ENERGY PILOT ANALYSIS

Deliverable D3.6

Co-funded by the European Union

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SHORT ABSTRACT	The deliverable at hand presents the findings across all energy-related pilots and use cases within the TARGET-X project. An analysis of the energy-related results is given per vertical and technology. Finally, the implication for 5G and future 6G technology from an end-user perspective is given.
KEY WORDS	6G, 5G, Energy, Construction, Manufacturing, Automotive
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Executive Summary

The deliverable at hand presents the findings across all energy-related pilots and use cases within the TARGET-X project. The deliverable provides a recap for the hardware and functionalities of slow-sampling Meter-X for power measurements and the fast-sampling 5G-edgePMU for synchronized power grid measurements. Both devices are deployed within the TARGET-X project.

Results of the Meter-X device deployed in the RWTH Aachen testbed are shown. This deployment focuses on power measurements of laboratory and server environments in the energy vertical, on the behavior of a material life in the construction vertical, and on the consumption of a robot arm in the manufacturing vertical. All these provide insights into the energy consumption of different types of processes and increase the energy awareness of the local users. For example, it was understood that the material list injects power back into the grid when descending. Furthermore, the analysis of the measurements revealed insights into the process itself. For the material lift, a warning horn is active just before the descent starts. This can be detected with the Meter-X device and could be used to increase safety on a construction site or provide additional environmental information to autonomous robots on the site.

The second topic is the discussion of measurement results of the 5G-edgePMU. Within this project, the deployment in five different countries was accomplished. Namely in Germany, Slovenia, Hungary, Italy, and Spain. The 5G-edgePMUs acquire synchronized measurements in all these countries and send these to the RWTH data platform. The results are discussed in terms of the phase, frequency, and amplitude.

Finally, each deployment poses its own 5G challenges. Most of the challenges are related to establishing the connection. This in particular includes the initial bearer configuration, where inconsistencies in the SIM configuration and the provider requirements were found. Debugging 5G connection issues is a complex topic since most of the time the UE owner is not the network owner. This results in the need to mostly communicate by mail to identify and resolve the connection issue. This is a cumbersome and slow process. As a key recommendation, a simplification of 5G or future 6G field provisioning of the UE is seen.

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List of Acronyms and Abbreviations

5G	Fifth generation of wireless technology
5G SA	5G Standalone
5G NSA	5G Non Standalone
6G	Sixth generation of wireless technology
AAS	Asset Administration Shell
APN	Access Point Name
FSTP	Financial Support to Third Parties
GPS	Global Positioning System
LTE	Long Term Evolution
NTP	Network Time Protocol
PMU	Phasor Measurement Unit
SIM	Subscriber Identity Module Card
SCADA	Supervisory Control and Data Acquisition
UE	User Equipment
URLLC	Ultra Reliable Low Latency Communication

1 Introduction

Within this deliverable, the final results of the tests done with the developed Meter-X device as well as with the enhanced 5G-edgePMU are described. The tests are done in all four TARGET-X verticals. The construction, automotive, manufacturing, and energy verticals. Furthermore, the 5G-edgePMU is deployed with FSTP project partners. These results are also discussed within this deliverable. Finally, this deliverable describes the challenges and possibilities of the 5G or future 6G solutions that can be derived from the work done within this deliverable. This deliverable is written from an end user perspective, and therefore the 5G and 6G considerations are mostly connected to an end user view on the technology.

1.1 Relation to other activities

The results presented in this deliverable have been acquired in cooperation with multiple other work packages within the TARGET-X project. The definition of use cases has been done within WP1 (Methodological assessment framework). Energy measurements were executed in cooperation with the construction vertical of WP5 (Construction), the robotics vertical in WP2 (Manufacturing), and the automotive vertical in WP4 (Automotive). This cooperation was fostered throughout the developments in the energy vertical. The Meter-X is a direct result of such cooperation since it was not planned to design and develop a specific device for the challenging outdoor construction environment.

1.2 Document overview

This document is structured in three blocks. First, a short summary of the used hardware in Section 2. This section provides a short overview of the used equipment and provides a context for the measurement campaign discussion that is following. In the Sections 3 to 6 the results of the different measurement campaigns are discussed. This includes a discussion of the measurements as well as the implications and challenges introduced by the 5G network. Finally, a conclusion for the measurement campaign and the challenges by the 5G infrastructure are given.

2 5G energy measurement equipment

Within this document, two different types of measurement equipment are used. Even though the devices are presented in other deliverables [1][3] a short recap on the device capabilities and structure is given in this section. Both measurement devices utilize a Raspberry Pi 4 for computing and a 5G modem for communication. The data acquisition of the two devices differs in speed and time accuracy. For the slow energy measurements, an off-the-shelf metering device is used, and the time synchronization is based on NTP, whereas for the fast voltage and current measurements, an analog-to-digital converter is used, and the time synchronization is done via a dedicated GPS receiver.

2.1 Slow energy measurements (Meter-X)

These devices are mainly targeting the energy awareness use case as given in D1.1 [1], where the major goal is to increase energy awareness in a process or acquire long-term energy measurements. For this device, an ABB B23 [6] metering device is used for the actual energy measurement. This device is capable of directly measuring three-phase low voltage and current up to 400 V and 63 A. The maximum sample rate achieved in the tests is about three measurements per second.

Two versions of this device have been developed. One version is built for stationary use and one for mobile use cases. The developed device is called Meter-X and pictures of the two devices are shown in Figure 1 and Figure 2. For more in-depth information on the Meter-X either deliverable D3.4 [1] or a publication [7] on the Meter-X device can be consulted.

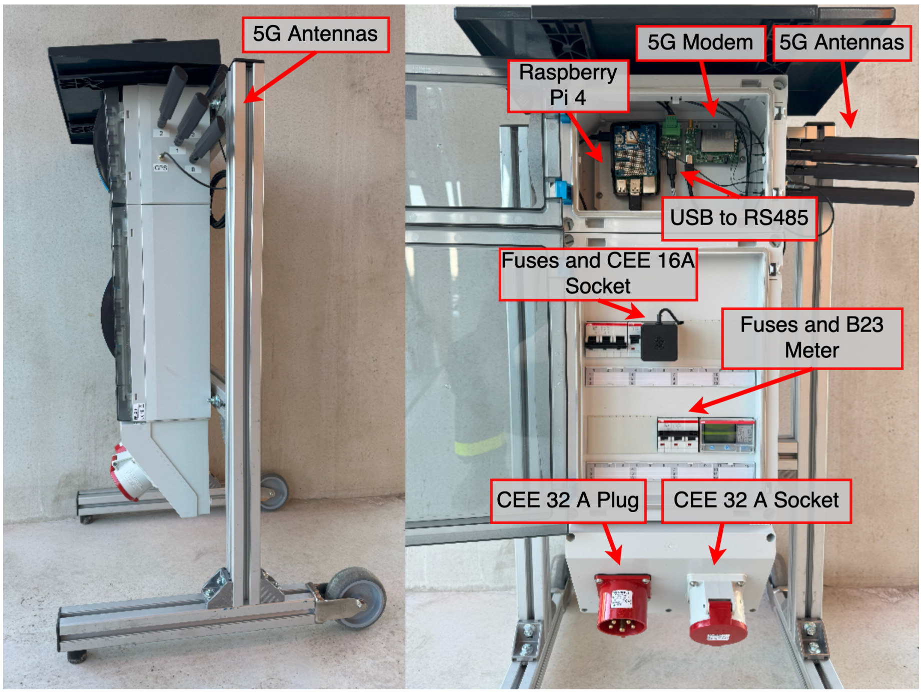

Figure 1: Meter-X for mobile outdoor use

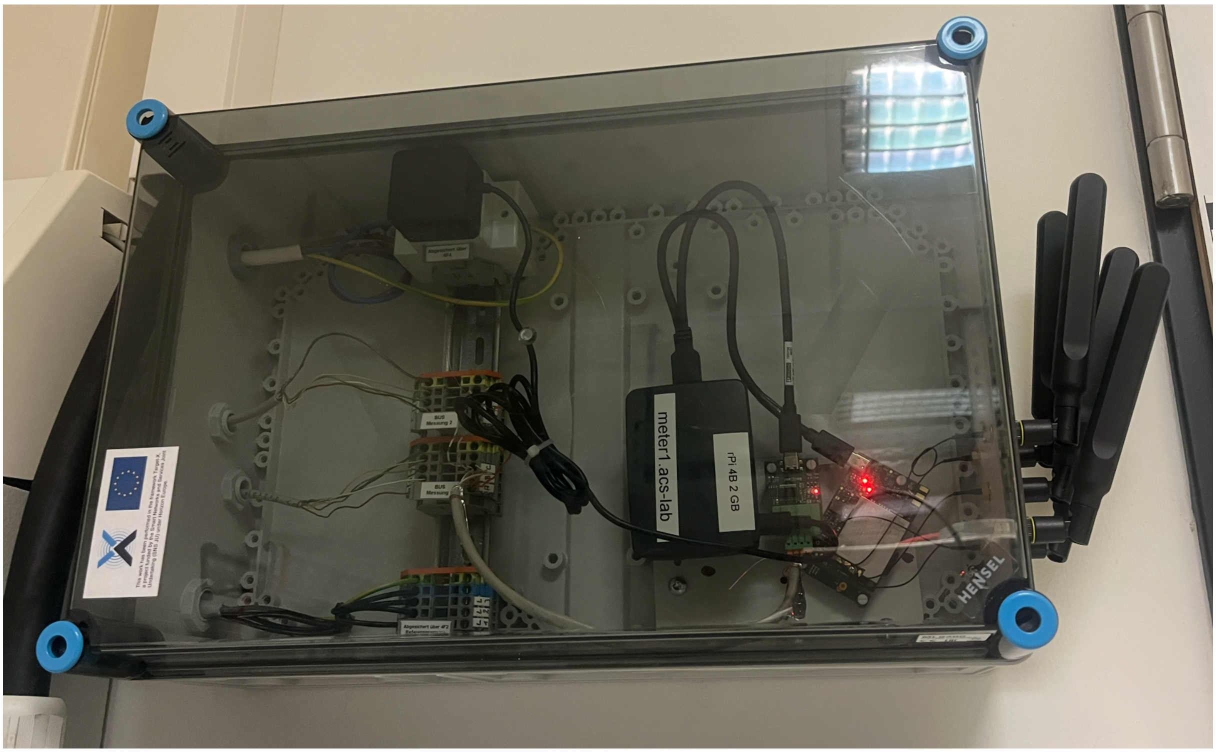

Figure 2: Meter-X for stationary indoor use

2.2 Fast voltage and current measurements (5G edgePMU)

The device for fast voltage and current measurements, (Figure 3) is targeting grid monitoring and especially the phasor measurement. A phasor is a precisely time-tagged measurement of voltage, frequency, change of rate of frequency, and phase of the connected grid measurement point. Further information on phasor measurements can be found in the corresponding standard [9]. The developed device is called a 5G edgePMU and utilizes an eight-channel analog-to-digital converter for the measurements and GPS, or more precisely the pulse-per-second signal of the GPS receiver for the sub-second time synchronization. The addition of a custom developed synchronization board allows for measurements with a global time precision of less than 10 microseconds. The time precision is necessary to be able to compare geographically distant measurements to each other. Since the analog-to-digital converter only allows for ±10 V inputs, an additional input signal conditioning device was developed (Figure 4). This allows for a connection to the power grid and for the direct measurement of three-phase voltage as well as the measurement of three-phase current up to 5 A. This is sufficient to connect to current converters usually used within a substation. The sample rate of the device is set to 80 kilosamples per second, and depending on the test, the samples are either forwarded to an edge cloud server or processed locally on the device. When processed locally, the device is set to a phasor rate of 25 phasors per second.

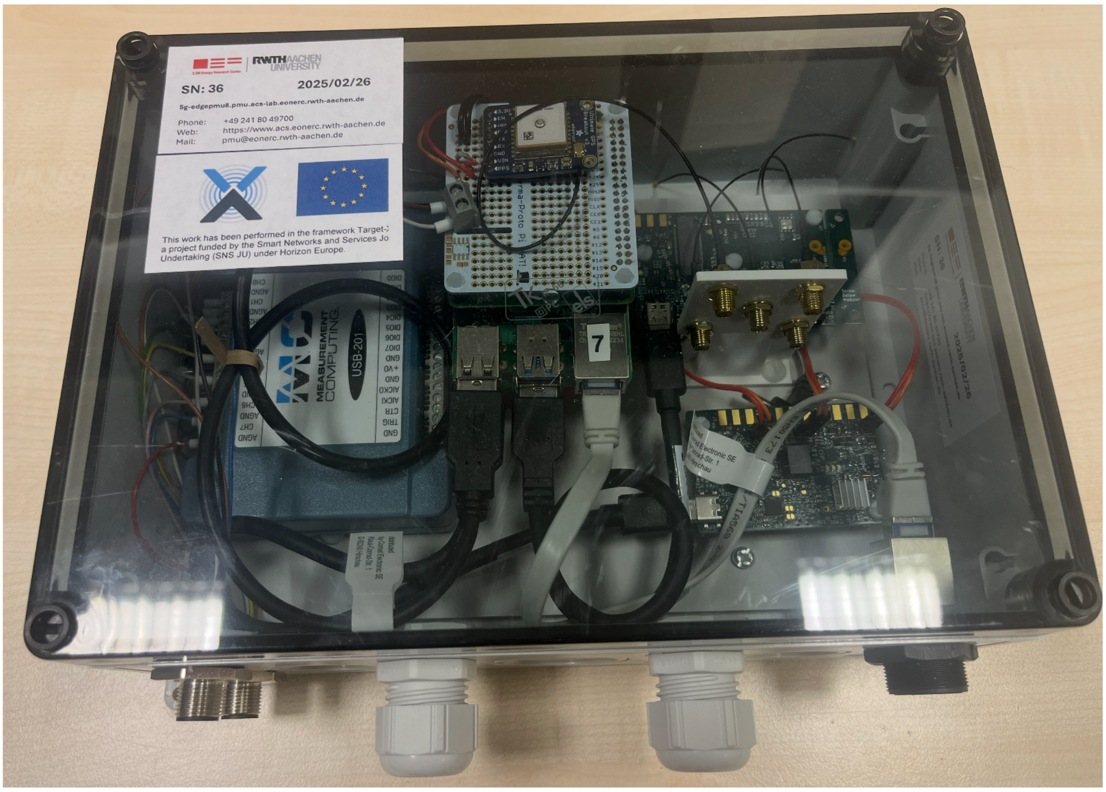

Figure 3: 5G-edgePMU

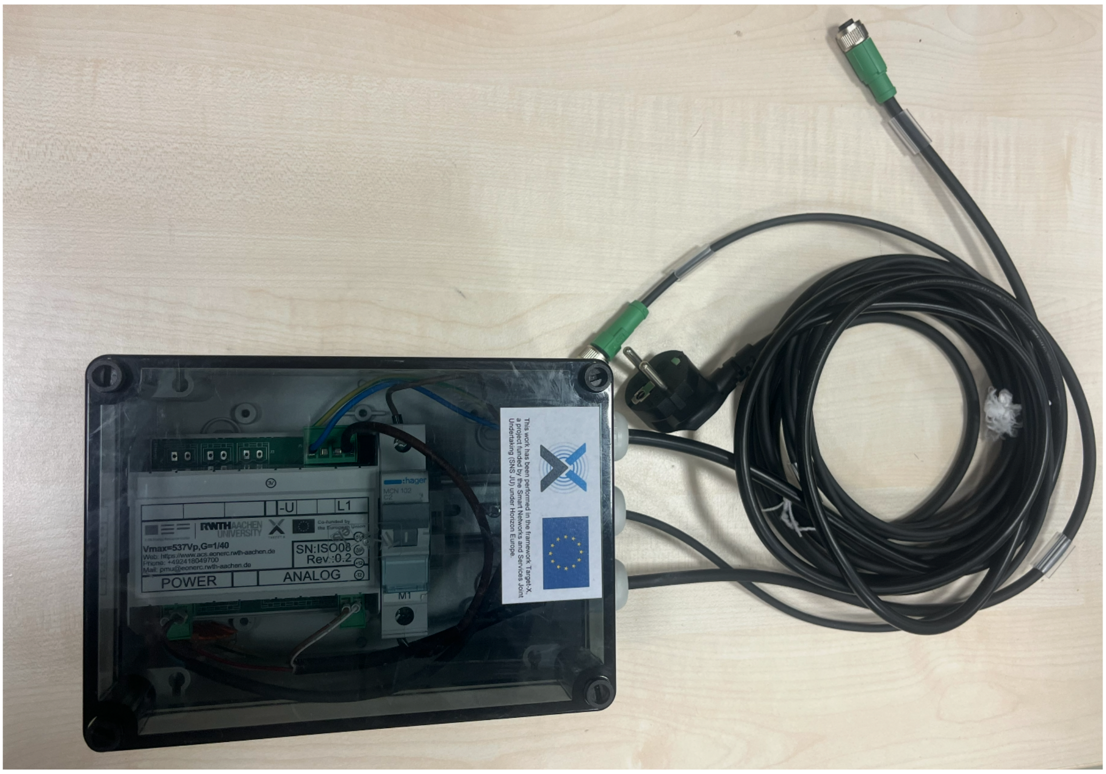

Figure 4: Voltage isolator set for single-phase use

3 Trials executed in the Energy monitoring testbed

Within this section, the tests executed within the Aachen Energy Trial site as well as the tests conducted with the deployed 5G-edgePMUs is described and analyzed.

3.1 Energy awareness

3.1.1 Test power consumption of a building

This test is run in the RWTH-ACS building on Campus Melaten in Aachen, Germany. The test utilizes the stationary version of the Meter-X device. Goal is to acquire information on the energy consumption within a laboratory, mechanical workshop and server room.

3.1.1.1 Goal

The goal of this test is to showcase the use of monitoring the power consumption of a building to identify potential energy savings and detect abnormal events. The low-latency 5G link allows for fast response to potential events.

3.1.1.2 Execution

In this test, a deployment of three indoor Meter-X in an institute building is used to gather long-term consumption data for different connected peripherals.

- Meter-X1 is connected to two ABB B23 power measurement devices, one of which is used to measure the power consumption of a server rack with networking and server clusters, while the second one measures the power consumption of simulation equipment.
- Meter-X2 is connected to one ABB B23, which measures the power consumption of a daily used laboratory
- Meter-X3 is connected to one ABB B23, which measures the power consumption of a mechanical workshop, equipped with a multitude of high power tools like lathes or mills.

The laboratory has multiple appliances and workspaces sharing the same phase.

3.1.1.3 Major findings

In the case of the simulation equipment, the high power consumption of the racks, even with no running simulation, can be seen in Figure 5. At the start of the test, 2 simulation racks were turned on. At 10:18 am, a third rack was turned on and turned off at 10:19 am. In that time period, the power consumption on Phase 1 increased by 600 W from 1250 W to 1850 W.

Since power control of the racks required on-site availability while running simulations can be done remotely, either a remote power solution or administrative rules about powering the simulation racks can be implemented.

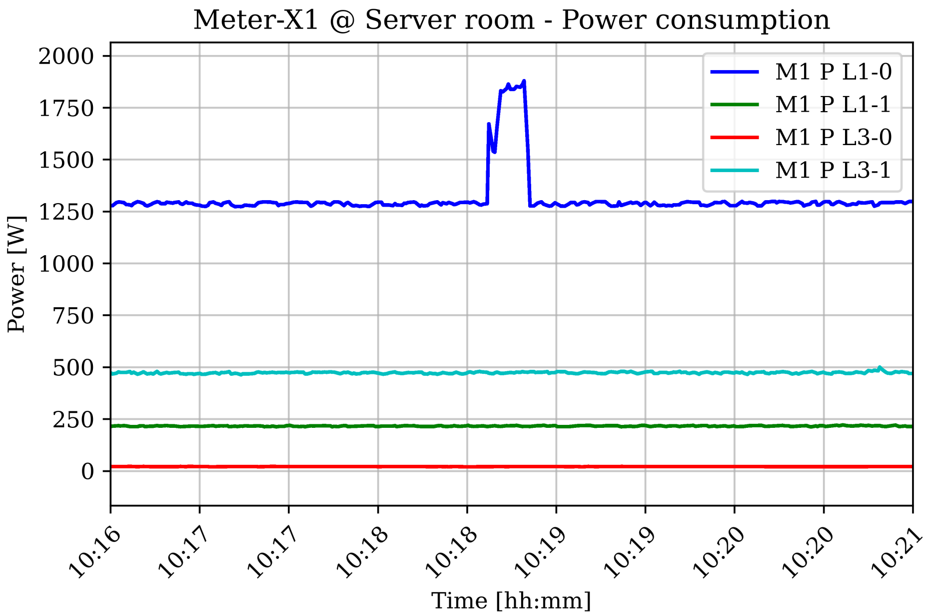

Figure 5: Power consumption in the server room. Showing power consumption L1 and L3 of two metering devices, 0 and 1.

In Figure 6 between 6:22 pm and 9:05 pm, there are short pulses of higher power consumption by the connected server on L1. This is likely due to simulation activity on the server. L3 is static throughout the tests, as the connected network switches have a constant power draw.

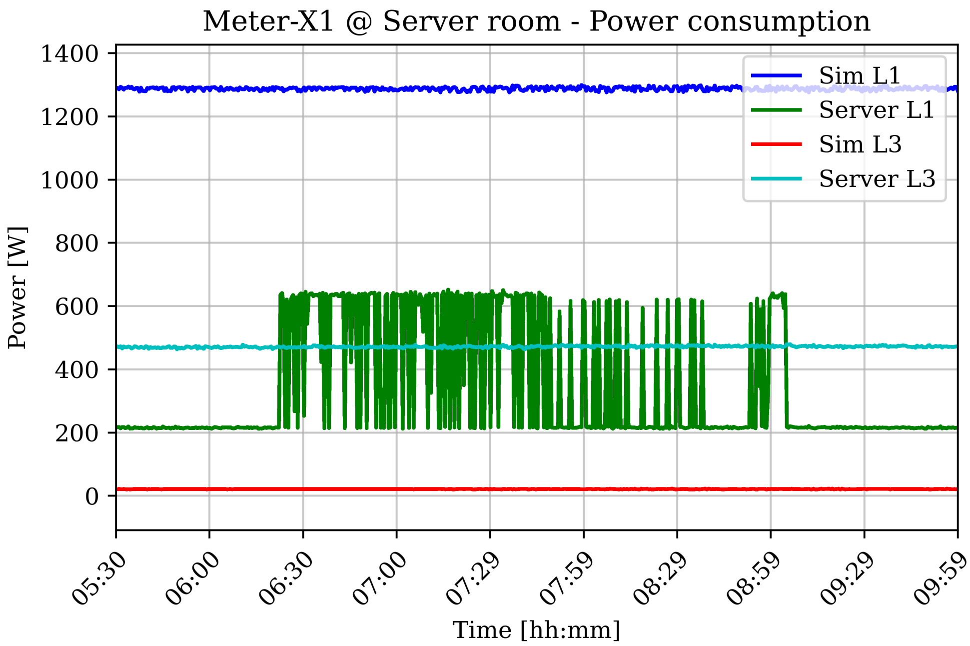

Figure 6: Power consumption of servers and simulators while simulation is running on one of the servers.

In the laboratory, the behavior of a household refrigerator was measured when freshly filled up. This is shown in Figure 7. At 07:33 pm the refrigerator was filled up, where a spike in power of 100 W occurred for 15 minutes when the refrigerator was open. While the typical power consumption on

L1 was 40W, the refrigerator had to cool down its content, which lead to an increased power consumption of up to 270 W during the cooldown period. It can be seen that the cool down is finished around 09:20 pm.

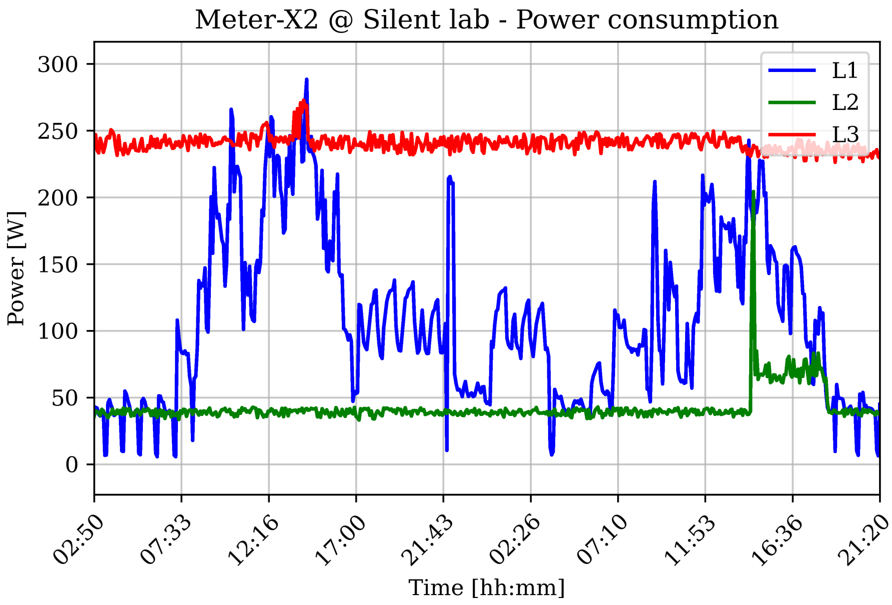

Figure 7: Power consumption of fridge in phase L1, switches on L2 and L3

3.2 Power system monitoring

Within this subsection, the different results related to grid monitoring and stability are discussed. The section is split into five subsections, where each shows a specific aspect of power grid monitoring, namely local frequency analysis, phase analysis, global frequency comparison, and voltage analysis.

3.2.1 European Power Systems Interaction - Frequency monitoring

Within this section, the measurements concerning monitoring the European power system are discussed. We will especially highlight the power outage in Spain and Portugal on 28 April 2025. During that time, measurements with the Meter-X device were taken at the RWTH Aachen trial site. Due to the sudden load change in the European grid, a change in frequency is to be expected. As can be seen in Figure 8 the event was recorded at the Aachen trial site. Contrary to most press releases, not only one event happened but two. The first large load change in the European grid happened around 9:00 in the morning. After that, the frequency was oscillating until the second event happened around 12:30. The second event had as a consequence a power outage in large parts of Spain and Portugal. Since this measurement was done with one sample per second, the actual low point of the grid frequency is expected to be even lower than given by the plot. The plot clearly shows frequency dips, which can only be explained with a large loss of power consumption in the European grid. Even though the frequency stays within the given boundaries of 49.8 Hz and 50.2 Hz, it should be mentioned that this fast loss puts a high amount of stress on the European power system. A corresponding news article is shown in Figure 9.

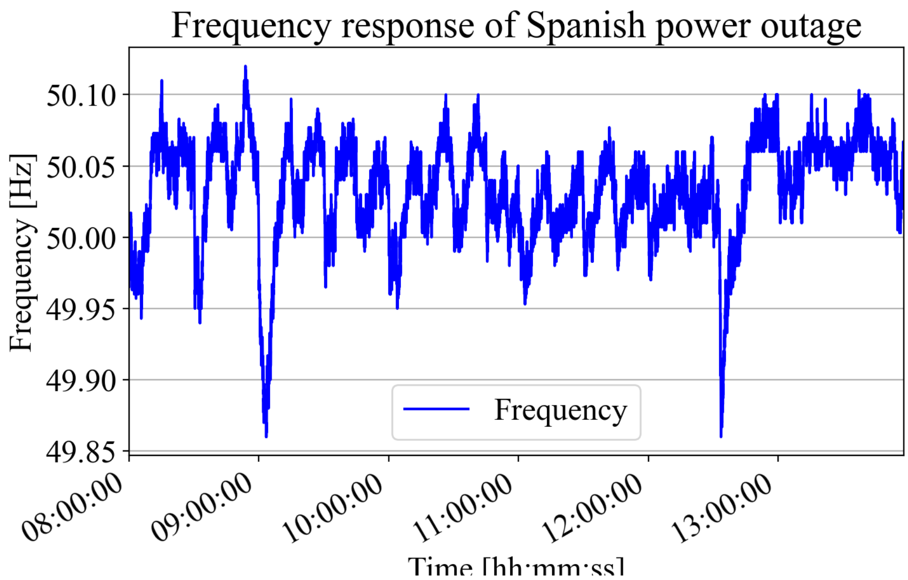

Figure 8: Frequency dip at Aachen measurement point

Figure 9: Screenshot CNN World on the power outage in Spain and Portugal

3.2.2 5G edgePMU Phase Estimation

The phase in the power grid is a local phenomenon and changes with the location of the measurement device. Within the RWTH energy trial site, three devices are connected to the same point, and therefore the phase estimation quality can be compared between the three devices. The results are given in Figure 10. It can be seen that all three devices follow each other within less than one degree of difference, which shows the high quality of synchronization. In this test case, all devices utilize GPS to synchronize their internal time base, and each has a separate acquisition device and analog isolation. A block diagram of the test setup is given in Figure 11.

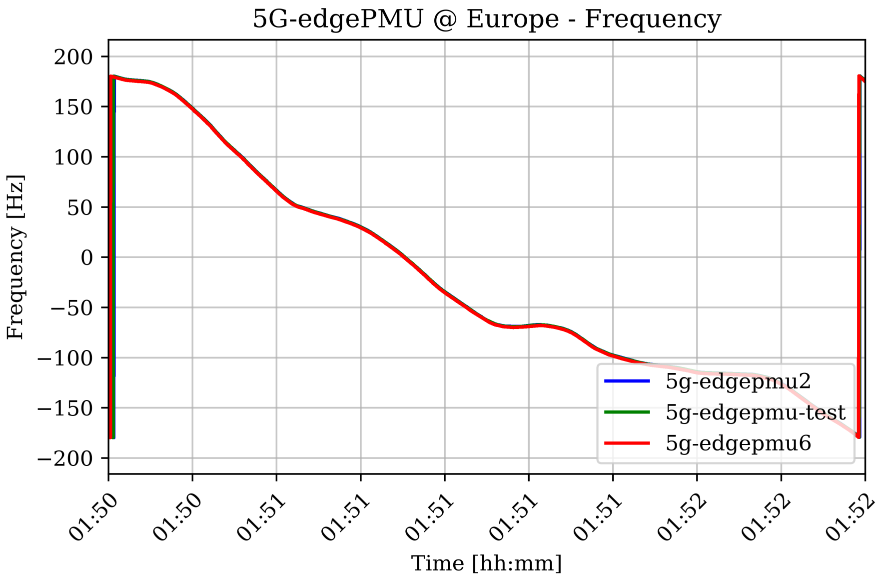

Figure 10: Phase estimation results

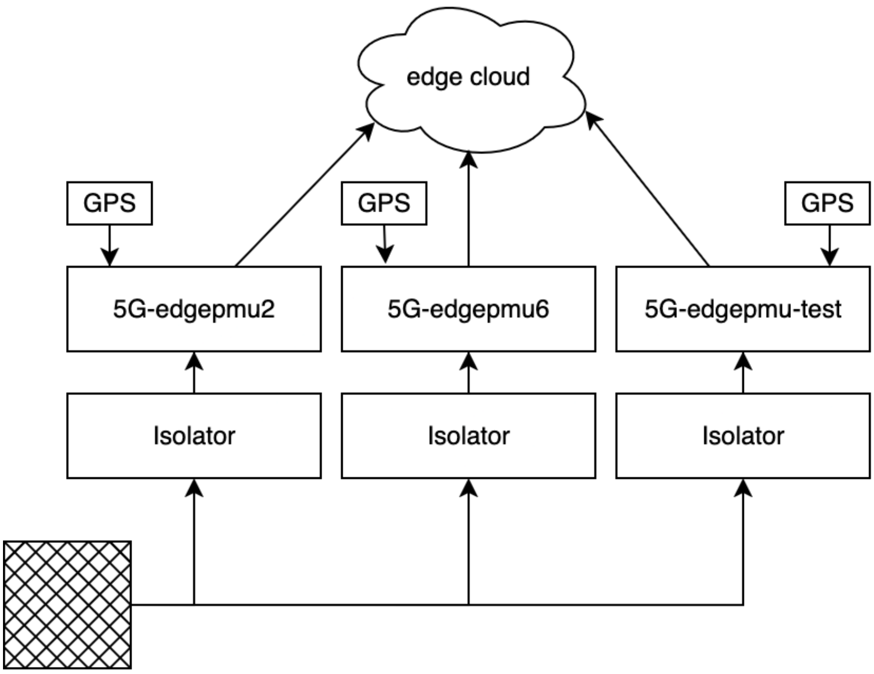

Figure 11: Testsetup for Phasevaluation

3.2.3 5G edgePMU - fast frequency estimation

3.2.3.1 Goal

The goal for this test is showing the monitoring capabilities of the 5G-edgePMU hardware in the electrical grid. With current SCADA technology often being limited to a few seconds or minutes per measurement taken, higher sampling measurement equipment will allow for more insight and faster reaction to changes in the grid quality.

3.2.3.2 Execution

Together with other project partners from WP4 and two FSTP projects, EdgePMU-5G IoT and PMU-EC, 5G-edgePMUs were successfully deployed. Furthermore, it was possible to spark the interest of partners outside the project, and one device was deployed with a research facility in Italy

The deployed 5G-edgePMUs and their use cases are:

- 5G-edgepmu2 is located in RWTH Aachen University, Germany, and is measuring the 3-phase voltage in the building, which is being fed from a local distribution grid transformer.
- 5G-edgepmu5 is located in Spain at the Neutroon facilities and is measuring single-phase voltage from the grid connected to the building.
- 5G-edgepmu0 is located in Hungary at a commercial workshop measuring three-phase voltage of the local distribution grid.
- 5G-edgepmu1 is located in Slovenia in a transformer station measuring three-phase voltage and current of the local distribution network.
- 5G-edgepmu6 is located in Italy in an office building of a research facility measuring single-phase voltage of the local distribution network.

The deployed devices are shown in a map in Figure 12. This shows the online devices with a green check marks. It can be seen that all devices are online.

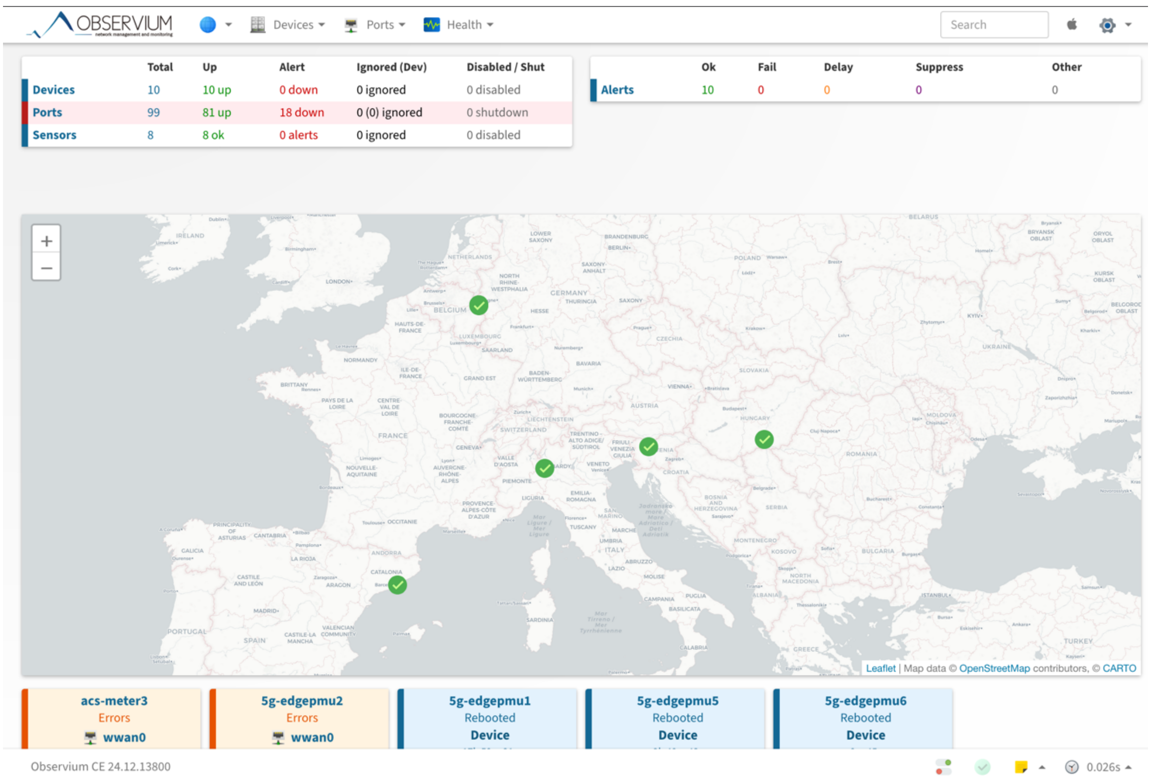

Figure 12: Deployment of 5G-edgePMUs within Europe

3.2.3.3 Major finding

Figure 13 shows the frequency measurement over a whole day. On average, the frequency was found to be 49.998Hz. More detailed comparisons are made between the measurements taken in Germany and in Slovenia (Figure 15), Hungary (Figure 16), Spain (Figure 17) and Italy (Figure 18). It can be seen that the frequencies match very well, which is an indication of good time synchronization and the quality of the European grid. Additional insights into the energy grid market can be seen when shorter timeframes are considered. Figure 14 shows a 2-hour close-up of the measured frequencies. Big drops in frequency happened at the full hour, with noticeable drops occurring every 30 minutes, after which frequency response reserves are used for recovery. This pattern aligns with the execution of trades on the EPEX SPOT platform, which happens at hourly, 30-minute, and 15-minute intervals. This shows that the effects of the European energy trading market can be seen in the grid frequency.

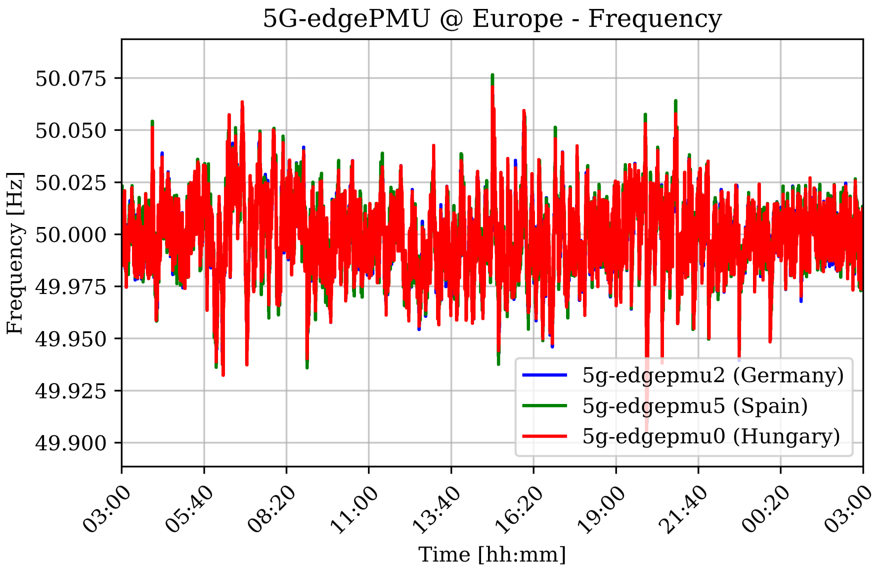

Figure 13: Frequencies measured by 5G-edgePMUs in Europe over a whole day

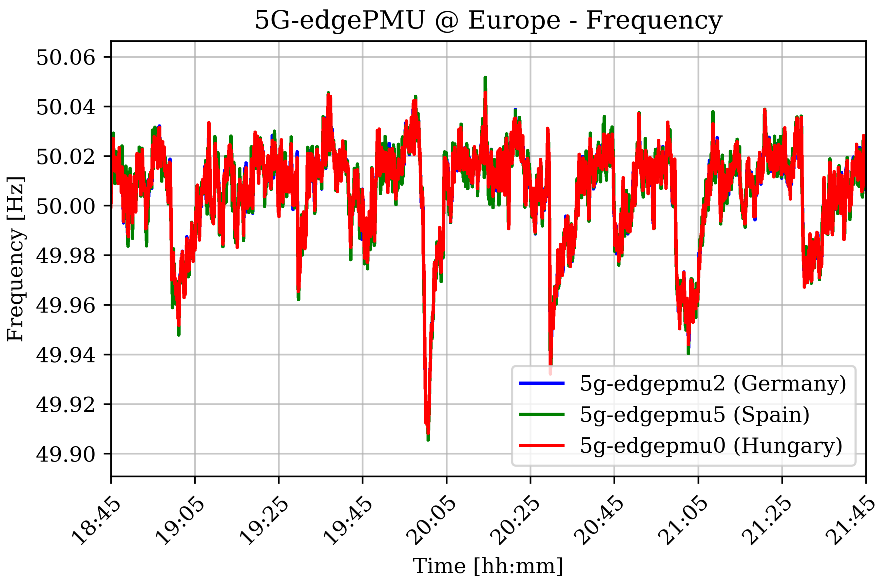

Figure 14: Frequencies measured by 5G-edgePMU, focused on market timing

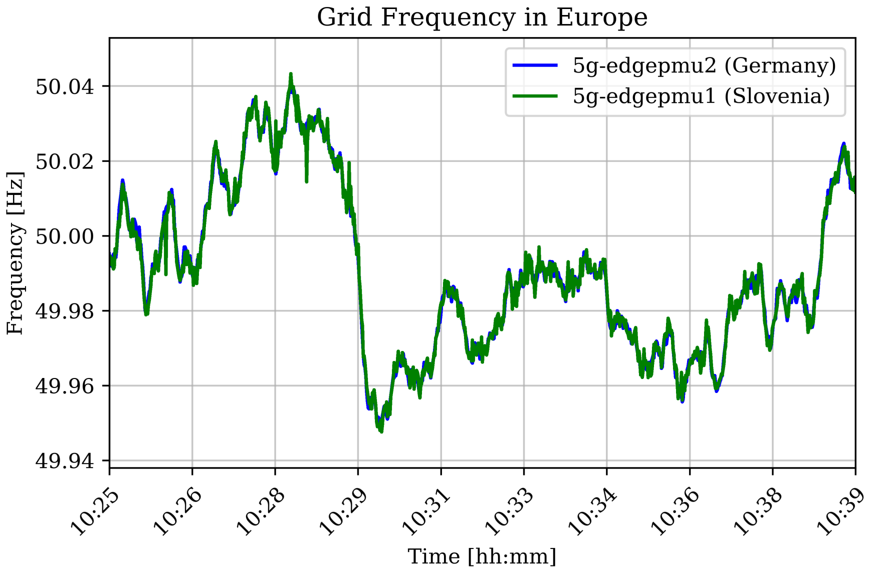

Figure 15: Frequency comparison of 5G-edgePMU deployed in Germany and in Slovenia

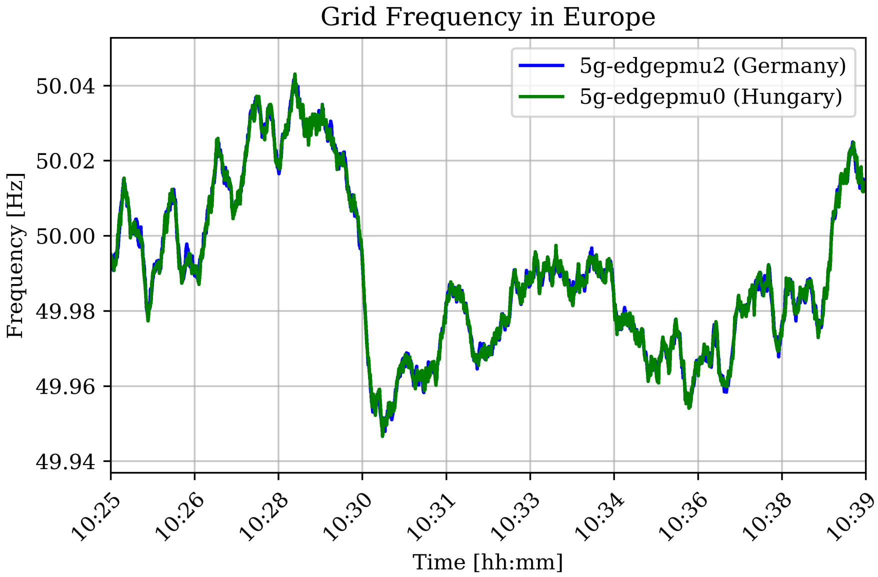

Figure 16: Frequency comparison of 5G-edgePMU deployed in Germany and in Hungary

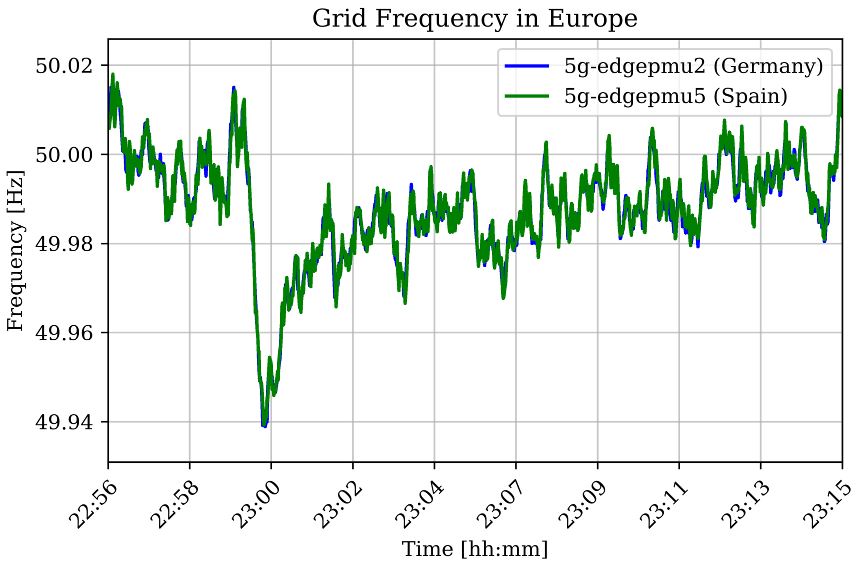

Figure 17: Frequency comparison of 5G-edgePMU deployed in Germany and in Spain

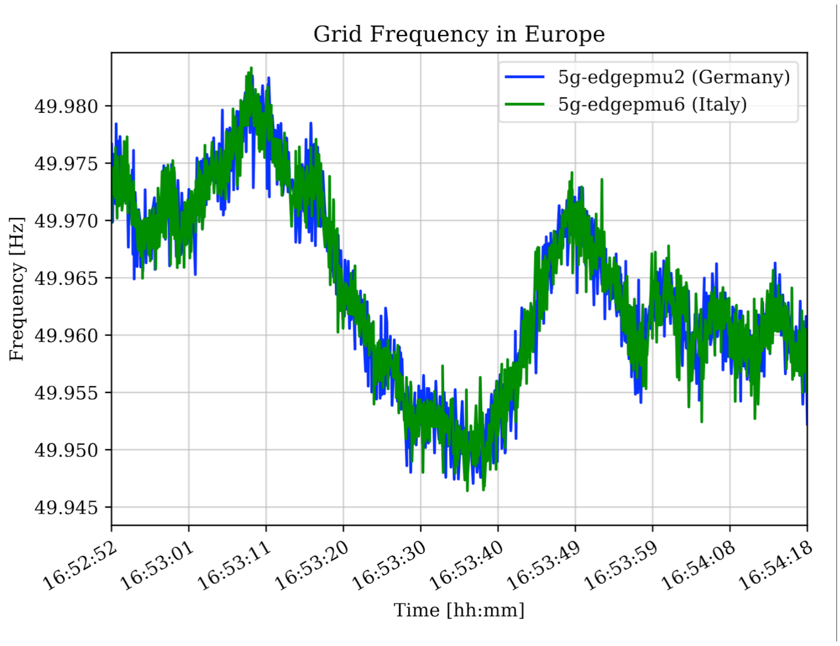

Figure 18: Frequency comparison of 5G-edgePMU deployed in Germany and in Italy

3.2.4 5G-edgePMU amplitude estimation

3.2.4.1 Goal

This test is meant to display the amplitude estimation capabilities of the 5G-edgePMU. Local grid monitoring is gaining importance due to more dynamic loads, which can have an increased effect on the power factor and thus voltage of the grid. As a first target, we try to find local grid behavior patterns in the measurement data.

3.2.4.2 Execution

Measurements were taken in Germany with three 5G-edgePMUs and a Keithley DMM6500 6.5 digit bench multimeter, all connected to the same phase. This will be used as a reference value to compare the 5G-edgePMUs to. The measurements were taken over a long timespan to detect events in the grid.

3.2.4.3 Major finding

In the resulting data, you can clearly see the tap changes of the local transformer feeding the building. At 07:45 pm and 7:00 am the taps of the transformer change to better fit the changing requirements of the distribution grid that it feeds. This roughly aligns with working hours on the campus.

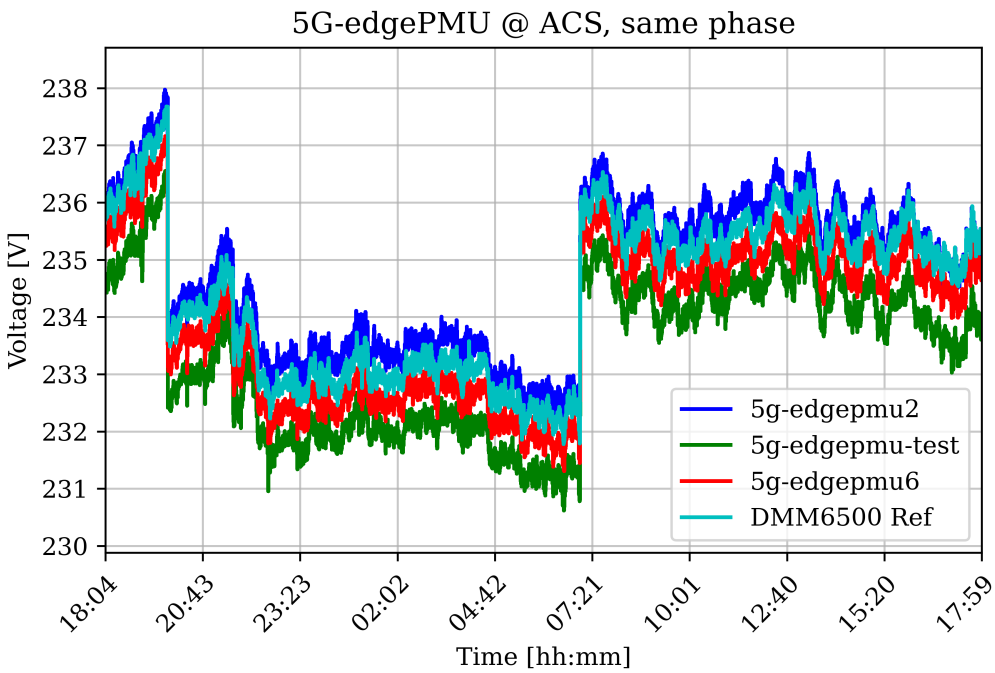

Figure 19: Estimated Voltage of L1, connected to the same grid point

3.3 Considerations on the used 5G network

5G is a interesting new technology for this use case. The shown sensors have been deployed in both private 5G SA and public 5G NSA networks. For the private deployment, the edge cloud plays a major role and is used for collecting the measurements and visualizing the results.

Special considerations for the private 5G infrastructure. For the deployment, a commercial infrastructure with eight antennas deployed within a building is used. To simplify the use of the deployment, the manufacturer decided to reduce the amount of information on the state of health or the connectivity of specific UEs. Unfortunately, this limits our ability to debug infrastructure problems by ourselves and increases communication overhead with the manufacturer's support.

One example is a device that experiences connection issues and reconnects about 200-300 times a day. The only way of debugging such a behavior is apparently to move the device to another antenna (proposal by the 5G SA system provider); no information on the connection quality is available. Furthermore, the UEs used unfortunately always report 50% signal strength, even though this number varies in other installations (SA and NSA). This seems to be a behavior of our specific deployment and might be resolved with future software updates. Such issues and intransparency should be challenged in future 5G or 6G deployments. A more open approach would be beneficial.

Consideration of the public 5G infrastructure. Within the deployments in public networks, a major hurdle was the stable connectivity. On one hand, there are not yet, to our knowledge, approaches to automatically provision and deploy the SIM Card. Limited default internet access would be very helpful to allow for the initial remote installation of connection parameters. This is especially the case if the device is shipped to a foreign country where SIM parameters are not clear. In addition to these issues, challenges with the initial connection to a public Telekom network have been discovered. The SIM card was initialized correctly, but the initial bearer APN was set to internet.v6.telekom. This was incompatible with the local Telekom network, and as a result, the device was stuck in searching mode. Only after changing this to internet.telekom was this resolved. This was not the data connection APN but an APN used a stage earlier for the connection. In this case a lack of deep knowledge made it difficult to initiate the connection. A similar problem was identified in an Orange-controlled network in Spain. In this case, the registration was successful, but it was not possible to connect. Later it was again identified as an initial bearer issue. This indicates that configurations are highly dependent on the local network provider's implementation. This poses a barrier for the deployment of large fleets of measurement devices utilizing the 5G network. Furthermore, it requires a telecom engineer to supervise the deployment. The complexity for the end user should be challenged in future 6G developments.

Finally, the deployment of 5G NSA networks brings up a caveat when configuring the modems. Instead of setting the modem to 5G mode, in case of an NSA network, the modem has to be set to 5G and LTE. This is confusing for the end user since, from a user perspective, 5G SA and 5G NSA are both 5G and not LTE.

4 Trials executed in the Mobile robotics testbed

Within this test executed with the TARGET-X mobile robotics testbed, a Kinova Gen 3 robot arm is evaluated. The robot arm follows a predefined trajectory and moves a fixture with changing weights from one side of a table to the other. The test setup is as shown in Figure 20. The robot arm is a single-phase load and compared to the designed power ratings of Meter-X can be considered a very small load. For this test, the robot arm is connected in line with the Meter-X device.

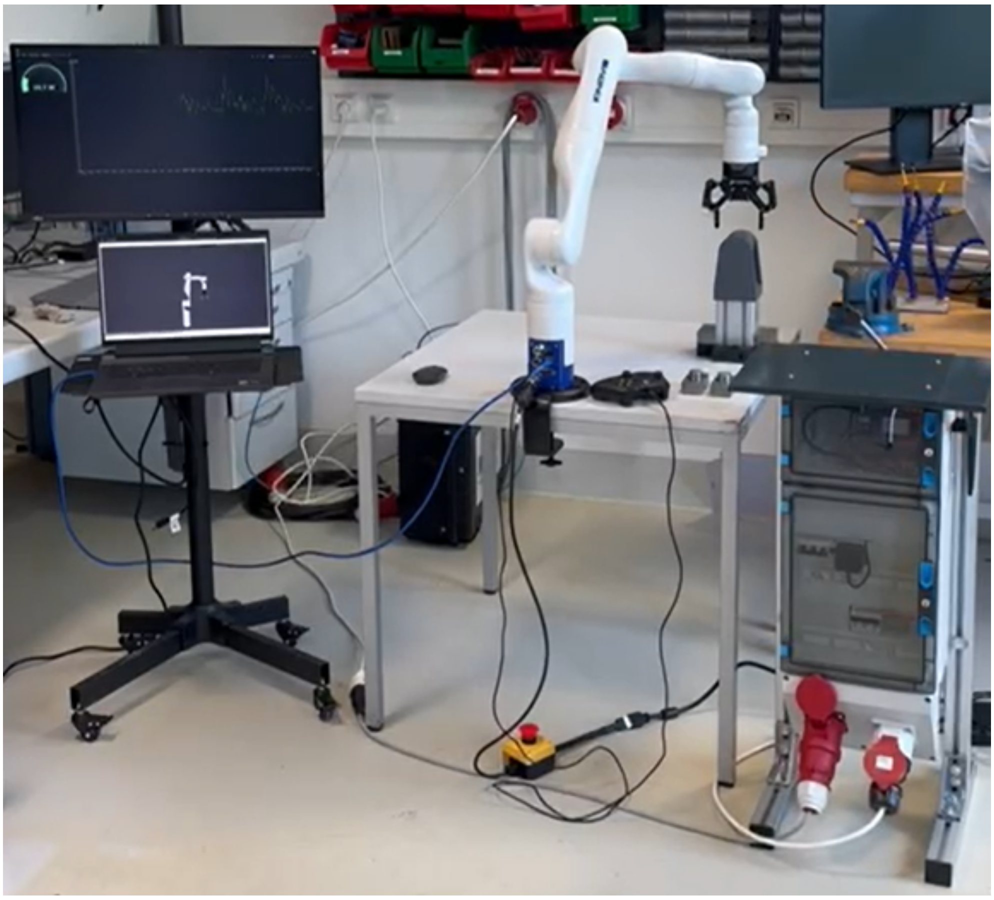

Figure 20: Robot arm test

4.1 Energy awareness

4.1.1.1 Goal

The goal of this test is to evaluate the capabilities of Meter-X to measure small load changes and understand if such a process can be analyzed with the Meter-X device.

4.1.1.2 Execution

For this test a weight is transferred from one side of a table to the other and back. The resulting power measurement is shown in Figure 21. Analyzing this plot, it can be seen that all eight transfers of the weight can be seen. The process always starts with the pickup of the fixture, either with or without the weights attached. The first four cycles are with weights, and the second four are only with an empty fixture. It can be seen that the highest peak happens when the weight is picked up, followed by a small plateau where the robot arm is moving horizontally, and finally a period of idling where the robot arm waits between cycles. The peak power in this case is around 60 W, and the idle power consumption is around 32 W. The idle power consumption can be allocated to the motor drivers and the motors holding their position, since the robot arm is not equipped with mechanical brakes. The presentation of our paper on the Meter-X device explains the behavior in more detail. It can be found, published by the conference, on YouTube [8].

4.1.1.3 Major finding

The major finding of this test is that the same Meter-X hardware designed for large three-phase loads up to 43 kW can be used for small single-phase loads in the range of less than 100 W.

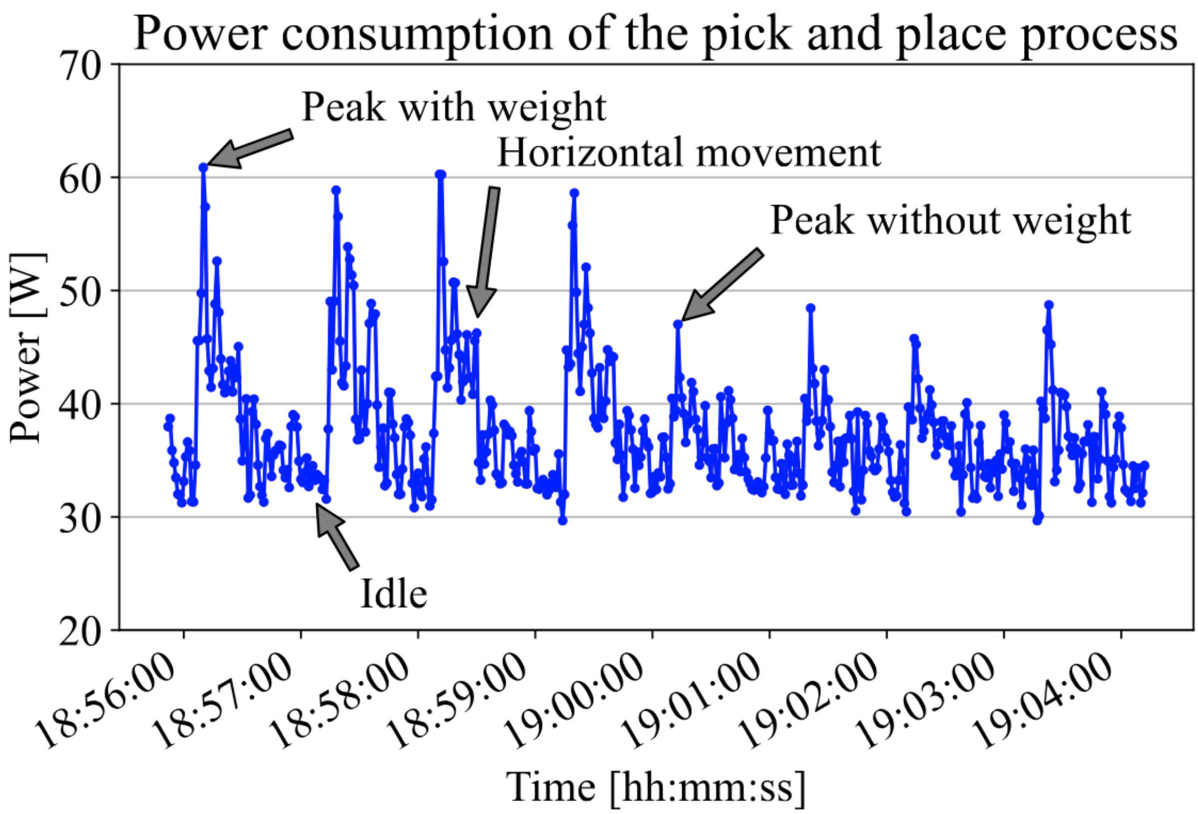

Figure 21: Power plot of robot arm with different weights

4.2 Considerations on the used 5G network

This application benefits from 5G technology. Especially the edge cloud technology for aggregation of multiple measurement devices and central storage and analysis of measurements can be beneficial. The use of an already existing private 5G installation on a shop floor enables a mobile analysis of different manufacturing equipment without the need for complicated reconfiguration. As a challenge, the configuration of the 5G connection should be mentioned. Since in this case a 5G NSA network was used, the modem had to be reconfigured in the command line to allow for a mixed LTE and 5G connection. The debugging of such a problem is complicated for non-telco experts. One possible solution is to utilize auto onboarding, as shown by the AAS approach developed in WP6. After this fix, the 5G connection worked without further problems.

5 Trials executed in the Construction testbed

5.1 Energy awareness

Within these tests, a GEDA 1200 Z/ZP lifter was evaluated. This lifter is used for transporting goods on a construction site of a building from the ground floor to the different floors of a building. In Figure 22 the Meter-X device can be seen as it is connected in line with the lifter in the background. Within this vertical, two different tests are executed. On one hand, the analysis of the lifter operation and the process of lifting, and on the other hand, event detection for the lifter. In both, the same test setup is used.

Figure 22: Lift measurement setup

5.1.1 Load dependent power consumption

5.1.1.1 Goal

The goal of this test is to showcase how insights into a process on a construction site can be used for increased energy awareness for a process on the construction site. This can then, in a later step, be used to identify major energy consumers and decrease the carbon footprint on a construction site.

5.1.1.2 Execution

For this test, the lifter is moved upwards to its end stop position and then down again. In Figure 23 the time series data of the power consumption is given. It can be seen that around 03:34:27 pm the operation starts. A peak in power demand can be observed. This peak of around 2.5 kW is correlated to the motor of the lifter starting to move and can be observed two more times in this test. Then after the first peak, a constant power consumption of around 1.2 kW on all three phases follows until the lifter reaches its end stop position. After a short pause, the lifter is moved downwards. In this case it was stopped for a moment, and therefore there are two peaks to be observed before the final descent. The peaks can be explained with the motor moving up a small amount to unlock the brakes. In the final section of the test, starting around 03:34:45 pm, a negative power consumption can be observed. This is during the descent of the lifter and can be explained by the motor feeding back into the power grid.

5.1.1.3 Major finding

A major new insight for the partners at the construction site is that the lifter is not purely an energy consumer but also feeds power back into the grid. This was not known before the tests. Furthermore, this information could be utilized for device-specific energy billing, which is not yet done widely on a construction site.

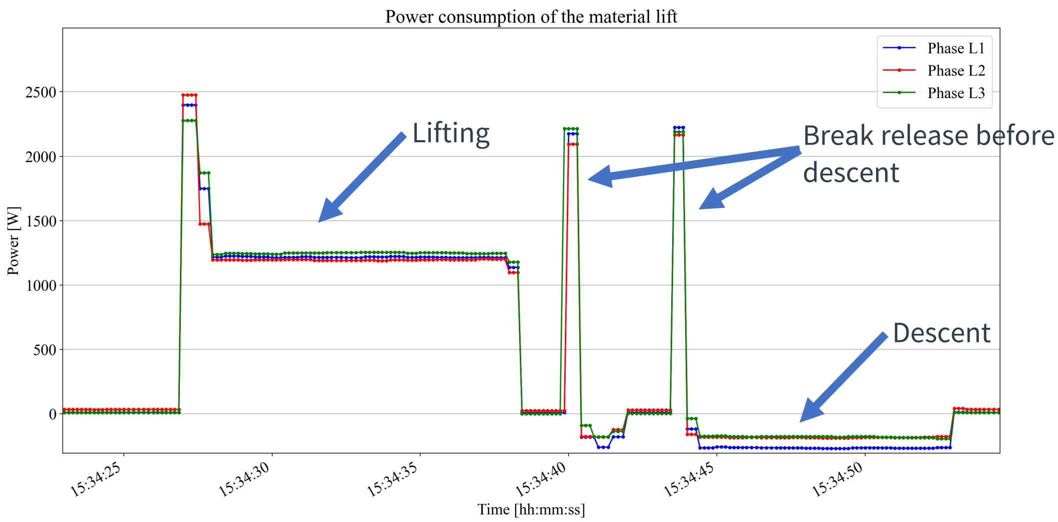

Figure 23: Power consumption of a Lifter, first the lifting process and then the descend

5.1.2 Event detection

5.1.2.1 Goal

The goal of this test is to detect process specific events while utilizing 5G communication to forward the measurements to an edge cloud system on the construction site.

5.1.2.2 Execution

Within this test, a lifter-specific behavior is exploited. Just before the lifter starts descending, a warning sound is emitted to inform all nearby personnel to keep clear of the lifter base. This warning sound can be measured with Meter-X. The events are identified with a Python script, and the result can be seen in Figure 24. All vertical red lines are detected warning sound events. For this test, the lifter was moved to the upper resting position, as can be seen in the first section of the plot between 03:52:30 pm and 03:52:40 pm. Then the descend button was pressed for a brief moment until the warning sound was audible. As soon as the warning sound was audible, the descend button was not pressed anymore. With this, only the warning sound events show up in the measurement and can be easily identified to tune the Python-based detector script. Finally, after 10 test runs, the lifter was descended, which resulted in the final event that was detected around 03:53:50 pm. A more detailed view of the warning sound events is given in Figure 25. Here it can be seen that the horn has a power consumption of around 10 W while in this phase the standby power consumption is 20 W. In the detailed figure, only the test events are shown.

5.1.2.3 Major finding

The results of this test can be utilized to increase the environmental awareness on a construction site. One possible use case could be to inform autonomous robots to clear the area below the lifter, and another would be to cross-check that the area below the lifter is cleared by humans when the lifter starts descending. This can enhance safety on a construction site.

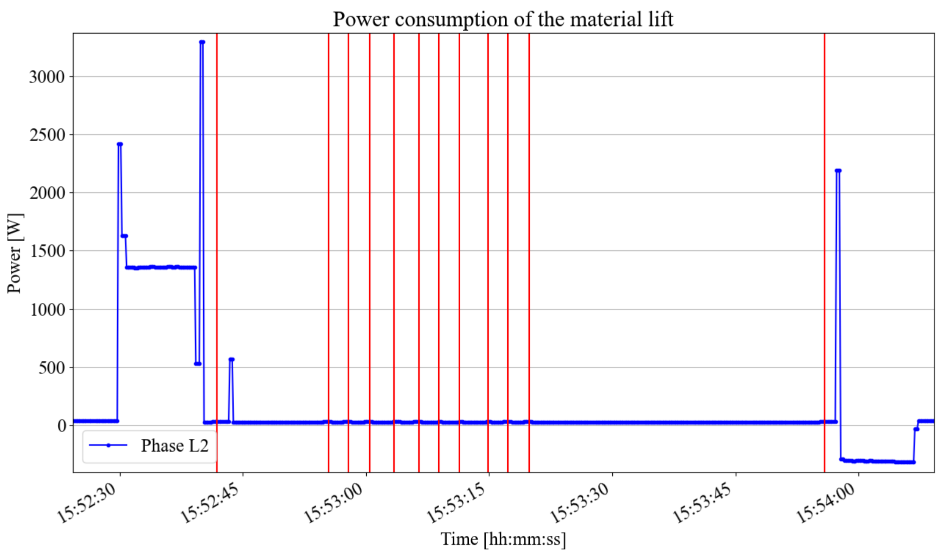

Figure 24: Warning sound event detection overview

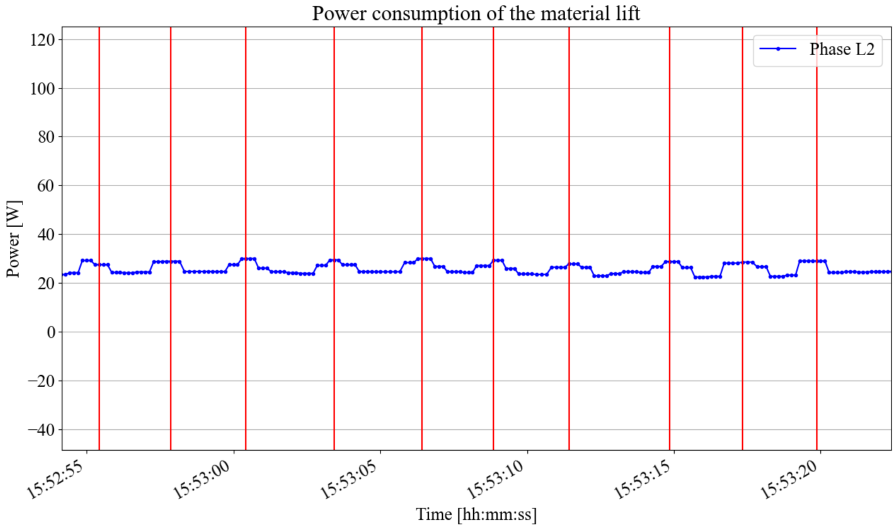

Figure 25: Warning sound event detection detailed

5.2 Considerations on the used 5G network

5G technology is beneficial for the above-mentioned use case. Specifically, the edge cloud feature for local data processing can be a selling point since data sovereignty and data privacy are important topics when utilizing energy measurements for billing or cost analysis purposes. For this, having the data transmitted and processed on-premises is an advantage. Furthermore, the coverage of a 5G network and the quality of service are important selling points for larger construction sites or construction sites with a high utilization of wireless communication resources. This would be, for example, the case in a densely populated city when trying to use WiFi.

On the other hand, the safety and event detection use case depends strongly on the achievable latency. Even though no tests with URLLC-based communication were executed, such technology promises advantages concerning not only the latency but also the expected latency jitter.

6 Trials executed in the Automotive testbed

Within the automotive vertical, the 5G-edgePMU is used to evaluate the possibility of migrating the power estimation algorithm between the 5G-edgePMU field device and the edge cloud. In the case of running the power estimation on the 5G edgePMU the amount of transmitted data is lower since the estimation is executed only 10 times per second but based on a sample rate of 10 kSamples per second. In the other case, the power estimation can be executed on the edge cloud, where then the raw samples are transmitted via 5G. The latter can be beneficial when the algorithm running needs more compute resources than a Raspberry Pi can provide, whereas the estimation on the 5G-edgePMU is beneficial when the uplink bandwidth is limited due to, for example, signal strength. Further details about the communication side of this experiment are given in Deliverable D4.4 [4]. This use case was not planned at the beginning of the project, but the synergies between the automotive and the energy vertical have been discovered during the project. For this test a special measurement head was designed. This head can measure the power consumption of devices connected to a 12 V on board power supply in a car. For the test, a small computer was connected in the car, and the 5G-edgePMU measured the power consumption of this device. Due to restrictions at the automotive testbed, it is not possible to show a picture of the test, but the setup was documented after the test outside the photo sensitive area. This photo is also used in D4.4 [4] where the focus is set on the communication, while in this deliverable the power measurements are the focus.

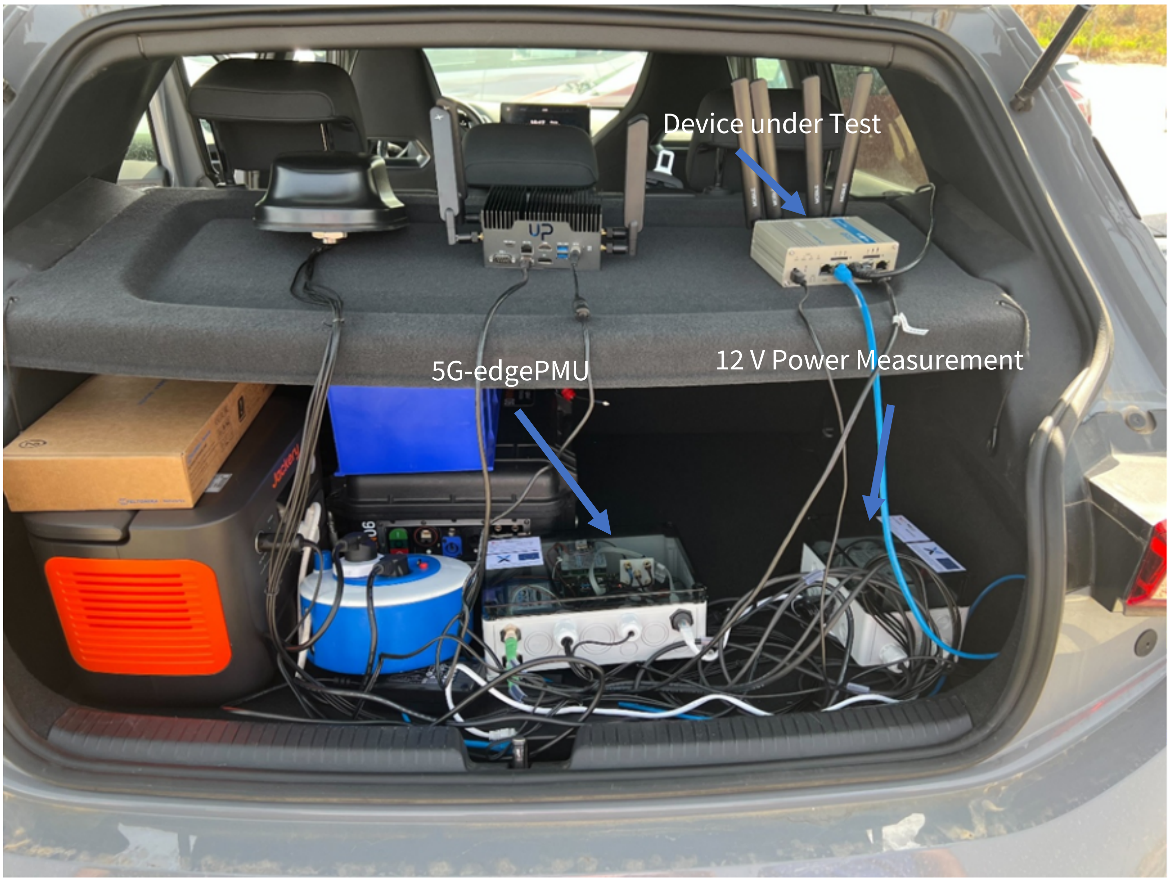

Figure 26: 5G-edgePMU mounted in car for consumption measurement

6.1 Energy awareness

6.1.1.1 Goal

The goal is to show the versatility of the 5G-edgePMU as a sensor system. While at the same time being able to be mounted in a substation and adhere to grid requirements, the system can be deployed within a car as a mobile measurement platform. This is a first test evaluation to further the deployment of 5G equipment in the field but also to understand if the 5G-edgePMU is also capable of handling the environment of a moving car. Within the car, a 5G router is connected as a device under test.

6.1.1.2 Execution

As can be seen in Figure 27 the test started recording around 11:01 am and the voltage was connected at 11:13 am. The 5G-edgePMU measured the voltage at slightly higher than 12 V during the whole test, which is explained by the use of a portable power station as a power source. Within the current measurement in Figure 28 and the resulting power plot in Figure 29 it can be seen that the device under test started around 11:13 am and then had a startup phase until 11:19 am. Then for the rest of the test, the power consumption stayed around 7 W.

6.1.1.3 Major finding

Utilizing the 5G-edgePMU as a flexible and modular sensor system to also estimate the power consumption in a mobile environment like a car is possible. No hardware issues due to the environment have been reported. It was also shown that the mobile operation with changing signal quality can be handled by the software stack. A mobile 5G router is used as a test load. The device startup phase can be clearly detected in the power measurements.

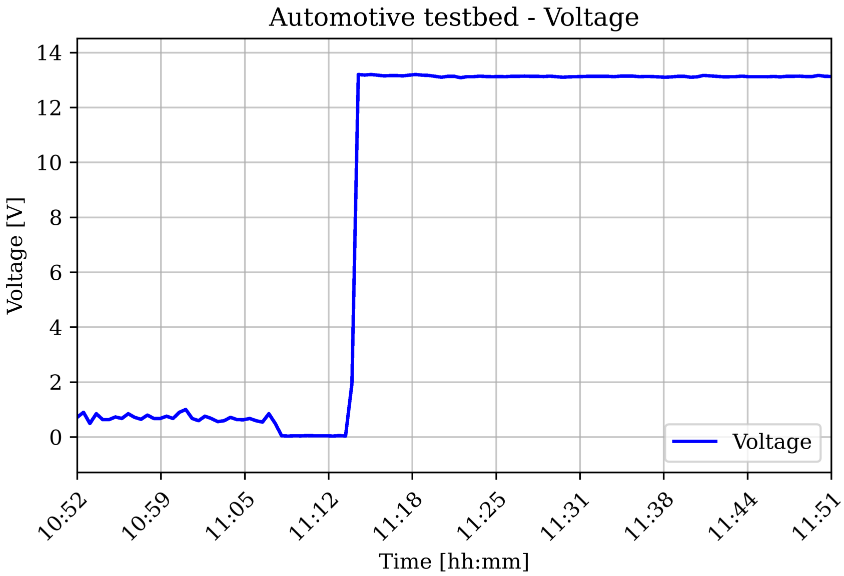

Figure 27: Voltage at car power outlet

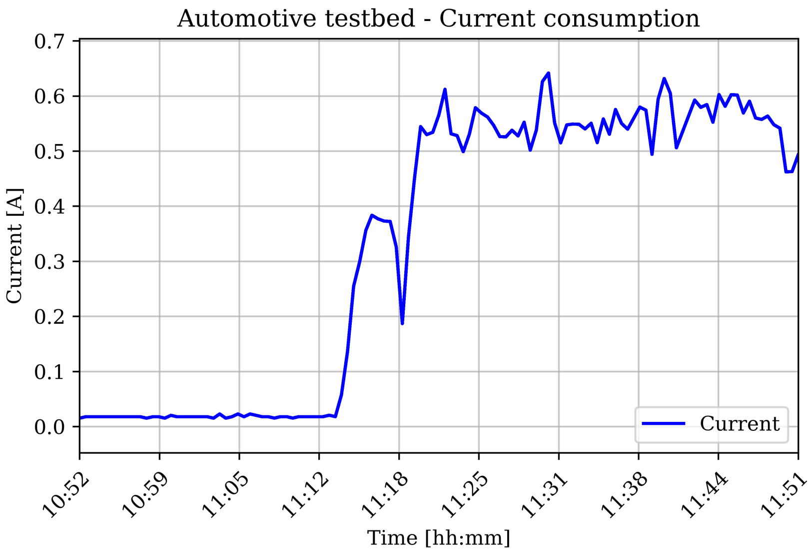

Figure 28: Current car power supply

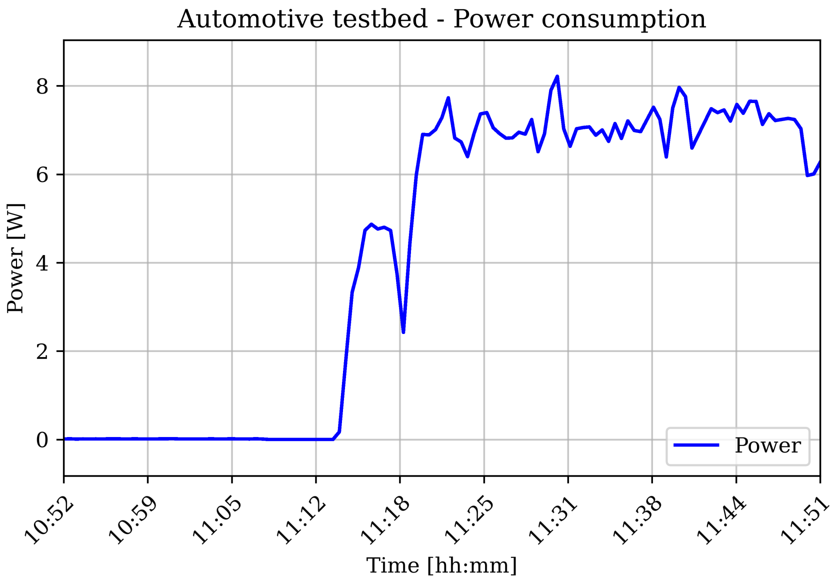

Figure 29: Power consumption of device under test in car

6.2 Considerations on the used 5G network

Within this test, mainly the migration was evaluated. This is discussed in deliverable D4.4 [4]. Even so, for other tests, the connection to 5G NSA networks worked. Within this testbed, a new connection challenge arose. The 5G modem was able to register to the 5G NSA network but could not connect the data channel. Even though the APN and other data connection settings were set correctly. After debugging, it was found that the initial bearer APN was set correctly, but the initial bearer IP configuration had to be limited to IPv4, while the modem default was IPv4 and IPv6. Such complications make the easy deployment of 5G equipment cumbersome. Furthermore, the understanding of what the limitations of a specific network configuration are is often not available to the end user and not easily found in publicly available documentation. This could be even harder when connecting to a private 5G network that is managed by a third party.

7 Conclusions

In conclusion, this deliverable shows the deployments of the 5G-edgePMU and Meter-X device within the TARGET-X project.

For the 5G-edgePMU, first results have been presented. In contrast to the initial planning, the devices have not been deployed in Aachen, Germany, only, but within five European countries. This was a result of additional cooperation within the consortium as well as cooperation with FSTP projects. A first set of measurements has been acquired and analyzed. Starting from well-known events like the power outage in 2025 in Spain and Portugal to more local events like voltage dips due to tap-changing events in local transformer stations. Furthermore, a comparison of the phase and voltage measurements has been done. Finally, the frequency measurements within different European countries have been recorded. Especially for such a comparison, the time synchronization accuracy is necessary.

In cooperation with the automotive vertical, the flexibility of the 5G-edgePMU has been shown by a first-ever deployment of the 5G-edgePMU hardware stack within a car. This first test was not planned in the beginning of the project but gave the automotive vertical the possibility to evaluate a communication use case, and the energy vertical was able to evaluate the hardware and software stack behavior in a mobile environment.

With the Meter-X device, it was shown that energy awareness, construction environments, and robotics environments can be increased. This was done in cooperation with the construction vertical and the robotics vertical. During the data analysis, it was found that within the construction vertical, real-time data analysis could be used to enhance the safety on a construction site. In this particular case, the warning sound of a lifting system can be detected by the Meter-X hardware. Such an event could be forwarded to an edge-cloud environment for further processing. In such a case, the low latency and reliability capabilities of the 5G network could play a major role in the realization. Within the robotics vertical, the movement of a robot arm was evaluated. A key point is that the same Meter-X hardware was used for both tests: the construction site test with multiple kW of power consumption as well as the robotics vertical evaluation with less than 100 W of power consumption. Still, in both cases the Meter-X device produced good results.

Since both devices, the Meter-X and the 5G-edgePMU, share the same software stack and the same 5G user equipment, the conclusions about the 5G considerations are combined. In general, it was found that if the communication is working, the 5G infrastructure was well suited for this use case. The devices were tested in private 5G SA and NSA environments as well as in public 5G networks within 5 European countries and with different providers. The major complication was the initial configuration. The different providers have very specific configurations that sometimes do not match the initial configuration of the SIM cards provided by the provider. In particular, the initial bearer configuration was an issue. In one case the device was unable to register to the network, and in another it was unable to communicate after registration. Debugging such issues is cumbersome for the end user. Therefore, the configuration should be done in an easier way for 6G since it cannot be expected that the end user understands the different stages of connecting to the network. Furthermore, the documentation by the providers should be made more transparent. Based on different internet communities that focus on projects like ModemManager [10] it was found that, e.g., for the initial bearer configuration, it is a choice of the provider to allow any, a set, or a very specific APN. This is especially confusing since this setting is sometimes not the same as the data channel APN setting.

The onboarding process could be optimized. One option is a cross-provider capability of deploying communication configurations to devices while the device is still unprovisioned. For this project, a two-stage process was needed. The device had to be connected via network cable to deploy the 5G configuration, and then the Ethernet cable could be removed and the device was moved in the field. This two-stage setup is time-consuming and complicated to communicate to electricians or distribution network operators. The update of configurations in the field, e.g., because of SIM card changes, needs careful planning. This might be a learning for future 6G standardization, which is already picked up by the AAS developments done within this project.

Full-stack deployment of IPv6. It has been seen that one of the issues with the connectivity was caused by the incompatibility of IPv4 and IPv6 or the capability of the mobile network to only provide one of the two. It should be transparent to the user what underlying IP version is used. Furthermore, the internet is migrating to IPv6. It is difficult to understand why still some mobile network operators or 5G equipment suppliers enforce the use of IPv4 only in their infrastructure. This should be resolved, and a future-proof IP stack should be deployed in all future 6G environments.

Control over private 5G instances is, together with data sovereignty, a key selling point for private 5G installations. With the current deployments, we encountered that the control is sometimes not fully in the hand of the hardware owner and the user interface is focused on basic day-to-day operation. This reaches its limits as soon as one encounters a networking issue. No sufficient debug information is available, and the support is often only reachable via mail. This increases the debugging time drastically and might result in considerable downtime or week-long connectivity issues. Systems that are deployed in a private 5G or 6G environment should come with a minimum of connectivity debug information for the user to directly see and understand.

8 References

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