3.

Overall, the following key values are determined in Table 1, with The Netherlands having an equivalent CO_2 factor for electricity of 435 gCO_2/kWh. For future performance evaluation, the estimated annual generation estimate of 104.8 ± 8.4 MWh can be used to check whether the system is performing as expected: if the annual total for that year is below 96.4 MWh (104.8 – 8.4 = 96.4), then the system is likely to be underperforming, and an investigation as to the causes for underperformance is warranted. For this, reports by IEA PVPS Task 13 (https://iea-pvps.org/research-tasks/performance-operation-and-reliability-of-photovoltaic-systems/) are recommended.

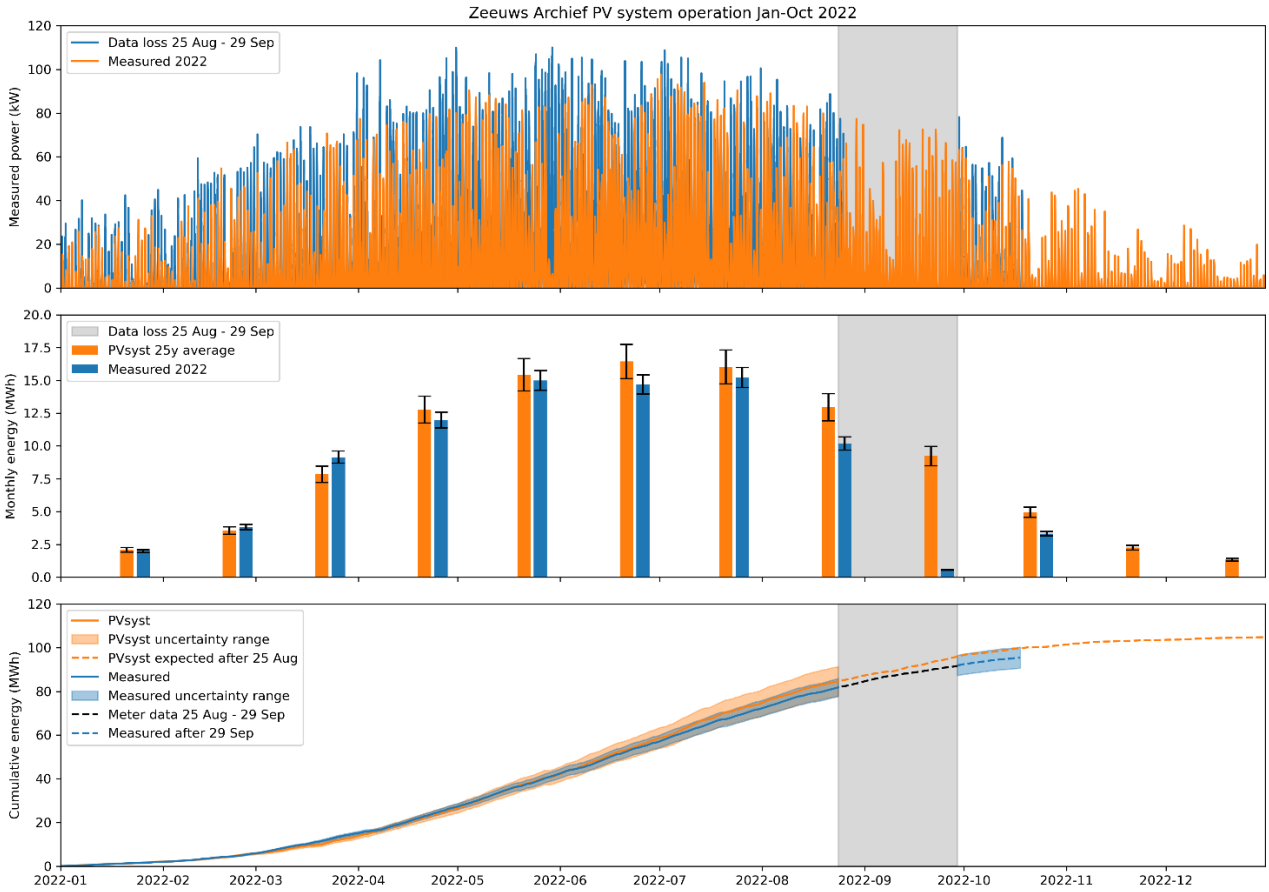

Figure 2: Zeeland Archives measured PV performance versus modelled by PVsyst. The data for 25 August to 29 September has been corrected using metering data (daily totals), as shown in Figure 3

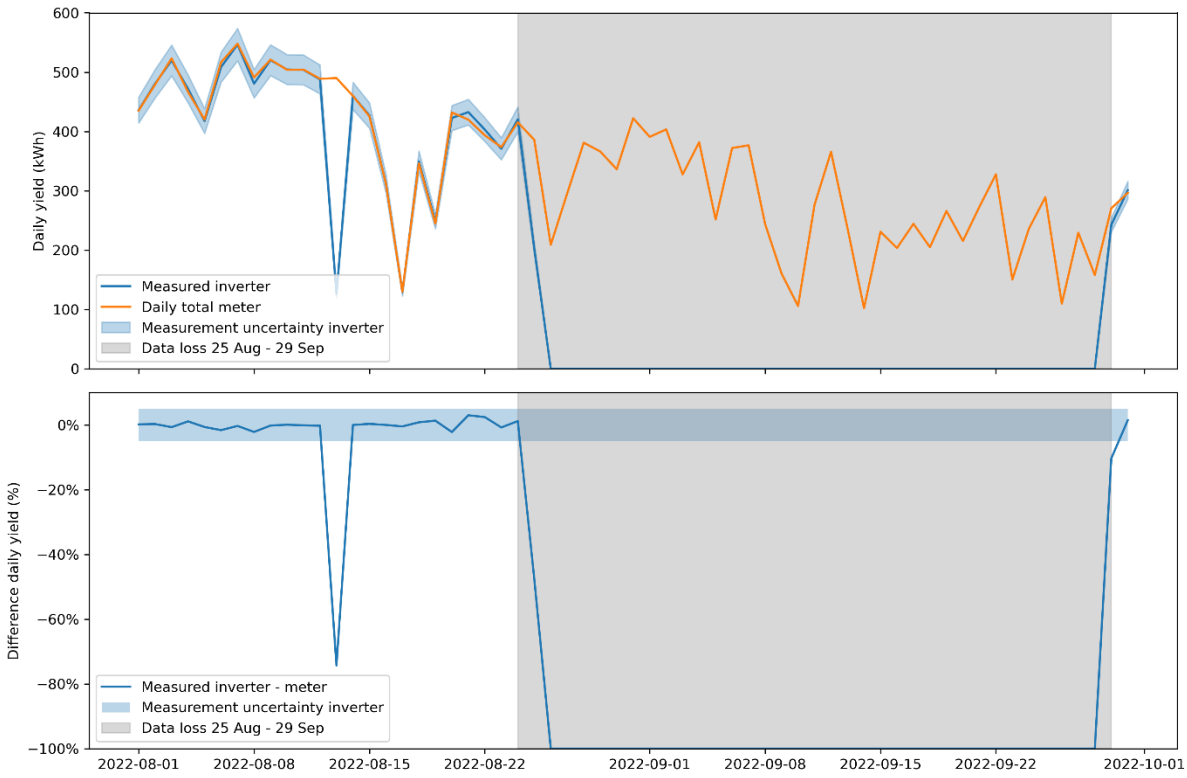

Figure 3: Zeeland Archives daily totals for August-September 2022 showing inverter monitoring data outage

Table 1: Zeeland Archives energy yield and CO_2 savings

Estimated annual PV production (PVsyst)	25-year average annual PV production	25-year total PV generation estimate	25-year annual generation (kWh/kWp) estimate	CO_2 savings over 25 years
104.8 ± 8.4 MWh	95.3 MWh	2381.2 MWh	811.0	1035.8 tonnes CO_2

3.2. Zeeland Concert Hall

Similar to the Zeeland Archives, the PV system at the Zeeland Concert Hall was completed in December 2021 (full operation from 21 December), a PVsyst model was also created to compare the performance, and extrapolate for the future.

Figure 4 shows that the PV system slightly outperforms the expected average yield by 18 October 2022, with a measured total of 19.4 ± 1.0 MWh , compared to the PVsyst expectation of 18.9 MWh (+3%). This system suffered no (known) data outage. Compared to the Zeeland Archives, the annual generation is slightly lower, due to the higher tilt angle at which the modules were placed.

Table 2: Zeeland Concert Hall energy yield and CO_2 savings

Estimated annual PV production (PVsyst)	25-year average annual PV production	25-year total PV generation estimate	25-year annual generation (kWh/kWp) estimate	CO_2 savings over 25 years
20.0 ± 1.6 MWh	18.2 MWh	454.4 MWh	798.2	197.7 tonnes CO_2

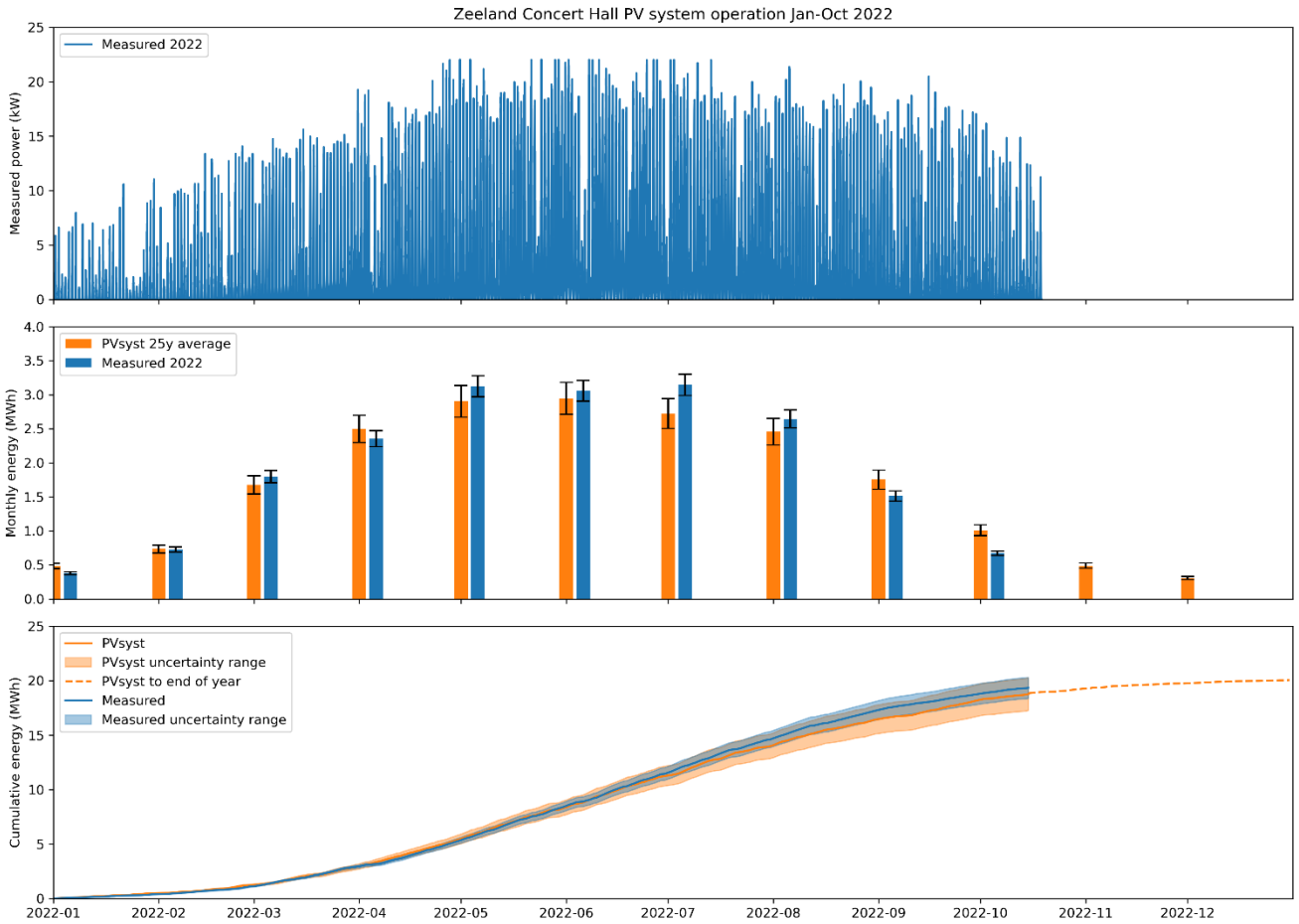

Figure 4: Zeeland Concert Hall comparison of measured versus modelled data

3.3. Total values

The summary of the energy yield and CO_2 savings are given in Table 3.

Table 3: Summary energy yield and CO_2 savings

Site	Estimated annual PV production (PVsyst)	25-year average annual PV production	25-year total PV generation estimate	25-year annual generation (kWh/kWp) estimate	CO_2 savings over 25 years
Zeeland Archives	104.8 ± 8.4 MWh	95.3 MWh	2381.2 MWh	811.0	1035.8 tonnes CO_2
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