PACE

Pathway to a competitive European Fuel Cell micro-CHP Market

REPORT

3rd report on performance validation of units installed

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PACE

Pathway to a competitive European Fuel Cell micro-CHP Market

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Executive summary

In the PACE project, micro-CHP (combined heat and power) units based on fuel cells are being demonstrated in private homes and small commercial buildings. More than 2,800 units will be demonstrated during the project period 2016-2023.

This third report on performance validation includes data from operation in the field until March 31, 2022. Data has been reported from six manufacturers: Bosch, BDR Thermea, Hexis, SOLIDpower, Sunfire and Viessmann.

As of March 31 2022 2154 units were installed throughout Western Europe with a high number of units demonstrated in Belgium and Germany. The total installed capacity was 2189 kW of electrical power and 1967 kW of thermal power.

The units operate with a high robustness. Availabilities for multiple products are at, or above, 99%. In general, availability is above 97%. Some failure and availability reporting may benefit from additional validation by the manufacturer.

Mean values of the gas utilisation (average electrical efficiency during the real-life operation) is found to correspond well with the rated efficiencies and the spread in utilisations are low and the means accurate. Clear seasonal trends can be seen for several heat-lead products. This validates the different characteristics and designs of the products in real operation conditions.

Of the installed units, 78% were reporting full performance data. Discounting units not connected to the internet by choice of the end-user this number goes up to 84%. In total these units have been operating for 23,390,524 hours and produced 23,991,535 kWh of electricity since the beginning of the PACE project.

Further data validation will take place and the data collection in the project will continue. The results will be followed up in the fourth and final report on performance validation.

PACE

Pathway to a competitive European Fuel Cell micro-CHP Market

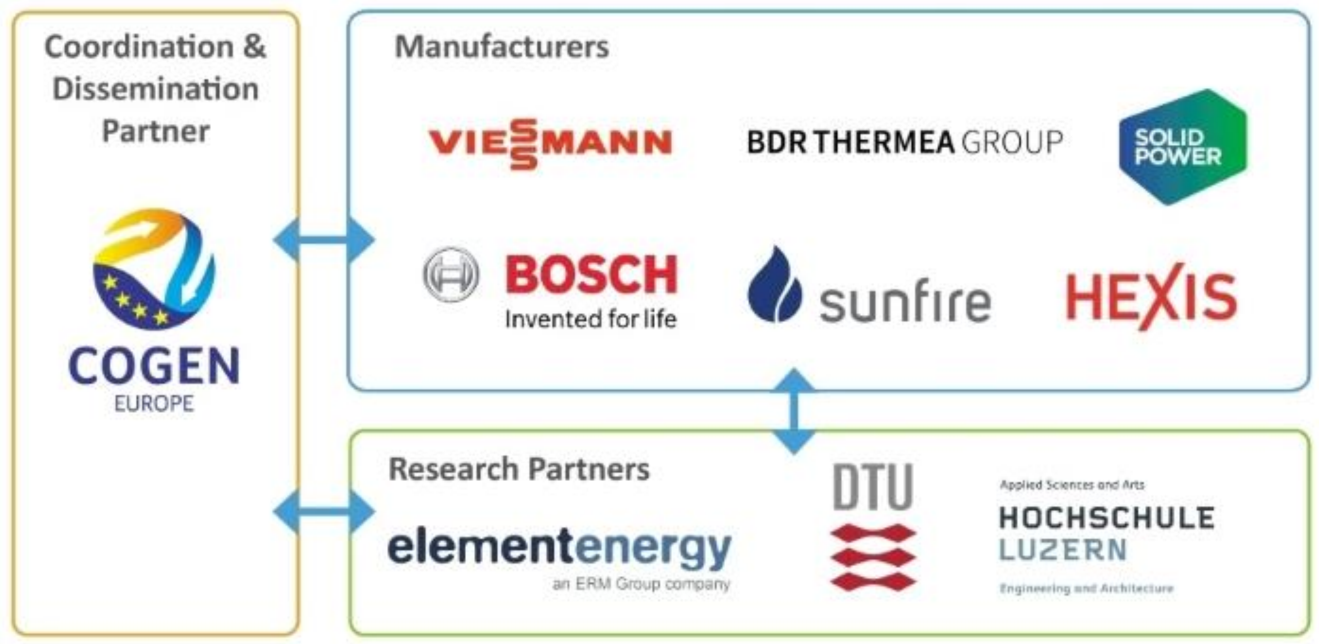
About PACE

PACE is a six-year project that will deploy more than 2,800 of the next generation Fuel Cell Combined Heat and Power (or Fuel Cell micro-cogeneration) units in 10 European countries by 2023.

The project brings together six leading European suppliers (Bosch, Hexis, SOLIDpower, BDR Thermea (Senertec), Sunfire, and Viessmann), and will focus on domestic housing and small enterprises. The manufacturers are supported by associations, consultancies, and research partners providing specific expertise (COGEN Europe, DTU, Element Energy and Hochschule Luzern).

PACE is a € 90 million public-private project co-funded by the *Fuel Cells and Hydrogen 2 Joint Undertaking* (FCH JU).

For more information, visit *www.pace-energy.eu*



1. Background

Summary of the chapter

The objective of this report, and it's associated task, is to report the technical performance validation and operational reliability of the demonstrated fuel cell based micro-CHP units. The collection of the performance data and the type of results to be reported are outlined in this chapter. Operational data until March 31, 2022 has been included in the reporting.

1.1 Objective

This document is the periodic reporting of performance validation of the demonstrated fuel cell micro-CHP (combined heat and power) units installed in the PACE project. These units are being demonstrated in domestic housing and small commercial buildings.

The objective with this deliverable is to report the technical performance and operational reliability based on actual measurements during real-life large-scale demonstration.

1.2 What is being measured and how?

As the PACE project is a demonstration of close-to or just market ready products in large scale, 2,800 units or more, in consumer households or small businesses, data collection needs be to simple and robust. Therefore, the data monitoring for the performance validation of the installed DC mCHP units in PACE is based on the array of sensors already part of the units. This avoids the significant costs associated with detailed metering equipment. The insights such detailed metering equipment could add into the performance of the mCHP units would not be sufficient to justify the expense associated with the procurement, installation and operation of the equipment. It should be noted that the units' internal gas sensors are designed for validation of flow and as such are not precision instruments. All validation calculations involving gas consumed by the units are therefore limited in precision by the gas sensors. However, as will be seen in section 2.4, the mean results are still of high accuracy.

The data obtained from the installed units is collected through online connections by each manufacturer. All data is then transferred to DTU for data validation and is analysed by DTU to validate the performance of the units. The data transferred includes:

- Gas consumption (in m^3)
- Electricity production (in kWh)
- Operating hours (h)
- Issues encountered (Failure date, type and duration)

Gas consumption, electricity produced and operating hours are all reported as quarterly data points; one point for each 3-month interval. Issues encountered are reported as one data point per failure event.

Besides the reporting of performance data to DTU, each manufacturer has reported, through a unit deployment tracker, the country and postal code of installation for each unit. Also stated is whether the unit is of first, second, or third development generation (labelled Gen X, Gen Y and Gen Z respectively. See Table 1). For each unit the manufacturer indicates to the project whether it will be part of failure recording and analysis. At least five percent of the units per manufacturer should be selected for logging of failures. The selection is done prior to the commissioning of the units. Finally, information on the calorific value of the natural gas available in the area of installation is stated when available. Alternatively, a general gas quality (L gas or H gas) is reported from which the calorific value can be estimated. The calorific potential is a measure of the specific energy content of the gas expressed in kWh per cubic meter of the gas.

Table 1: Product name and characteristics of the installed generations of units for each manufacturer

	Product Name	Electrical output (kW)	Thermal output (kW)	Electrical efficiency	Overall efficiency	Calculated Thermal efficiency	Stack technology
Bosch, Gen X	Cerapower FC10-2, Logapower FC10-2	0,7	0,56	45%	85%	40%	SOFC
Bosch, Gen Y	BlueGEN	1,5	0,6	60%	88%	28%	SOFC
Bosch, Gen Z	BlueGEN BG-15	1,5	0,85	57%	90%	33%	SOFC
BDR Thermea, Gen X	Dachs InnoGen	0,7	0,95	38%	89%	51%	PEM FC
BDR Thermea, Gen Y	Dachs0.8, eLecta300	0,75	1,1	38%	92%	54%	PEM FC
Hexis, Gen X	Leonardo	1,5	2,1	40%	95%	55%	SOFC
Viessmann, Gen X	Vitovalor 300-P	0,75	1	37%	90%	53%	PEM FC
Viessmann, Gen Y	Vitovalor PT2	0,75	1,1	37%	92%	55%	PEM FC
Viessmann, Gen Z	Vitovalor SA2	1,5	2,1	40%	95%	55%	SOFC
Sunfire, Gen X	Sunfire-Home 750	0,75	1,25	38%	88%	50%	SOFC
SOLIDpower, Gen X	BlueGEN	1,5	0,6	60%	88%	28%	SOFC
SOLIDpower, Gen Y	BlueGEN BG-15	1,5	0,85	57%	90%	33%	SOFC

Viessmann, SOLIDpower, Bosch, BDR Thermea, Hexis and Sunfire all had units in operation prior to 31 March 2022 and are actively collecting and transferring performance data to DTU for the analysis. The manufacturers are actively involved in the validation of the data sets, including correction of faulty data. Performance data has been collected for operation through March 31, 2022.

For some units, the performance data cannot be logged due to the unit not being connected to the internet. This is most often a result of the end costumer not agreeing to have the unit connected. For these units, only the general information (location and generation) is available. Table 2 gives an overview of the number of units installed and the number of units reporting performance data in the PACE project until March 31, 2021. 78% of the installed units report full data. If units not connected to the internet, due to the wishes of the end-customer, are discounted 84% of eligible units are reporting data. 2% of the units have only recently been installed and are not eligible for data reporting yet.

Table 2. Status of units installed and units reporting performance data as of March 31, 2022.

	Installed units	Units reporting full data	Recently installed	Not connected to internet
Bosch, Gen X	96	64	0	26
Bosch, Gen Y	190	179	0	-
Bosch, Gen Z	25	23	5	-
BDR Thermea, Gen X	36	36	0	0
BDR Thermea, Gen Y	406*	336	19	13
Hexis, Gen Z	3	3	0	0
Viessmann, Gen X	403	253	1	56
Viessmann, Gen Y	401	268	27	28
Viessmann, Gen Z	30	16	0	0
Sunfire, Gen X	13	9	0	-
BlueGen,SP Gen X	428	386	0	-
BlueGen, SP Gen Y	123	112	0	-
Total	**2154**	**1685**	**52**	**123**

*It should be noted that the discrepancy between installed units and units reporting data for BDR Thermea Gen Y is a result of units being reported as installed may not yet be commissioned or they are installed in newly build premises but these premises are not yet occupied.

1.3 What is being reported and how?

This purpose of this report is to validate the performance of the FC mCHP units deployed in the project, covering geographic locations of installed units, number of units, installed capacity, operating hours, electricity produced, gas utilisation (average electrical efficiency), and reliability (availability and types of issues encountered). Any quantifiable and notable changes in the unit performance with respect to time will also be recorded where applicable. As mentioned above, the nature of the internal gas sensors used to report gas consumed by the deployed units confers an uncertainty on the results derived from the gas consumption. As will be discussed in detail in Section 2.4 – "Gas-to-power utilisation", these uncertainties appear to be randomly distributed which has the upside that mean values are a reliable expression of performance even when the individual values are associated with a certain amount of uncertainty.

This annual report includes performance data from operation in the field until March 31, 2022 for all manufacturers.

The data has undergone a validation check, and obvious faulty data has been omitted. The majority of data points removed have been so because the data surpassing physical limits (conversion rates greater than 100%, negative values for gas consumption etc.)

2. Results

Summary of the chapter

The technical performance of the demonstrated fuel cell based micro-CHP units in PACE has been analysed and the results until March 31, 2022 has been reported.

2154 units has been installed throughout Western Europe. The total installed capacity is 2154 kW electrical power and 1967 kW thermal. The units operate with a high robustness. Availabilities for multiple products are at, or above, 99%. In general, availability is above 97%. Some failure and availability reporting may benefit from additional validation by the manufacturer.

Mean values of the gas utilisation (electrical efficiency during the real-life operation) is found to correspond well with the rated efficiencies and the clustering of utilisation values are tight and the means accurate. Clear seasonal trends can be seen for several heat-lead products. This validates the different characteristics and designs of the products in real operation conditions

Of the installed units, 78% have been reporting performance data. In total, these units have been operating for 23,390,524 hours and produced 23,991,535 kWh of electricity since the beginning of the PACE project.

2.1 Geographic locations

By the end of March 2022, in total 2154 PACE units were installed. In Figure 1, sites of installation are presented on a map of Europe. Data was resolved by postal code of the location of installation.

Comparing with state of installation presented in the previous performance validation report (status as of March 2021, see map insert in Figure 1) most new installations have occurred in Belgium and central Germany, though other markets such as France and Italy show an increase in installations as well.

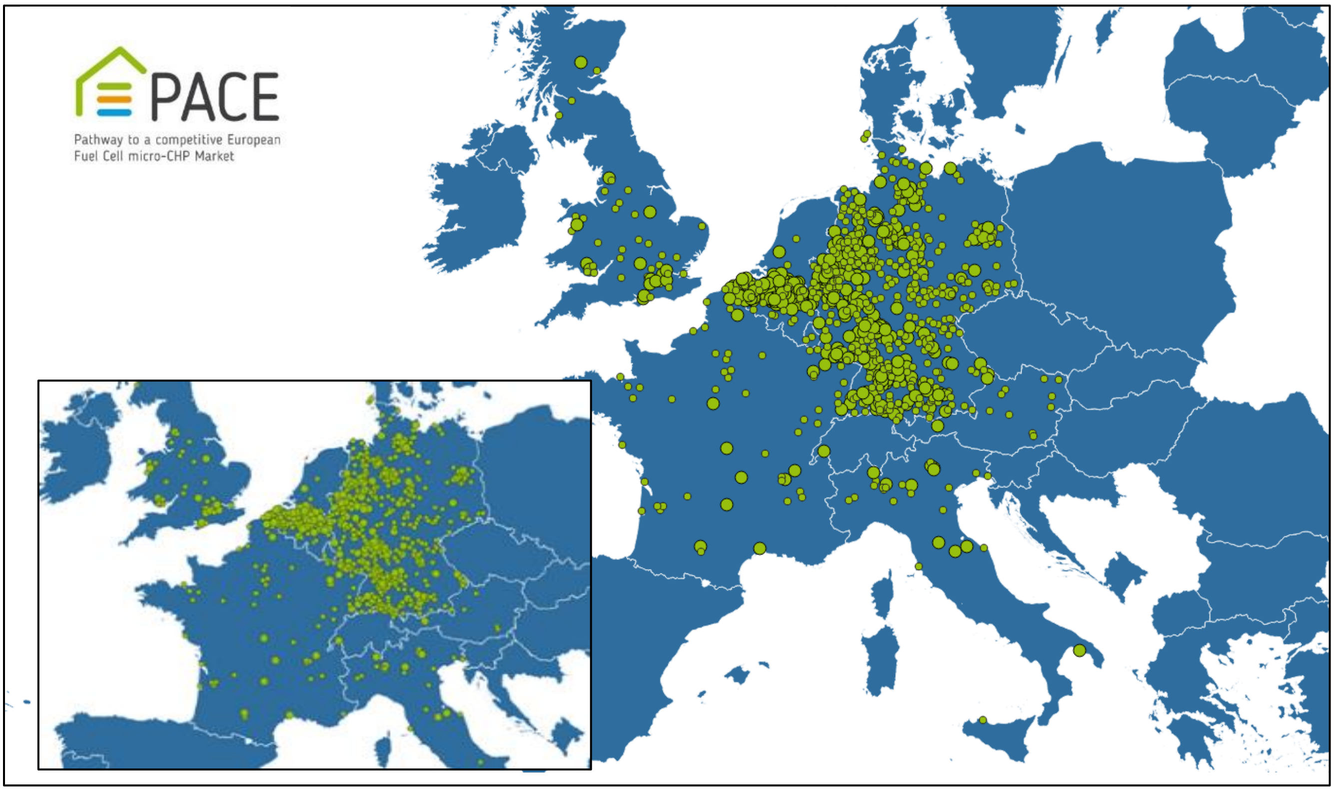


Figure 1. Geographic locations of PACE units installed before April 2022.

2.2 Installed capacity

The FC mCHP manufacturers in PACE have each deployed one or more generations of their products in domestic or small business settings. The first product generation demonstrated by each manufacturer is labelled "Generation X" (Gen X), the second "Generation Y" (Gen Y) and so forth. Based on the characteristics of each product type, in terms of electrical capacity and thermal capacity, the total installed capacity is calculated and presented in Table 3. A visual representation of the information from Table 3 is shown in Figure 2.

With a number of 2154 units installed, the total installed electrical capacity is 2189 kW_e and the total installed thermal capacity is 1967 kW_{th}. This corresponds to in average 1.01 kW_e and 0.91 kW_{th} per unit. The averages reflect the current mix of units installed.

Table 3. Installed number of units, electrical capacity and thermal capacity as of March 31, 2022.

	Number of units	Installed capacity, kW_e	Installed capacity, kW_{th}
Bosch, Gen X	96	67	54
Bosch, Gen Y	190	285	114
Bosch, Gen Z	25	19	28
BDR, Gen X	36	25	34
BDR, Gen Y	406	305	447
Hexis, Gen X	3	4	6

Viessmann, Gen X	403	302	403
Viessmann, Gen Y	401	301	441
Viessmann, Gen Z	30	45	63
Sunfire	13	10	16
SolidPower, Gen X	428	642	257
SolidPower, Gen Y	123	185	105
Total	**2154**	**2189**	**1967**

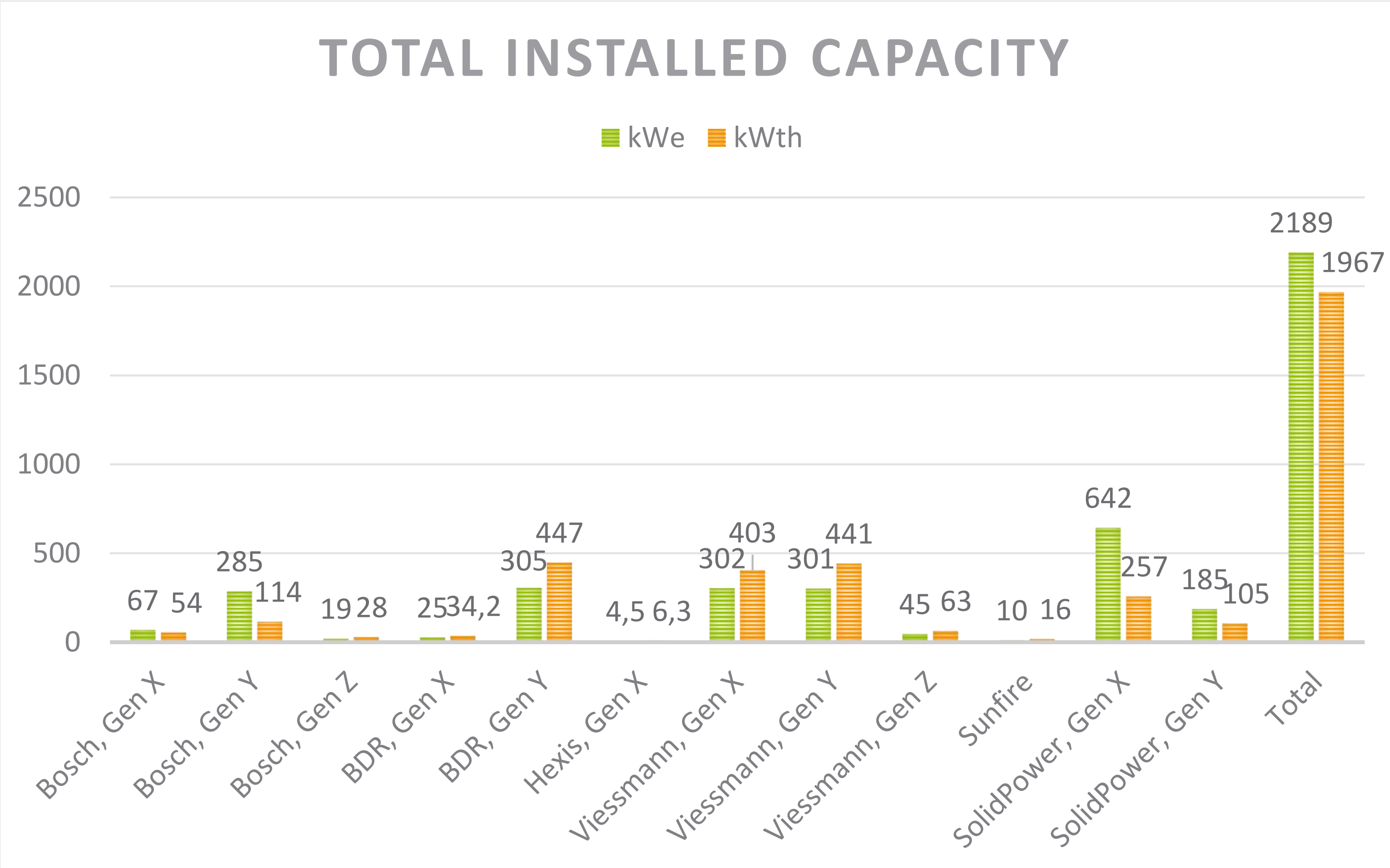


Figure 2. Installed capacity for each product and total as of March 31, 2022.

2.3 Operating hours and electricity produced

All PACE manufacturers log hours of operation, defined as hours in which a commissioned unit is producing electricity, and report there to DTU. Similarly, the amount of electricity produced, in kWh, is collected and reported. The resolution of the data is 3-month sums.

A summary of total operating hours and total kWh_e, produced up to and including March 31 2022, is presented in Table 4. The PACE units have been operating for a total of more than 23,390,000 hours and have produced more than 23,990,000 kWh of electricity. The corresponding average electrical capacity of 1.03 kW is in good correspondence with the average installed capacity, with the difference likely being a result of variety of operation modes across the various unit types.

Note that these values only include units for which full performance data is being logged and transferred to DTU. Units where operating hours are reported but no production of electricity is reported will not be included in the tally of total operating hours, and vice versa.

Table 4. Operating hours and electricity produced until March 31, 2022.

	Total operating hours	Total kWh_e produced
SOLIDpower	10,947,072	14,728,929
Viessmann	7,911,604	6,222,836
Bosch, Gen X	1,612,385	978,055
Bosch, Gen Y and Gen Z	3,081,607	4,109,029
Sunfire	80,602	49,283
Hexis	8,022	5,987
BDR	2,830,839	2,006,446
Total	**23,390,524**	**23,991,535**

A visual representation of the temporal evolution of operating hours and electricity produced is shown in Figure 3-Figure 6 below. As the resolution of the data reported to DTU is quarterly so is the resolution of the figures.

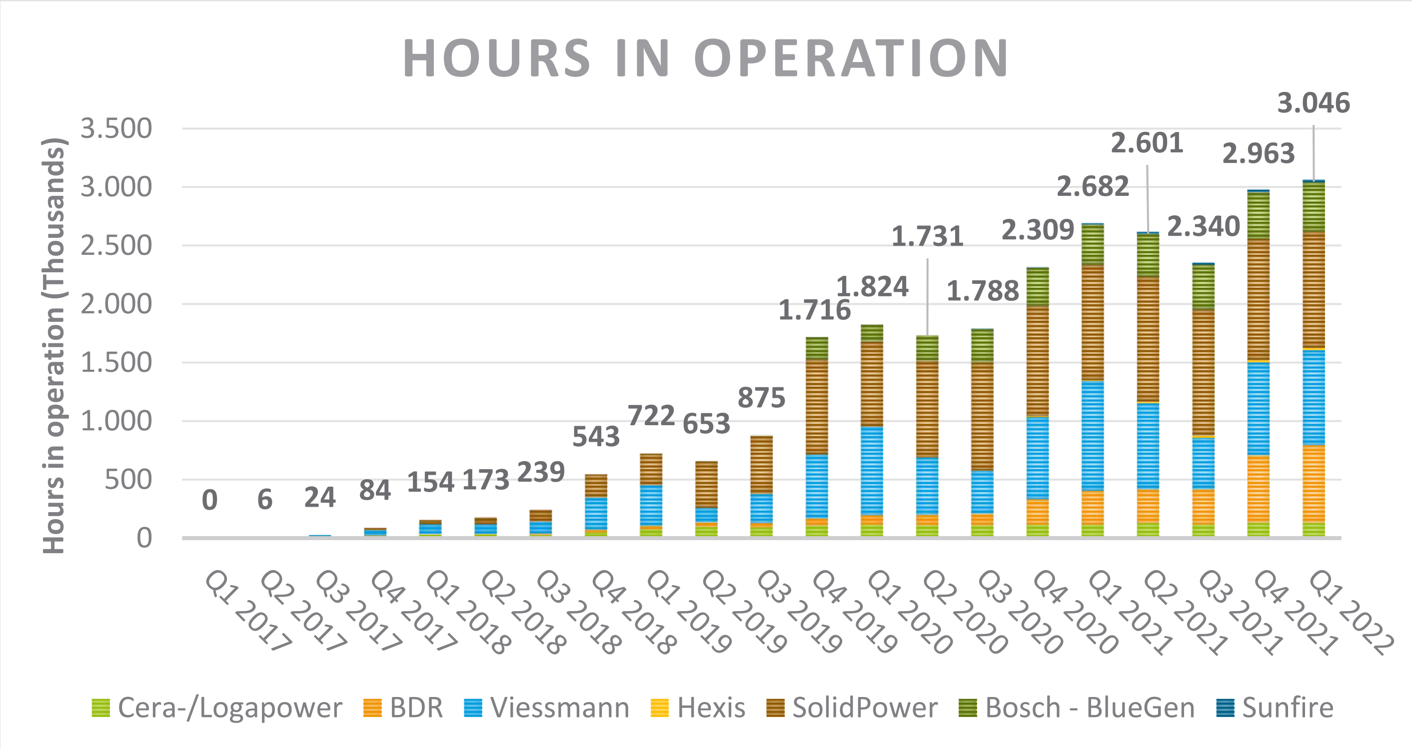


Figure 3. Operating hours per product for each quarter.

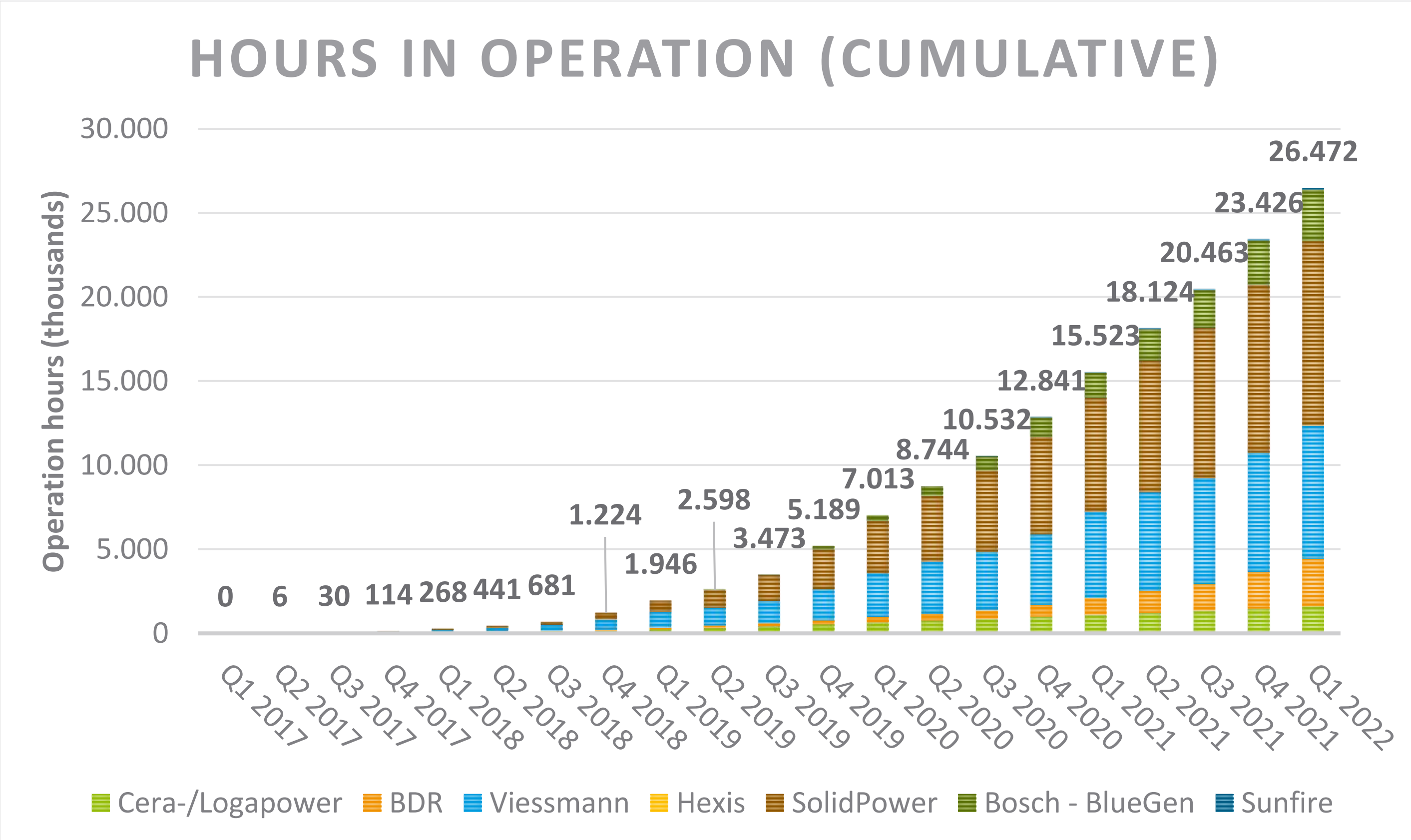


Figure 4. Cumulative operating hours presented per quarter for all products.

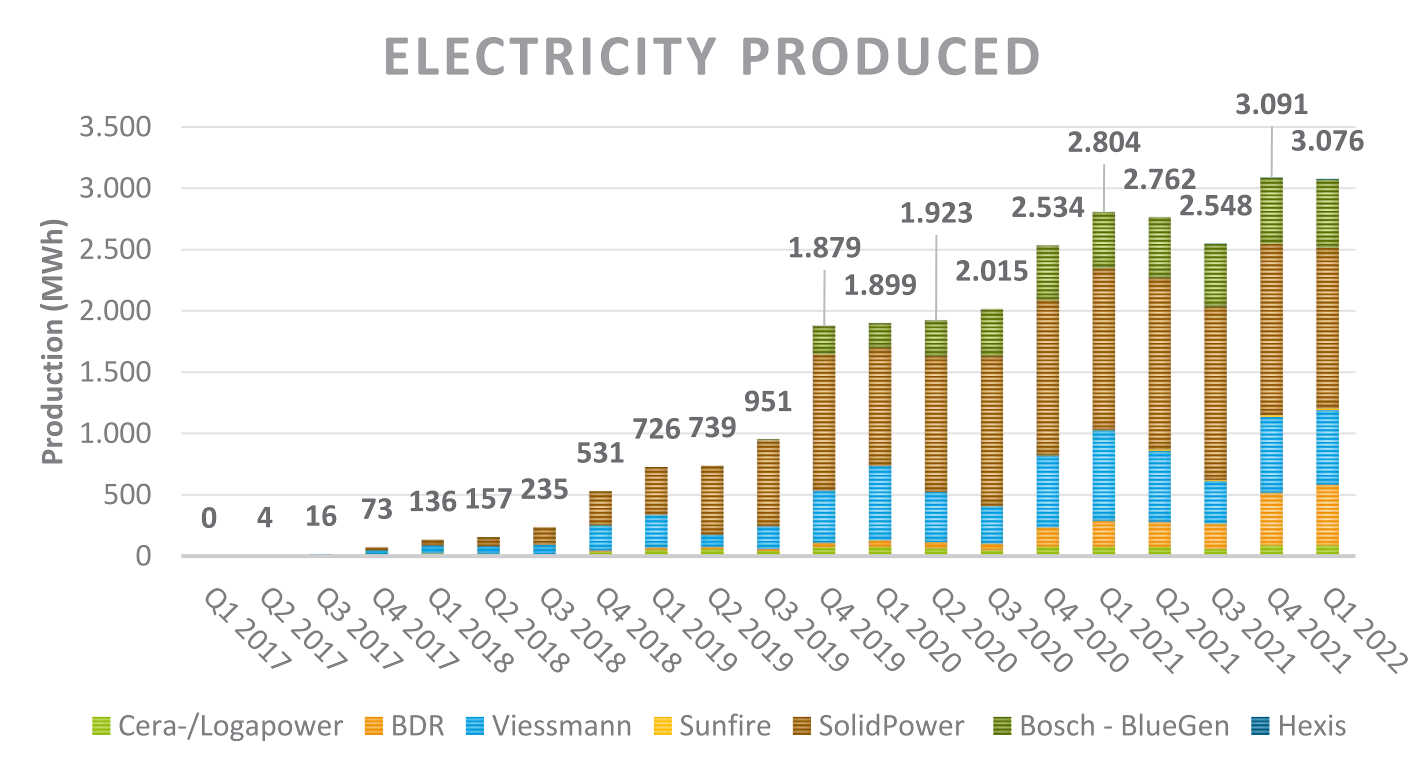


Figure 5: Electricity produced per product presented per quarter

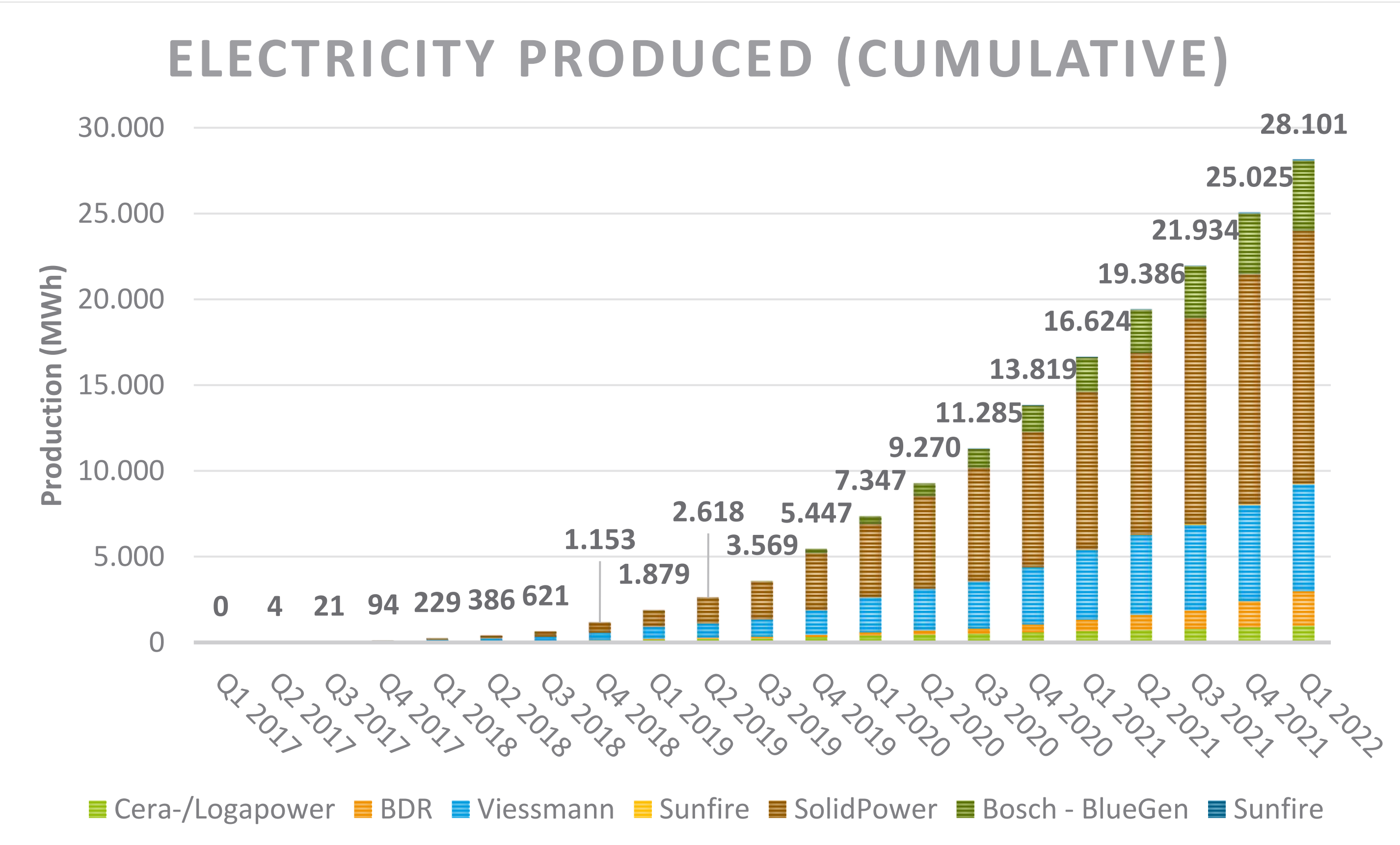


Figure 6. Electricity produced per quarter summed up for all products.

2.4 Gas-to-power utilisation

For each FC mCHP unit, gas-to-power utilisation is calculated based on electricity production and gas consumption is calculated for each quarter the units is in operation. The calculated value, while it takes the form and unit of electric efficiency, should not be seen at a direct expression of the electrical efficiency of the FC mCHP unit. This parameter is directly dependent on the operation point of the unit. This operation point may deviate, constantly or over time, from the one used for the rated efficiency in case of variable mode of operation.

Equation 1 below presents the calculation method for gas-to-power utilisation.

A parameter in this calculation is the calorific value of the gas consumed by the FC mCHP. For some units a precise calorific value of the gas supply at the site of installation is known. However, for some installation sites only broad energy content categorisations are known, L gas and H gas. For units at such sites the calorific values have been estimated as 9.28 kWh/m^3 and 10.22 kWh/m^3 respectively.

Equation 1:

$$\text{Gas-to-power utilisation} = \frac{\text{electricity produced [kWh]}}{\text{gas consumed } [\text{m}^3] \times \text{calorific value } [\frac{\text{kWh}}{\text{m}^3}]}$$

Only units in operation for a full quarter or more have been included in the analyses in this section. Units with less than a full quarter of operation tend to deviate from everyday operation points, most likely due to varied operation during and right after commissioning. This result in data not representative of the performance the end-user experiences when the unit is fully commissioned. The best way to eliminate the data noise generated round installation and commissioning of a unit is, unfortunately, to disregard the quarter in which the units were commissioned. As data for each quarter is only one data point there is no other way of sanitising the data than removing the data points for the quarters in question. This is done for all units to ensure consistency.

The average result for each product generation deployed by each manufacturer is shown in Table 5. Data for units deployed by the PACE partner HEXIS is absent in Table 5. HEXIS was recently introduced into PACE. HEXIS, at time of data collection, only had three units in operation and only one of these had reported data for two consecutive quarters. This was deemed to be insufficient to make any reasonable claims regarding the utilisation of the units.

Most mean values for utilisation are within 1 percentage point of their rated efficiency. Some of the units with modulated operation have a lower mean due to their seasonal variation in operation. One notable exception is the installations of Sunfire. There it should be noted that only 10 units from Sunfire reports data and have done so for only a few quarters.

Table 5. Average gas-to-power utilisation, calculated from the utilisation of the individual units. For each unit, data from the quarter of commissioning of the unit has been excluded. Data up to and including first quarter 2022 has been included.

	Gas-to-power utilisation mean	Standard deviation
Bosch, Gen X	0.45	0.050
Bosch, Gen Y	0.58	0.048
Bosch, Gen Z	0.55	0.032
BDR, Gen X	0.35	0.006
BDR, Gen Y	0.37	0.015
Viessmann, Gen X	0.35	0.041
Viessmann, Gen Y	0.35	0.041
Viessmann, Gen Z	0.35	0.038
Sunfire	0.32	0.018
SOLIDpower, Gen X	0.57	0.049
SOLIDpower, Gen Y	0.53	0.053

In the Figure 7-Figure 13 below, the detailed results on gas to electricity utilisations are shown for each product. The data is presented as a boxplot for each manufacturer, or generation in certain cases where comparison between generations does not make sense due to differences in technology between generations. Each box represents the gas to electricity utilisation for a given quarter calculated from gas consumed and electricity produced. The horizontal line in the box represents the mean value for the utilisation and the notch in the box represents a 95% confidence interval for said mean. The extend of the box represents the lower and upper quartiles; the 25% of the data which lies below and above the mean respectively. The lines, or whiskers, represents the range between the 5th and 95th percentile of the calculated utilisations. Outliers are shown as diamonds. Not all outliers are shown due to readability concerns of the graphs.

For all figures a scale is chosen which makes it as easy as possible to identify trends for units and manufacturers are as easy to identify as possible. In Annex 1 the same figures are presented with a common universal scale.

It should be noted that for some quarters the confidence interval of the mean may extend beyond the box it-self, giving the box the appearance of having ears or wings. This phenomenon appears when the dataset for a given quarter only consists of a few data points and/or only a few points lie above the mean. Given the nature of the data, this behaviour is to be expected. Given certain types of technology and seasons, the units will most likely operate closed to the upper rated efficiency. Any deviation of utilisation from the mean, not related to measurement uncertainty, will most likely be below the mean. The box will therefore not extend far beyond the mean in upwards direction.

It is further worth noting here that, as previously noted, the gas measurements forming the basis for the calculated utilisations were conducted by the fuel cell units' internal gas metering. These gas meters are designed and calibrated primarily for determining whether gas does or does not flow. The exact flowrate of the gas is of lesser importance when validating the existence of a flow and as such these gas consumption measurements carry a noticeable uncertainty. All results point to, as can be visually seen below, this error is a randomly distributed uncertainty without bias which has limited effect on the accuracy of the mean results. This should be kept in mind before conclusions from the presented data are drawn.

Bosch

Figure 7 shows the utilisation boxplot for Cerapower and Logapower units from Bosch. Please note that the results for 2017 is based on 6 units or fewer, and should not be seen as representative.

For fourth and first quarters, the utilisations are at or above the rated electrical efficiency of 45%. The 50% of units seen by the box is clustered close around the mean. This makes fully sense, as these quarters must be expected to be the ones where most units are run with as high an electrical efficiency as possible for as many hours as possible.

For quarters two and three the utilisations deviate much more from both the rated electrical efficiency and the mean. This is an expected behaviour of the data as the Bosch Cera-/Logapower units are operated heat lead mode, meaning that the operation of the unit is controlled by the heat demand of the building. In the summertime where the heat demand is small, the unit still has a high number of operating hours. This high number of operation hours for a heat lead system in summertime is a result of the modulation capabilities of the system, as the system can modulate its operation point in terms of power output based on the state of charge of the attached hot water tank, ensuring fewer hours of shutdown due to lack of thermal headroom. When modulating down in power output a smaller part of the unit's capacity is being utilised, meaning that less heat and power is produced per hour. This leads to less electrically efficient operation of the fuel cell unit which is reflected in the lower gas-to-power utilization values. Again, this confirms expected behaviour as operation point will be more dependent on geography, through local differences in climate and weather, in these quarters. Were all units installed in a local cluster this behaviour would most likely not be observed, but the Bosch units are installed throughout Germany and we expect that this is the reason for the spread in results we observe.

The conclusion that this pattern is a result of difference in use of the units is supported by the similarity between quarters from year to year. This is especially striking when comparing the years 2019 and 2020. Means and confidence intervals are practically identical and the 50% of units closest to the mean show very similar clustering.

The similarities in first quarter data in all five first quarters represented in the figure shows no indication of loss of performance over time as means, confidence intervals, boxes and whiskers are of similar magnitude over time.

Based on the above we consider both data and expected use of the Cera-/Logapower FC micro-CHPs validated.

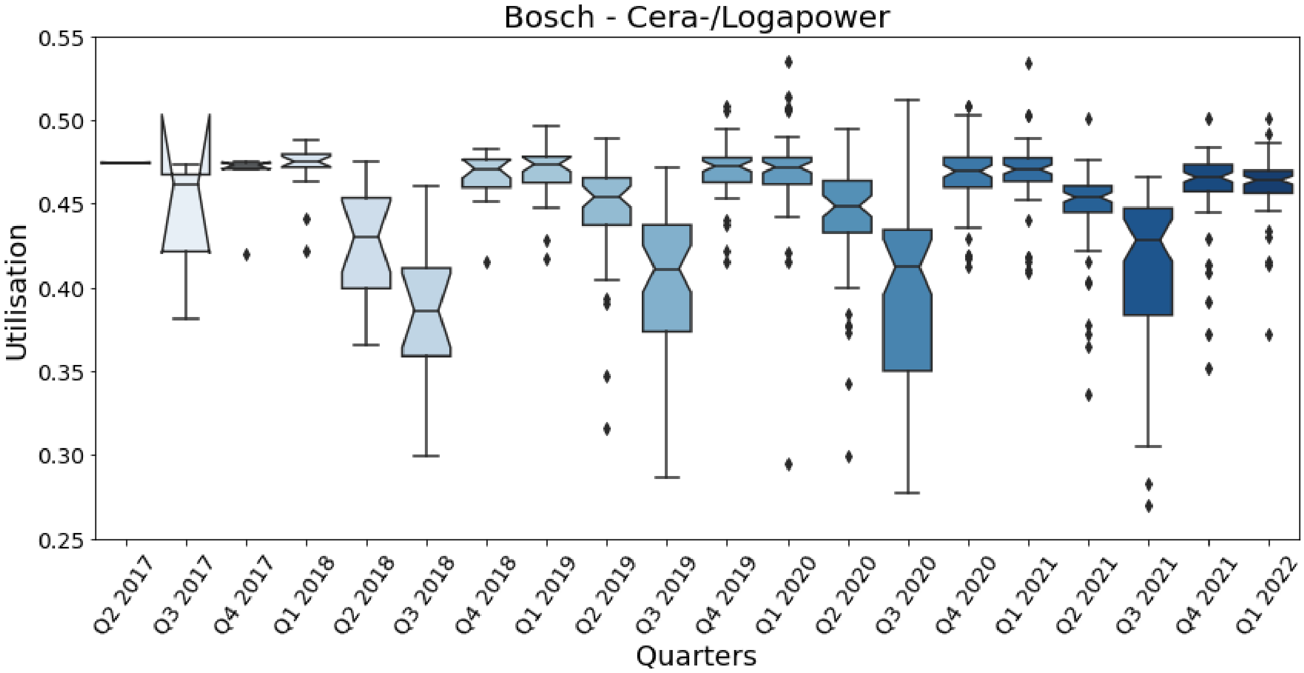


Figure 7: Boxplot representation of utilisation for Cera-/Logapower units.

The utilisations for Bosch installed BlueGen and BlueGen-15 units are found in Figure 8.

For Generation Y all quarters show a mean very close to the rated electrical efficiency of 60% and thus no seasonal variation is observer. While more outliers and larger boxes are seen with time this is most likely the result of an increased number of units providing data. Very similar clustering of the boxes (50% of values closest to the mean) and the whiskers (the 90% of values closest to the mean) is observed. The expanse of boxes and whiskers may be explained by a combination of uncertainty in the gas measurements, magnified by an increasing number of units, and not all units being run at full rated power at all times.

Generation Z show a tight groping of data around a mean with a confidence interval which is not as tight at the one seen for Generation Y. This may be a result of the smaller number units reporting data. The mean is however close to the rated electrical efficiency of the BlueGen-15 units.

As a clear trend in seen, in line with the expected operation of the units, the performance of the units is considered validated.

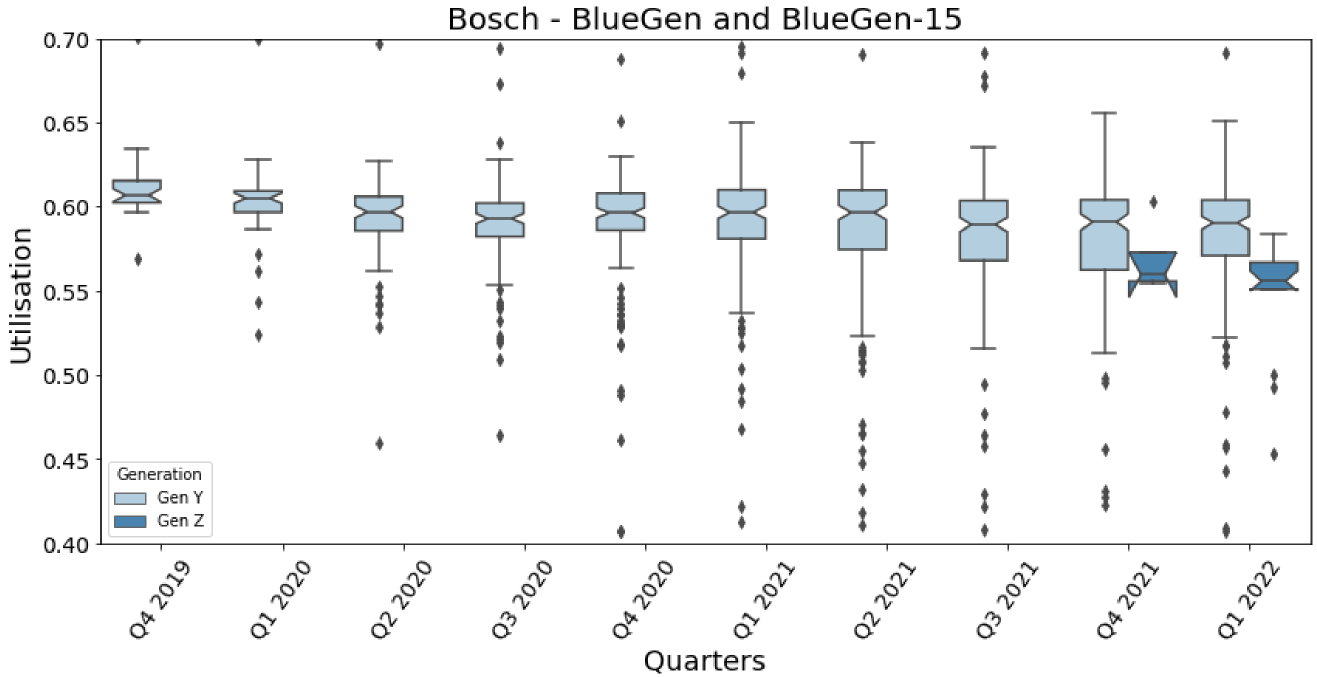


Figure 8: Boxplot representation of utilisation for Bosch Bluegen units.

SOLIDpower

Figure 9 below shows the utilisations for SOLIDpower installed BlueGen (SolidPower Gen X) and BlueGen-15 (SolidPower Gen Y) units. Please note, less than 20 eligible BlueGen units reported data before the third quarter 2018 and less than 25 eligible BlueGen-15 units reported data before fourth quarter 2019.

Generation X show a mean utilisation close to the rated efficiency of 60% for all quarters and no seasonal variation is observed. From Q2 2019 forward the utilisations are tightly grouped and whiskers are consistent over time. More outliers are seen, most likely a result of an increase in number of units in operation.

From Q3 2020 onward **Generation Y** shows a clear mean from quarter to quarter with close to identical boxes and whiskers. The mean is very close to the rated 57% efficiency and the utilisations are more tightly grouped above the mean than below. This is most likely a result of user demanded modulation of operation point showing that some units are intentionally running below maximum rated efficiency. This difference becomes less pronounced in later quarters. This is a likely result of more Generation Y units being commissioned.

In earlier quarters, the **Generation Y** units show a higher degree of deviation from quarter to quarter. Before the year 2020 few units were in operation and deviations in operation of a few units can have a high impact on the overall utilisation picture. Thus, user demanded modulation and any potential need for adjustments of units related to first commissionings in the field of this unit generation would acutely affect the resulting utilisations. This being said the clear stabilisation of the result and the behaviour of the mean and the boxes is very encouraging and clearly validates the operation of the unit generation in the field.

As a clear trends are seen, in line with the expected operation of the units, the performance of the units is considered validated.

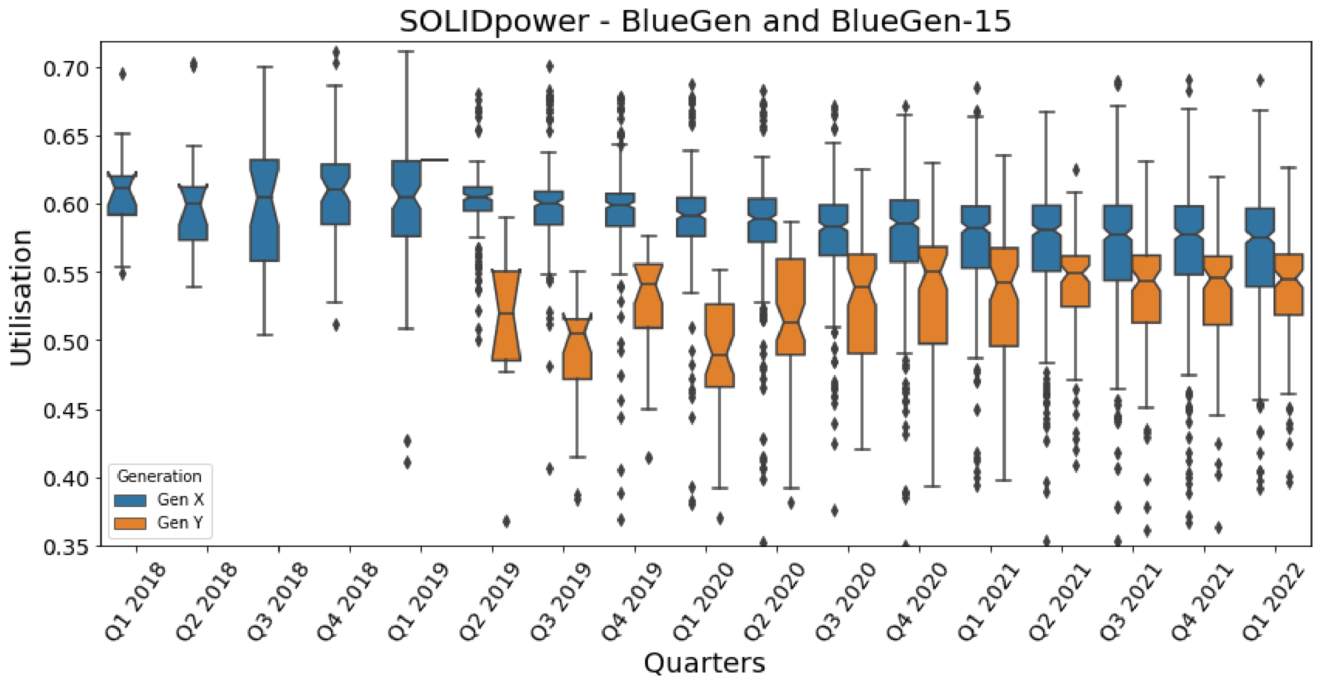


Figure 9: Boxplot representation of utilisation for SOLIDpower BlueGen and BlueGen-15 units.

Viessmann

In Figure 10, the gas-to-power efficiency for the units from Viessmann has been shown. Three generations of units are present. As the Vitovalor SA2 is based on SOFC technology rather than the PEM technology both Vitovalor 300-P and Vitovalor PT2 are based on, it has been dubbed 'Gen Z'. Vitovalor PT2 has been dubbed 'Gen Y' as it is more directly the successor to Vitovalor 300-P.

When investigating Figure 10 the following data limitations should be kept in mind:

- Only 6 Gen X units (blue) reported data in Q3 2017. 18 units reported data in Q4 2017
- One Gen Y unit (orange) reported data prior to Q3 2019. 82 units reported data in Q3 2019
- Fewer than 10 Gen Z (green) units reported data prior to Q4 2019

The mean of **Generation X** units is close to the rated efficiency of 36%. With more installations the boxes and whiskers tightens. No clear seasonal variation is seen and no trend in utilisations above or below the mean is seen indicating no modulation of the systems based on season. **Generation Y** show almost identical behaviour with mean results close to the rated efficiency of 35%. The random unbiased deviation around the mean is most likely a result of uncertainty in measurement of gas consumed.

Generation Z has a mean utilisation of close to the rated 34% from Q4 2019 forward. The results are tightly grouped for all quarters. It should also be noted that only 30 Generation Z units are installed, 16 of which reported full data for Q1 2022, and therefore their mean results will be more susceptible to deviations in operation of a few units.

For all generations the spread of values is within what can be expected based on measurement tolerances of the meters installed in the micro-CHP units and therefore we consider the performance of the units validated.

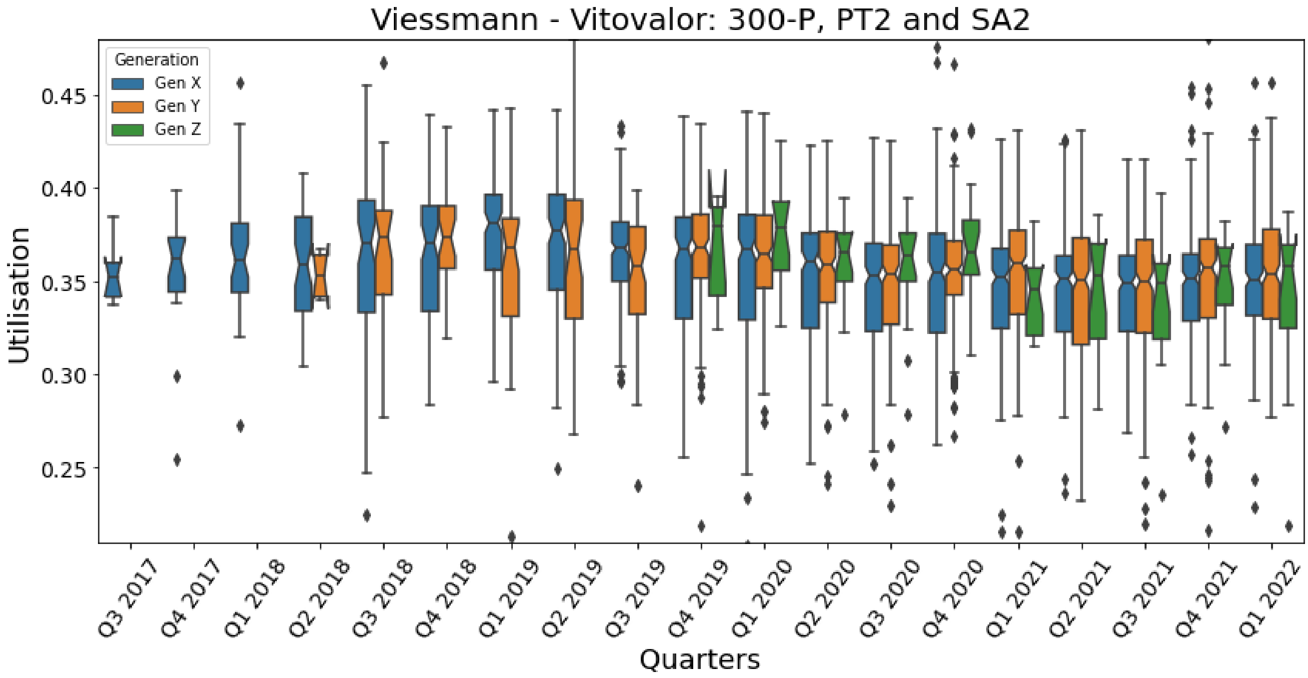


Figure 10: Boxplot representation of utilisation for Viessmann units for each quarter.

BDR Thermea

In Figure 11 the gas-to-power utilisation of Gen X units (Dachs InnoGen) and Gen Y units (Dachs0.8 and eLecta300) from BDR Thermea are shown.

We will note that prior to Q1 2019 fewer than 10 Gen X units were in operation and in Q1 2020 only 3 units were eligible for analysis.

Both generation of units operate close to the point of rated electrical efficiency, 38%, with **Generation X** favouring a slightly lower operation point. Both generations of units show a tight grouping of utilisation data (please note the scale of the y-axis). Even with this tight clustering, **Generation X** shows a pronounced seasonal variation with a high mean utilisation with a small spread seen in the coldest quarters and lower mean utilisation with higher spread in warmer quarters. This, as discussed above in connection to Bosch Loga-/Cerapower units, is the expected behaviour for geographical distributed units following the heat demand of a building. These patterns are closely mirrored from year to year with practically identical clustering.

The similarities in first quarter data in all four first quarters represented in the figure shows no indication of loss of performance over time as means, confidence intervals, boxes and whiskers all are of similar magnitude over time.

For **Generation Y** the same clear seasonal variation is not seen for the data from Q1 2020 to Q1 2021. On the contrary, at first glance the means seem to follow trends opposite to the expected seasonal variation in Q2 and Q3 2020. Here we will note that not just the 95% confidence intervals, demarked by the notches in the boxes, but the boxes themselves for all of the first three quarters of 2020 overlap. Therefore, from a statistical point of view, the quarters from Q1 2020 through Q1 2021 are all identical and no conclusions should be drawn concerning seasonal variation.

After installation and commissioning of additional units, Q2 2021 onward, **Generation Y** does begin to exhibit the same seasonal variation as seen for unit **Generation X**. The confidence intervals for the means are tightened, and means for Q4 2021 and Q1 2021 are very close to the rated efficiency of 37% electrical efficiency. The indicates real seasonal operation.

Based on the above, we consider both data and expected use of the Dachs InnoGen, Dachs0.8 and eLectra300 FC mCHPs validated.

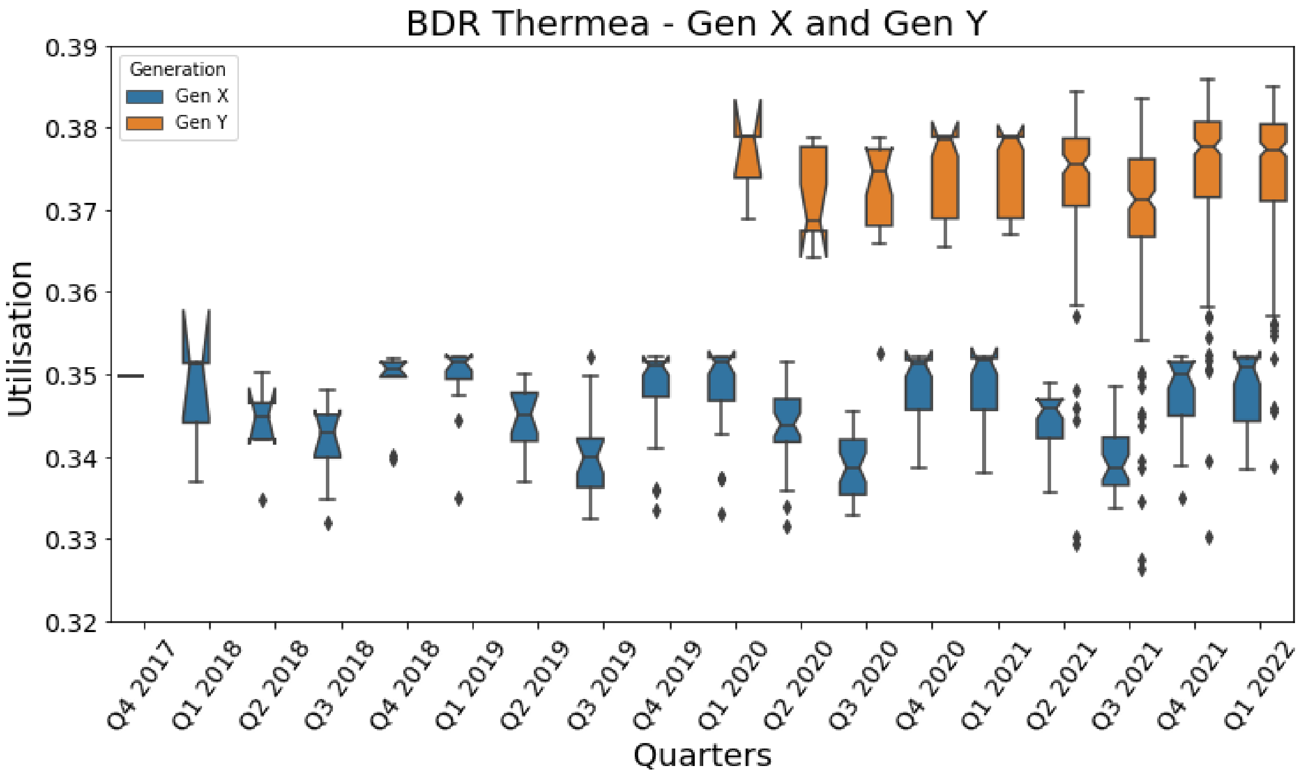


Figure 11: Boxplot representation of utilisation for BDR Thermea units for each quarter.

Sunfire

Sunfire currently only have 10 units reporting data. This limited number of units reporting data and limited range of data makes it unreasonable to make any specific judgement of the performance of the units in terms of gas-to-power utilisation. It is our hope that more data will be available for the final version of this report, scheduled for spring 2023.

A preliminary version of the visual representation of the utilisation of Sunfire units is included below for completeness. No concrete conclusions will be drawn on the performance of the units in this report.

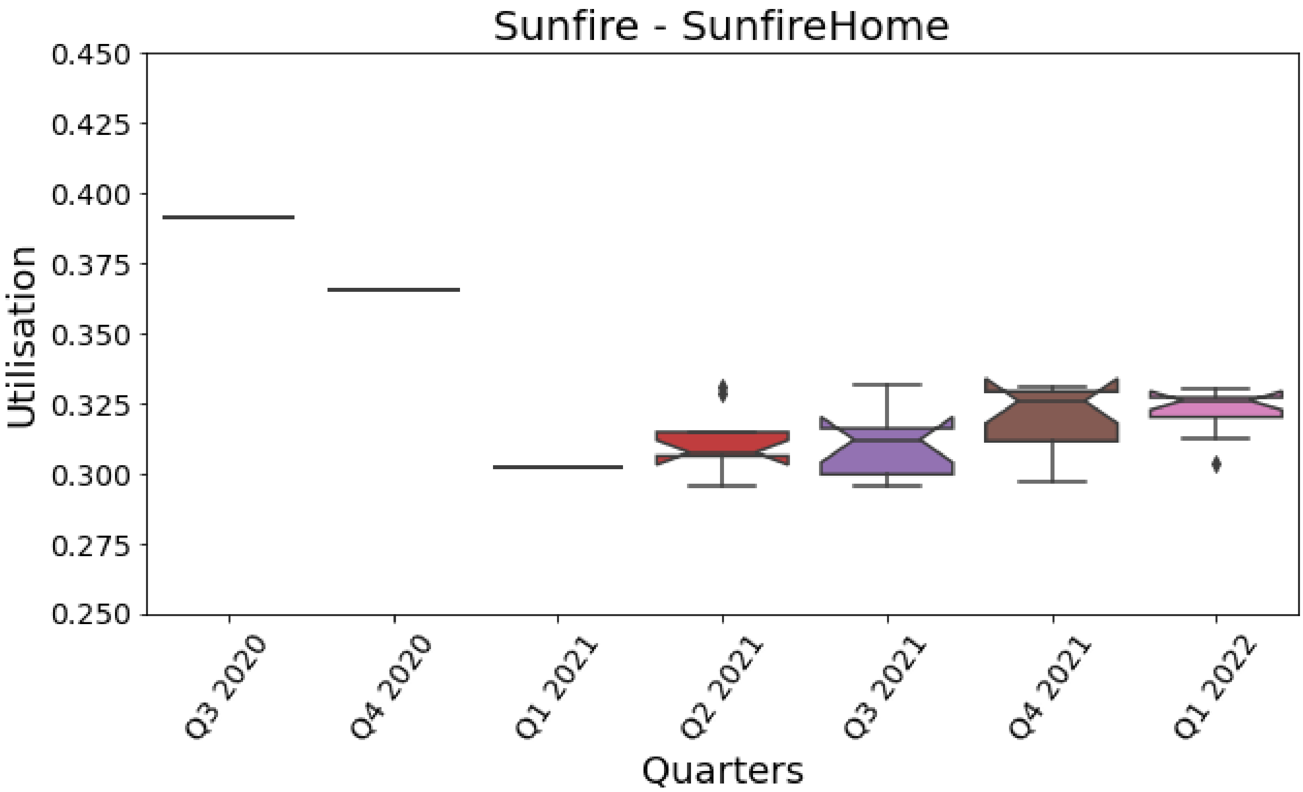


Figure 12: Boxplot representation of utilisation for SunfireHome units for each quarter.

Hexis

As per the Grant Agreement and the PACE Data Collection Protocol HEXIS is reporting performance data from their units in the field to WP2. HEXIS only recently joined the PACE project and therefore only few units are eligible for utilisation analysis; too few for any real analysis. To reach a sufficient amount of units fulfilling the requirement of commissioning before the quarter of analysis, more time needs to pass. We have therefore not included any graphical validation of the utilisation. Graphical validation will be included in the final version of the performance validation, scheduled for spring 2023.

Utilisations: Conclusions and further work

All unit generations for all manufacturers have been validated in terms of gas-to-electricity utilisation, with the exception of HEXIS as not enough data is yet available. When a critical mass of units of a generation is reached, generally above 20 units, clear results in the form of mean utilisations can be seen.

For some, heat lead, systems clear seasonal trends can be seen, showing a spread in points of operation in the warmer seasons. This result should not be over interpreted as the data resolution is low; only one data point per quarter. Each quarterly data point should be seen as an average of operation over that quarter, and nothing can therefore be deduced about the actual operation of individual units, or even the unit generation, in a quarter.

For further work, we would like to subdivide the reported data sets into subsets based on geographical zones in order to investigate any geographical trends. This would be especially interesting for heat lead systems. We also consider investigating trends over time for groups of similar units. Due to the nature of the data this investigation should be conducted with care, making sure enough data is available to get a relevant result and being careful with drawing conclusions based on the results.

2.5 Logging of failures

Before commissioning, a manufacturer may select a unit for failure logging and analysis. Selection is done prior to installation to ensure no selection bias. A manufacturer must select at least 5% of their projected fleet of units for failure logging and analysis. For the selected units, any issue leading to the unit being unable to operate will be registered by failure date, type and duration. Four different failure categories have been defined and examples of these have been given in the data collection protocol. The failure categories are:

A. Fuel cell unit; internal effects. Failure in the fuel cell part of the unit, primarily caused by internal effects.
B. Fuel cell unit; external effects. Failure in the fuel cell part of the unit, primarily caused by external reasons.
C. Other; internal effects. Failure in the remaining part of the unit, primarily caused by internal effects.
D. Other; external effects

Below is the logging of failures for each product summarized.

Please note: *some products the results are based on a low number of failures and hence are quite uncertain.*

Please note*: All Viessmann units are in principle selected for failure logging. Only units with no connection to the internet or lack of information necessary for data collection are not logging failures.*

For unit generations where sufficient failure data is available Mean Time Between Failures (MTBF) is calculated and reported alongside failures per 100,000 hours. MTBF is calculated as:

Equation 2:

$$\text{MTBF} = \frac{\sum(\text{start of downtime - start of uptime})}{\text{number of failures}} = \frac{\sum(\text{operational hours})}{\text{number of failures}}$$

Operational hours are reported directly for the units as part of the performance validation.

BlueGen (by SOLIDpower)

					Notes
Number of units logging failures	17				
Total hours in operation of these units	436,475 h				
Number of failures reported	20				
Corresponding failures per 100,000 hours	4,6				
MTBF	20,795 h				
Hours in failure mode	17,935 h				
Number of failures by type	**A**	**B**	**C**	**D**	
	12	3	5	1	

BlueGen-15 (by SOLIDpower)

					Notes
Number of units logging failures	3				
Total hours in operation of these units	40,269 h				
Number of failures reported	2				
Corresponding failures per 100,000 hours	5,0				
MTBF	20,134 h				
Hours in failure mode	1224 h				
Number of failures by type	**A**	**B**	**C**	**D**	
	2	0	0	0	

BlueGen (by Bosch)

		Notes
Number of units logging failures	19	
Total hours in operation of these units	438,480 h	

Number of failures reported	17				
Corresponding failures per 100,000 hours	3,9				
MTBF	25,793 h				
Hours in failure mode	12,408 h				
Number of failures by type	A	B	C	D	
	16	1	1	0	

BlueGen-15 (by Bosch)

At his stage, Bosch has selected only one BlueGen-15 unit for failure logging. This unit has been in operation for 2160 hours and have reported no failures.

Logapower (by Bosch)

					Notes
Number of units logging failures	5				
Total hours in operation of these units	173,255 h				
Number of failures reported	12				
Corresponding failures per 100,000 hours	6,9				
MTBF	14,438 h				
Hours in failure mode	4,177 h				
Number of failures by type	A	B	C	D	
	7	5	0	0	

Vitovalor 300-P (by Viessmann)

Please note the large number of units reporting failures while evaluating the results below.

The failure data from Viessmann requires further validation.

		Notes
Number of units logging failures	368	Failures have been reported for 278 units
Total hours in operation of these units	4,120,033 h	
Number of failures reported	1,133	For only longer failures (> 1 hour) the number is 855

Corresponding failures per 100,000 hours	29				For only longer failures (> 1 hour) the number is 22
MTBF	3,399 h				For only longer failures (> 1 hour) the number is 4,417 h
Hours in failure mode	325,880 h				
Number of failures by type	**A**	**B**	**C**	**D**	
	500	556	62	15	
Number of failures by type, longer than one hour	**A**	**B**	**C**	**D**	
	400	420	23	12	

Vitovalor PT2 (by Viessmann)

					Notes
Number of units logging failures	362				Failures have been reported for 291 units
Total hours in operation of these units	3,336,947 h				
Number of failures reported	3066				For only longer failures (> 1 hour) the number is 1191
Corresponding failures per 100,000 hours	92				For only longer failures (> 1 hour) the number is 36
MTBF	1,088 h				For only longer failures (> 1 hour) the number is 2,802 h
Hours in failure mode	312,550 h				
Number of failures by type	**A**	**B**	**C**	**D**	62% of failures lasted less than one hour
	428	1239	1399	0	
Number of failures by type, longer than one hour	**A**	**B**	**C**	**D**	
	178	523	490	0	

Vitovalor SA2 (by Viessmann)

					Notes
Number of units logging failures	29				Failures have been reported for 6 units
Total hours in operation of these units	216,207 h				
Number of failures reported	27				
Corresponding failures per 100,000 hours	12				For only longer failures (> 1 hour) the number is 11
MTBF	8,007 h				For only longer failures (> 1 hour) the number is 8,648 h
Hours in failure mode	6,520 h				
Number of failures by type	**A**	**B**	**C**	**D**	
	16	3	5	3	
Number of failures by type, longer than one hour	**A**	**B**	**C**	**D**	
	16	2	4	3	

Dachs InnoGen, Dachs0.8 and eLecta300 (by BDR Thermea)

It has been decided not to log failures for BDR Thermea's Generation X unit.

No eLecta300 units have so far been selected for failure reporting.

Dachs0.8 (by BDR Thermea)

					Notes
Number of units logging failures	10				Failures have been reported for 3 units
Total hours in operation of these units	72,736 h				
Number of failures reported	6				
Corresponding failures per 100,000 hours	8				
MTBF	15,980 h				
Hours in failure mode	1,272 h				
Number of failures by type	**A**	**B**	**C**	**D**	

	0	6	0	0	

Sunfire-Home 750 (by Sunfire)

When reviewing the information below it should be noted that failures have only been reported up to and including Q1 2021. The cumulative hours in operation for Sunfire's failure reporting units were by Q1 2021 less than 10,000 hours. Given the low number of operation hours, any average based on hours will be misleading. The failures per 100,000 hours and MTBF should therefore not be seen as a result that can be extrapolated to a general expectation, and it is only included for completeness.

					Notes
Number of units logging failures	4				
Total hours in operation of these units	9,957 h				
Number of failures reported	5				
Corresponding failures per 100,000 hours	50				
MTBF	2,611				
Hours in failure mode	243 h				
Number of failures by type	**A**	**B**	**C**	**D**	
	5	0	0	0	

2.6 Availability

Based on failure logging, the availability of the units has been calculated. Only units in operation for at least a full quarter have been included as commissioning and start-up often prompt failures, and since the unit is not as such in operation we exclude the period close to commissioning. An additional reason for this exclusion is the uncertainty of time of commissioning. It is sometime tricky to define where installation and start-up ends and where operation begins. For this reason, information from the first 3-month period wherein a unit has been installed has been disregarded in the calculations.

We have defined the availability in Equation 3: It is defined that when a unit is operating or is in standby mode, ready to start up on request, the unit is available. We have also defined, that if a unit is not available, it is in "failure mode", although this term may be a bit misleading. By this definition, any occurrence that makes the unit unable to operate will be counted as time in "failure mode", including any time for scheduled maintenance stops.

Equation 3:

$$\text{availability} = \frac{\text{operation hours} + \text{standby hours}}{\text{total possible hours}}$$

'Total possible hours' is the total number of hours the eligible units could have been in operation in the observation period.

For units logging time in "failure mode", the availability may be calculated from Equation 4. This is the default way availability has been calculated for this report.

Equation 4:

$$\text{availability} = \frac{\text{total possible hours - failure hours}}{\text{total possible hours}}$$

In case a product is designed to never go into standby mode, the standby hours are by default zero. Hence, the availability may be calculated only from the operational hours as shown in Equation 5. This is the case for the BlueGen and BlueGen-15 units. This means the availability from these units may be calculated from Equation 5, based only on the reported operating hours. Hence, the availability of units from SOLIDpower, and Bosch Gen Y units, has been presented below both based on the units logging failures (using Equation 4) and based on all units (using Equation 5).

Equation 5:

$$\text{availability} = \frac{\text{operation hours}}{\text{total hours}}$$

The results of the availability analysis can be seen in Table 6 below.

The availability for the units from SOLIDpower and Bosch are above 99%. For the Viessmann units, the calculated availability is 96%. The logged failure information from Viessmann is planned to undergo a further validation process. For the units from BDR Thermea, no availability results can be calculated yet.

Table 6. Availability of the PACE units until March 31, 2019.

	Availability	**Comments**
SOLIDpower Gen X	95.9% (based on failure logging) 98.7% (for all units)	Based on 17 units logging failures and 415,896 operation hours. Based on 385 units reporting data. In total 8,559,525operation hours of eligible units
SOLIDpower Gen Y	97.1% (based on failure logging) 97.2% (for all units)	Based on 2 units logging failures and 40,269 operation hours. Based on 112 units reporting data. In total 1,745,363 operation hours of eligible units.
BOSCH Gen X	97.7%	Based on 5 units logging failures. 159,133 operation hours.
BOSCH Gen Y	97.3% 98.8% (for all units)	Based on 19 units logging failures. 400,196 operation hours Based on 175 units reporting data. In total 2,675,496 operation hours of eligible units.
BOSCH Gen Z	100% 99.3% (for all units)	Based on 1 units logging failures. 2160 operation hours Based on 18 units reporting data. In total 47,712 operation hours of eligible units.
Viessmann Gen X	95.6%	Based on all 300 units reporting data including logging failures. In total 4,120,033 operation hours
Viessmann Gen Y	94.8%	Based on all 286 units reporting data including logging failures. In total 3,105,808 operation hours
Viessmann Gen Z	98.1%	Based on all 21 units reporting data including logging failures. In total 226,993 operation hours
BDR Thermea Gen Y	99.0%	Based on 10 units logging failures and a total of 72,736 operation hours
Sunfire	99.9%	Based on 14 units logging failures and a total of 71,428 operation hours

3. Future work

The data collection will continue and the performance data will be reported to DTU once more, in spring 2023.

Further validation of the incoming data will be made. It is likely that at a later stage some of the results will be subject to change as the manufacturers go through the reported raw data again and further errors are identified. Furthermore, additional performance data may be added to these data reporting periods if further data becomes available to the manufacturers as well as to DTU.

In the last performance validation report, scheduled for spring 2023, we intent to update the analysis by including the data reported in the final performance data reporting. No further analyses will be added to the report.

Pathway to a competitive European Fuel Cell micro-CHP Market

4. Conclusions

In the PACE project, micro-CHP (combined heat and power) units based on fuel cells are being demonstrated in private homes and small commercial buildings.

This report on performance validation includes data from operation in the field until March 31, 2022. Data has been reported from six manufacturers: SOLIDpower, Bosch, HEXIS, Viessmann, Sunfire and BDR Thermea.

This performance validation report also includes performance data from operation in the field until March 31, 2022. Data has been undergoing a validation check, and obvious faulty data has been omitted.

As of March 31 2022, 2154 units were installed throughout Western Europe with a high number of units demonstrated in Belgium and Germany. The total installed capacity was 2189 kW of electrical power and 1967 kW of thermal power.

The units operate with a high robustness. For three of the products, the availability is above 99%. For most other products, availability was above 97%.

The performance of field fleet units has been validated through the investigation of gas utilisation. All products exhibited a mean utilisation close to the rated efficiency of the product. For some heat lead units clear seasonal variations were seen.

Of the installed units, 78% were reporting full performance data. Discounting units not connected to the internet by choice of the end-user this number goes up to 84%. In total these units have been operating for 23,390,524 hours and produced 23,991,535 kWh of electricity since the beginning of the PACE project.

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Pathway to a competitive European Fuel Cell micro-CHP Market

Annex 1

Utilisation figures with universal scale

In the report proper utilisations are presented in a manner where trends for a given unit and a given manufacturer are as easy to identify as possible. In this annex utilisations are presented for each manufacturer with the same scale to better show the diversity of system and operation types.

Bosch

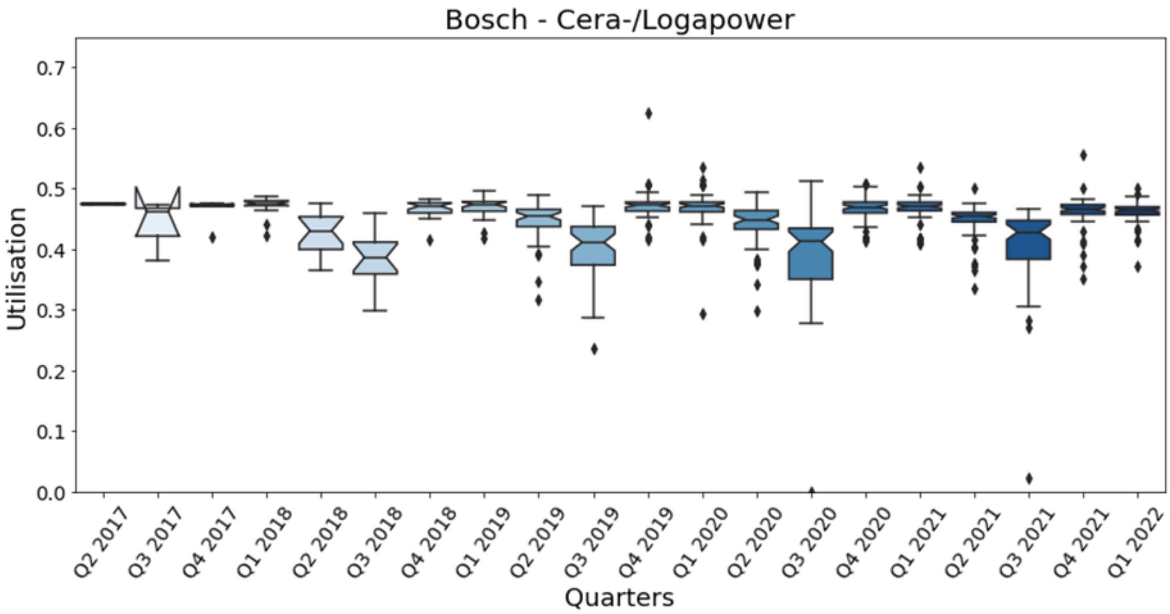


Figure 14: Boxplot representation of utilisation for Cera-/Logapower units with universal scale

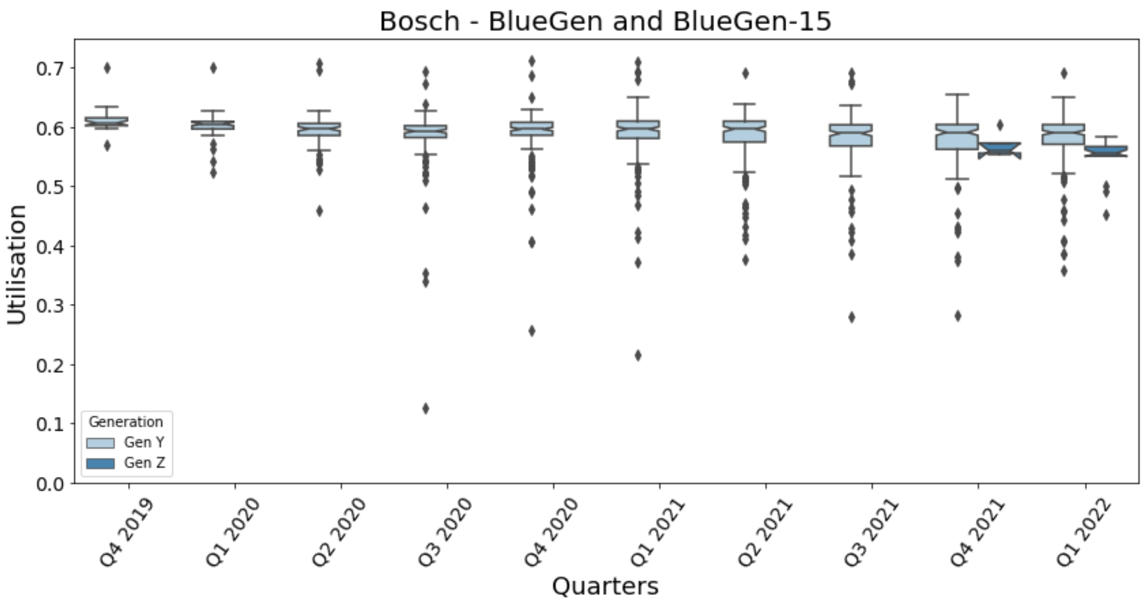


Figure 13: Boxplot representation of utilisation for Bosch BlueGen units with universal scale

SOLIDpower

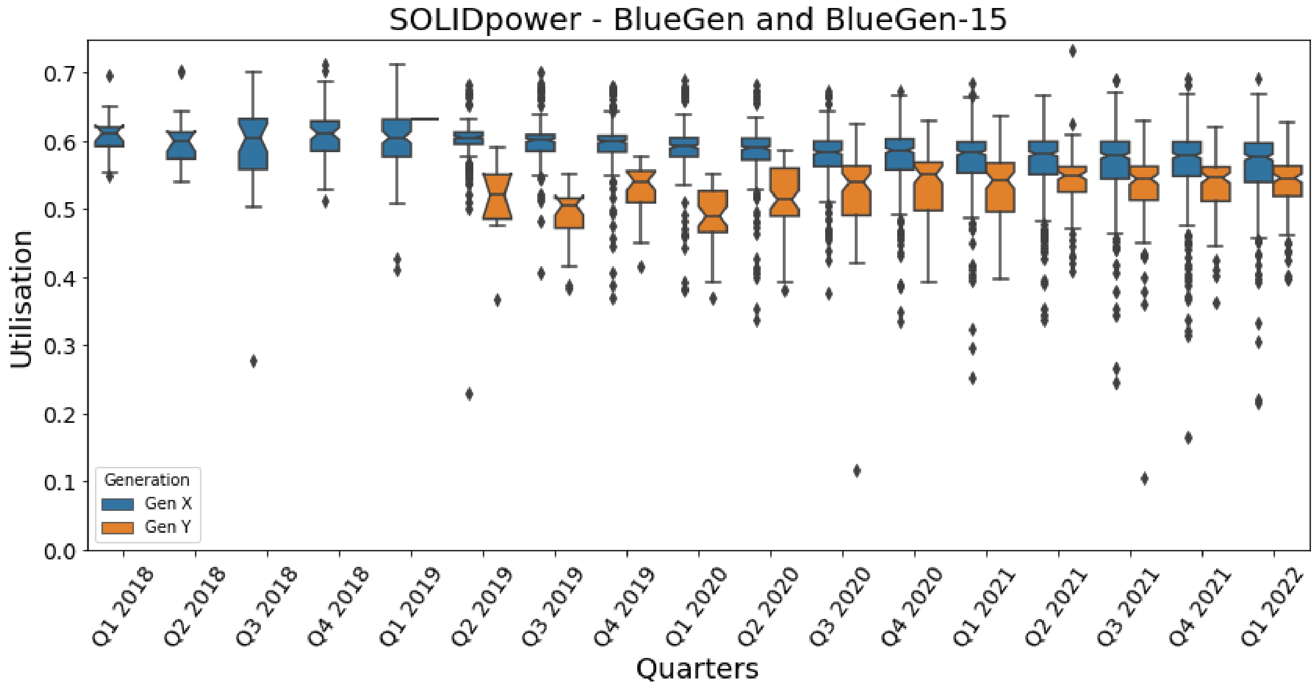


Figure 15: Boxplot representation of utilisation for SolidPower BlueGen and BlueGen-15 units with universal scale

Viessmann

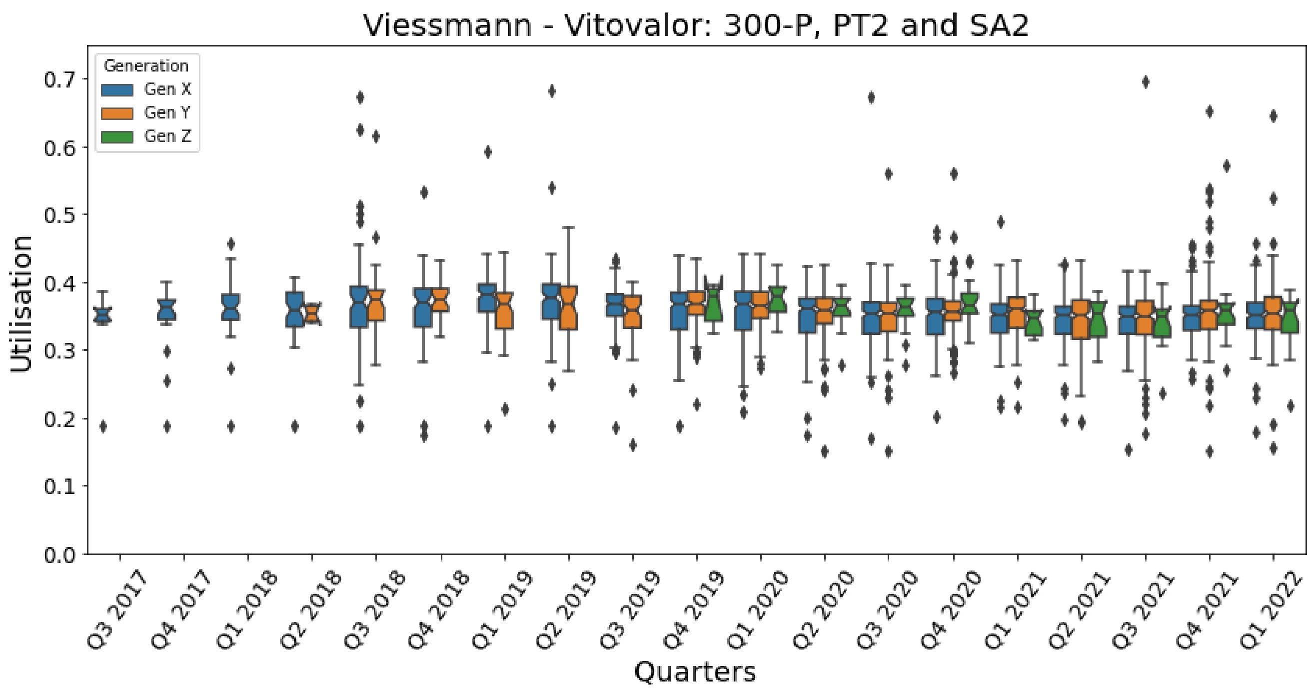


Figure 16: Boxplot representation of utilisation for Viessmann Vitovalor units with universal scale

BDR Thermea

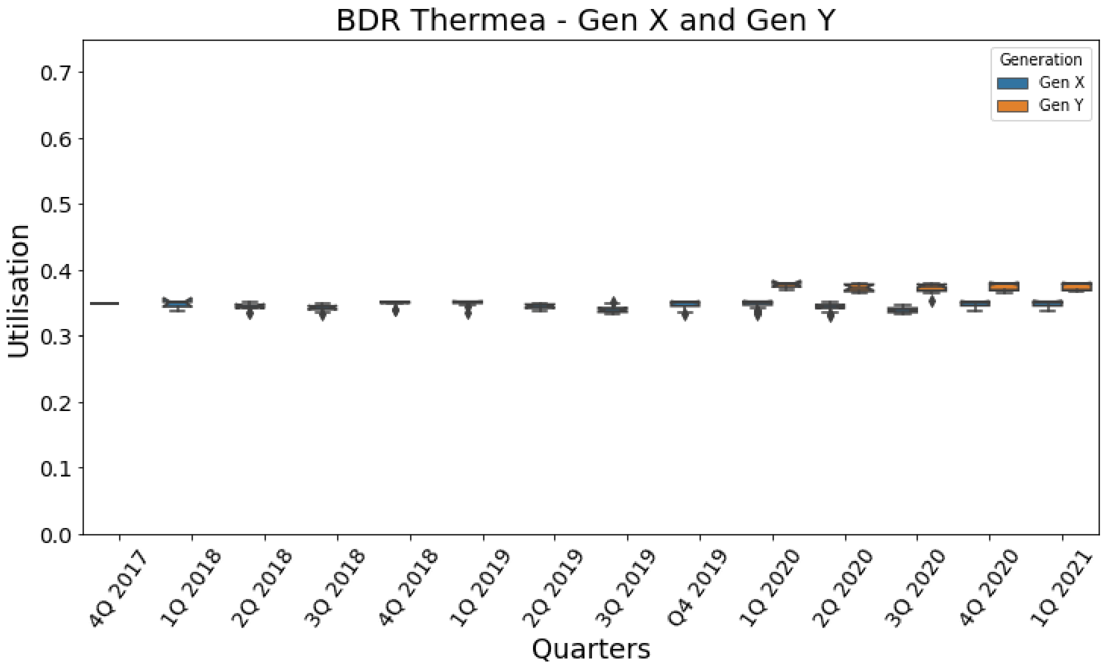
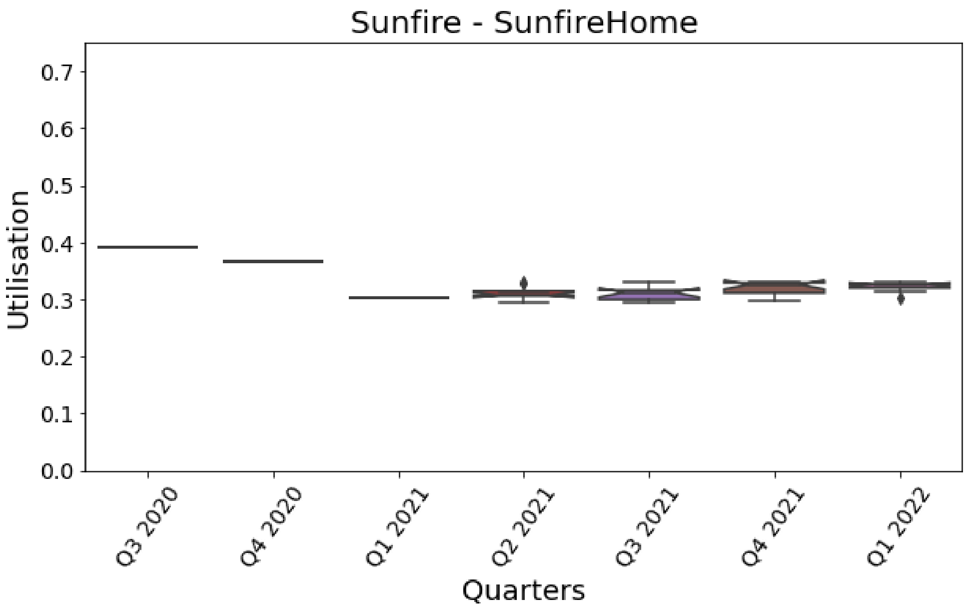


Figure 17: Boxplot representation of utilisation for BDR Thermea units with universal scale

Sunfire



Hexis

More data from HEXIS installations is needed to make a useful presentation and interpretation of the utilisations calculated