



ENHANCING ENERGY MONITORING IN CONSTRUCTION AND ROBOTICS WITH PLUG-AND-PLAY SOLUTION METER-X

Manuel Pitz¹, Marit Zöcklein², Lucas Manassés Pinheiro de Souza³, Kedar Rajpathak³, Amon Göppert³, Sigrid Brell-Cokcan^{2 5}, Robert H. Schmitt^{3 6}, Antonello Monti^{1 4}

¹Institute for Automation of Complex Power Systems, ACS, RWTH Aachen University, Germany

²Construction Robotics GmbH, Aachen, Germany

³Laboratory for Machine Tools and Production Engineering, WZL, RWTH Aachen University, Germany

⁴Fraunhofer Institute for Applied Information Technology, FIT, Sankt Augustin, Germany

⁵Chair for Individualized Production, RWTH Aachen University, Germany

⁶Fraunhofer Institute for Production Technology, IPT, Aachen, Germany

Abstract

With the Corporate Sustainability Reporting Directive (CSRD), the EU requests companies to report their greenhouse gas emissions related to energy consumption. Particularly, in verticals with complex technical environments like construction or manufacturing the tracking of individual devices and equipment is challenging. To approach this challenge a versatile and easy-to-use monitoring solution is necessary. Therefore, we propose a plug-and-play energy metering device, Meter-X, with 5G-enabled edge-cloud connectivity for live monitoring that can be installed by non-professionals. The paper describes the hardware and software stack, analyses the measurement accuracy and demonstrates the potential of the device in two field tests.

Introduction

As reported by the Global Alliance for Buildings and Construction of the United Nations Environment Program in the 2022 Global Status Report for Buildings and Construction, 37% of all emissions are related to the construction and operation of buildings (United Nations Environment Programme, 2022). At the same time, the demand for housing in metropolitan areas is increasing and the infrastructure needs maintenance, which in turn requires construction. Therefore, it is essential to improve the sustainability and energy efficiency of existing construction processes in order to drastically reduce the environmental footprint of this sector.

Another vertical that plays a critical role in modern industry is robotics in manufacturing, particularly in automating repetitive tasks such as pick-and-place operations (European Parliament, 2023). These processes demand consistency, speed, and precision that exceed human capabilities, especially at high production volumes (EU-OSHA, 2025). Beyond process optimization, robotic systems offer flexibility, enabling reprogramming for various applications and rapid adaptation to changing market demands and trends in customization (CORDIS, 2025).

However, the rise in robotics and automation in manufacturing has led to increased energy consumption, contribut-

ing to the environmental impact of the industry (Yang et al., 2024). In 2023, the industrial sector, including manufacturing, accounted for approximately 24.2% of global CO₂ emissions (Our World in Data, 2025), with Europe alone contributing nearly 2.5 billion tonnes in 2022 (IEA, 2025). While the adoption of robotics as an automation solution has the potential to reduce CO₂ emissions through increased efficiency (Zhang and Shen, 2023; Li and Tian, 2023), this widespread deployment simultaneously intensifies energy demands, highlighting a critical need for effective energy monitoring and optimization strategies (Vásárhelyi et al., 2023).

The described verticals have a high potential for CO₂ reduction. This is recognized by the EU, where new legislation is coming into effect. Since 1st January 2025 the CSRD requires a first group of large European companies to report their social and environmental information according to the new European Sustainability Reporting Standards (Council of European Union, 2022). In the coming years, the group of companies for which reporting is mandatory will be steadily expanded to also include small and medium enterprises.

For environmental reporting, CSRD distinguishes between different emission categories: Scope 1, Scope 2 and Scope 3, as described in (The Greenhouse Gas Protocol Initiative, 2015). Scope 1 emissions are direct emissions of a company, e.g. through the operation of machinery with combustion engines. Scope 2 emissions are indirect emissions, e.g. caused by the purchase and consumption of electricity. Scope 3 emissions are other indirect emissions that occur along the supply chain. Consequently, to provide adequate information, companies will develop a growing interest in understanding how their emissions are composed. Looking at Scope 2 emissions, these can be tracked via the total electricity consumption. However, this quantity can be insufficient for a differentiated analysis of the individual emitters - on a construction site, for example, this could be individual electrical construction machines or individual industrial robots in a production line. In these cases, a targeted measurement of individual consumption is necessary. The key to this approach is an

easy-to-use measurement device that allows mobile measurement of electrical energy consumption. Using such a device, the equipment used on a construction site or in a manufacturing environment can be analysed for each process individually.

State of the Art

Since the main purpose of the developed device is mobile power measurement, commercially available systems were analysed under this aspect. Furthermore, changes introduced by 5G compared to previous industrial wireless networks were considered.

Energy Monitoring

For the energy consumption and power quality analysis in stationary and mobile applications, different devices are available. This includes platform solutions for finished buildings (Spacewell Energy (Dexma), 2025; DEOS AG, 2025; WAGO, 2025), to monitor the consumption during building operations. Other solutions are specifically designed to monitor power quality metrics and detect issues caused by the power grid. Some examples are Schneider (2025) and Siemens (2025). For in mobile measurements in the field, also different large vendors offer solutions, but mainly target electricians for in-field inspection of equipment. Some examples of products are Fluke (2025) and A.Eberle (2025). The complexity of the consumer structure on construction sites hinders the integration of such monitoring systems. Constantly changing trades and separately or jointly used construction site infrastructure complicates the clear identification of individual, particularly large consumers. Centralized energy monitoring solutions become even more impractical if the installation of sensors and devices can only be done by certified electricians, as this costs extra time and money. Moreover, real-time monitoring devices dedicated to robotics remain scarce. Previous works such as (Paryanto et al., 2014) analysed energy use in a six-axis industrial robot with existing tools, but faced generalizability issues. (Ahmed et al., 2016) and (Fadhil et al., 2021) developed wireless monitoring systems for biped and industrial robots, respectively, though both encountered challenges in data latency and sensor accuracy. Other works focused on energy modeling rather than hardware solutions, such as (Liu et al., 2018) using simulated power data and (Hou et al., 2019) employing a Monsoon power monitor for mobile robots. Although these efforts contribute to understanding robotic energy consumption, limitations in real-time accuracy, scalability, and adaptability underscore the need for more advanced monitoring solutions.

Radio networks in industrial use

With the introduction of fifth generation of the mobile network, there is another alternative to cable-based communication infrastructure for industrial applications. These are particularly necessary wherever the working environment is unsuitable for static cable installations, e.g. on construc-

tion sites or in mobile production facilities. 5G introduced major changes to the core network as well as the spectrum used. In the case of the core network, this results in a simplification that enables the deployment of small 5G networks. Now not only can large vendors offer 5G solutions, but small network-in-a-box solutions can also be deployed. In addition, the new core network of 5G enables features such as quality of service and edge computing. The edge computing solution enables the implementation of custom functionalities near the 5G user equipment. In contrast to this, earlier mobile network solutions relied on routing the traffic to compute infrastructure hosted outside the mobile network. This usually results in the traffic being routed via the internet to the compute resource, and therefore in higher latencies and increased cost for applications with a need for large amounts of traffic. The introduction of private 5G networks challenges technologies such as WiFi. Since private networks must be registered with the local spectrum authority, an overlap with adjacent network segments can be minimized. In contrast to that, with Wi-Fi there is a fixed spectrum range, and all users are allowed to utilize this spectrum as they see fit. In the case of Wi-Fi, this can result in communication issues due to the large number of active networks on the same spectrum as reported by Maldonado et al. (2021). For private 5G solutions, this can increase reliability, which is an important aspect for industrial usage.

Metering Hardware

The Meter-X device is a mobile, weatherproof measurement device that can be used to measure three-phase and single-phase electric loads. It is specifically designed for mobile use and is connected in line with a load under test. In this section, the Meter-X device is described. This includes a discussion of the key design requirements and how they are achieved, and then the hardware and software stack of the device is described. Finally, the expected accuracy is analysed by comparing the device readings with a power analyser.

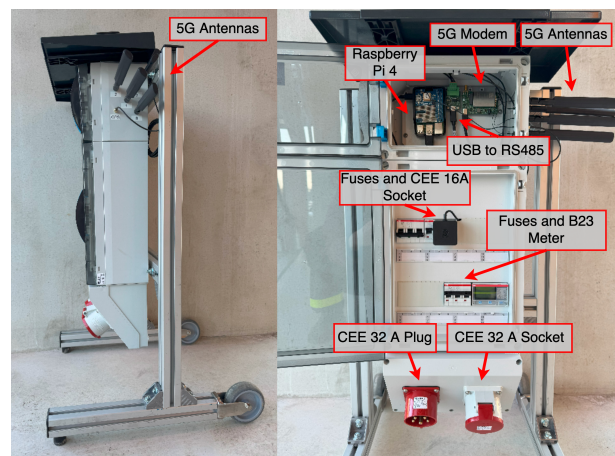


Figure 1: Meter-X Box in side view (left) and front view (right).

Requirements

The key requirements provided by the construction and robotics user during development have been ease of use, standalone operation, edge cloud operation, and weather resilience.

Ease of use: The Meter-X device should be mobile, to allow flexible use on a construction site or in a manufacturing facility. To achieve this, the device is equipped with wheels and a handle so it can be easily moved. Furthermore, it is important to enable non-electricians to connect and disconnect the device. Usually, metering devices are hard-wired in an electrical installation, which results in the need for an electrician when a reconfiguration is needed. In the case of the Meter-X device, the hardware is connected with a common three-phase connector, and thus the device can be used in a plug-and-play fashion. Even though this allows for flexible use, the wiring and fuses still have to be selected according to the maximum rating of the device under test. Besides three-phase loads, single-phase loads are very common, and the Meter-X should be able to monitor such devices, too. This is supported by using adapter cables since the metering device used already supports both single-phase and three-phase operation.

Standalone operation: The Meter-X should be usable without the need for additional communication infrastructure. To achieve this, the device automatically starts a Wi-Fi hotspot on startup. A simple tablet or mobile phone is enough to connect to the device with a web browser and receive the current and historic readings of the devices. Due to its short range, the user must be within around 10 m of the Meter-X device when using the Wi-Fi hotspot. This is not always feasible, and monitoring multiple Meter-X devices would mean that the user must switch the Wi-Fi networks frequently. Still, the onboard Wi-Fi is well suited for direct monitoring, configuration, and debugging of the hardware.

Edge cloud operation: As discussed above, for monitoring multiple devices or on a larger site, the use of Wi-Fi is not feasible. Furthermore, the use of Wi-Fi hotspots on the Meter-X does not allow aggregating the data of multiple devices. Therefore, the Meter-X device should also include the capability to connect to mobile networks. Due to its edge cloud and private 5G capabilities, 5G is chosen for the wireless communication. The integrated 5G modem can either be used with a normal SIM card or programmed with an eSim for reduced deployment overhead. Furthermore, since the M2 module can be replaced, it is also possible to equip the Meter-X with a 5G Redcap device to reduce the cost and energy consumption of the Meter-X. The modem currently used is a Quectel RM520N-GL, which is compatible with the available public and private 5G networks. Using an edge server, multiple Meter-X devices can stream their measurements. This allows for a central supervision of the energy consumption at a specific site.

Weather resilience: Since the Meter-X device is specifically designed for construction sites and manufacturing environments, a key feature is weather resilience. This is

not only needed for the reliable functioning of the device, but also for the safety of the personal using the Meter-X device. To achieve weather resilience, the box is built with a modular IP66-rated enclosure. IP66 means that the device is sealed against dust and can resist water jets. The rating of the whole box is evaluated before deployment by using a water hose.

Hardware

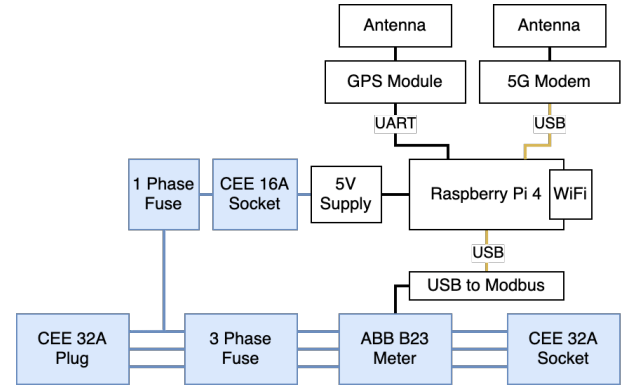


Figure 2: Meter-X hardware schema.

The Meter-X hardware is built around a Raspberry Pi 4 and a B23 313-100 (B23) (ABB, 2025) metering device manufactured by ABB. A schema of the hardware is shown in Figure 2 and the actual built of the Meter-X in Figure 1. The key components in the schema are highlighted in the photo of the built device. For inline power measurement, a three-phase plug (CEE 32A Plug) is used as an input and a three-phase socket (CEE 32A Socket) is used as an output. The device under test is connected to the output and the power supply or power grid to the input side of Meter-X. All connections that are 230 V_{rms} or 400 V_{rms} are marked blue in the schema. In line between input and output is a set of fuses for cable protection and the metering device. The power rating of the Meter-X is defined by the input plug, the output socket, the fuses, the meter, the box, and the cabling used within the Meter-X. The fuses, cabling, socket, and plug can be easily replaced by drop-in replacements with a higher current rating. The maximum current for the Meter-X is defined by the box and the ABB meter used. The enclosure is rated for up to 63 A_{rms} and the meter for up to 65 A_{rms}. This means that the Meter-X can be easily retrofitted from its current 32 A_{rms} configuration to 16 A_{rms} or 63 A_{rms} operation. This results in a power rating of up to 22.08 kW for the current 32 A_{rms} configuration and a maximum power measurement capability of 43.47 kW for the 63 A_{rms} configuration.

For internal electronics, an additional socket is branched off the input. The single-phase socket provides power to the Raspberry Pi and the communication hardware. All other components are supplied and running with 5 V or less and are marked in black within the schema. In the Meter-X, a Raspberry Pi 4 is used, but it could also run based on other single-board computers since the 5G modem as well as the Modbus interface are USB-based and

drivers for Linux are available and independent of the single-board computer used. Only the GPS receiver is currently mounted as a Raspberry Pi HAT, but could be easily replaced with a USB-based version, or removed if the time precision of the 5G network is sufficient. This approach of using mostly USB as interfaces allows for a highly flexible platform where the compute component is not only easily replaceable, but hardware testing and software development can also be done with a more capable computer, and thus test and development cycle times can be reduced. The 5G modem is based on a custom 5G carrier board that allows for USB 3 speeds and can mount M2-based modem modules. In the case of the Meter-X, a Quectel RM520N-GL is used. The interface to the metering device utilizes a USB-to-Modbus adapter. To reduce the size of the hardware, this module was also developed in-house.

Software

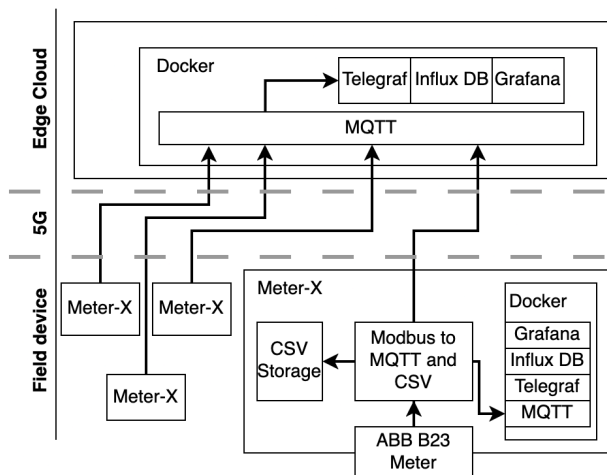


Figure 3: Meter-X software schema.

The software stack of the Meter-X device is built so it can be automatically deployed, which reduces the deployment and administration time. This begins with the automated generation and customization of the Raspberry Pi image files as described in (Pitz et al., 2024). Then, during deployment, the device can be reconfigured remotely using Ansible. With Ansible, software can be installed, configured, and modified on the basis of a so-called playbook. The playbook can be defined specifically for a device or based on device groups. The different steps of configuration, installation, and software modification are defined within so-called roles. A role could be used to install all the necessary software requirements for a 5G modem and to apply the necessary software configuration changes to the system. The software stack is shown in Figure 3. The software stack is divided into three layers. The bottom layer shows the software stack running on the Meter-X device in the field. The second layer depicts the communication channel. Finally, the third layer is the edge cloud infrastructure, which runs the same software stack for data storage and visualization as that running on the field device. The following roles are the most important and most

needed for the basic functionalities of the Meter-X device: Wi-Fi, Grafana, 5G Modem and RS485-reader.

Grafana: The Grafana role includes the deployment of MQTT, Telegraf, Influx DB, and Grafana. MQTT is used as message broker to exchange measurements, then Telegraf receives the measurements sent by the local MQTT server and stores them in an Influx DB. Finally, Grafana can read the measurements from the Influx DB and display them in a Web UI. This stack is deployed using containers. The main advantage is that the same stack can be deployed on an edge server to provide an aggregated view of multiple Meter-X devices, or on the Meter-X device itself to allow for direct supervision of a single device. A screenshot of the Web UI is given in Figure 4. In the screenshot, the symmetric load on all three phases can be observed. This screenshot was taken during the accuracy analysis of the metering device, which is described in more detail later in this paper.



Figure 4: Grafana dashboard showing live data.

5G Modem: The 5G modem role configures the Meter-X to use different QMI-based 5G modems. This includes a script for automatically connecting to a 5G network and the necessary configuration changes to enable the 5G network interface within the operating system.

Wi-Fi: The Wi-Fi role enables a Wi-Fi hotspot that can be used to access the Meter-X device when standing nearby. This includes a device-specific password for Wi-Fi encryption and other necessary configuration changes. Wi-Fi is then automatically started on boot and the user can access the readings instantly.

RS485-Reader: The RS485-Reader is a Python-based program that enables the reading of a Modbus RTU-based device. In the case of the Meter-X this is the B23 meter. The program periodically reads the meter, then forwards the readings to MQTT as well as stores them in a csv file for later download. The program is started automatically when the Meter-X is connected to power.

Accuracy

For measurement acquisition within the Meter-X, a commercial metering device by the manufacturer ABB is used. This is a B23 three-phase direct connected metering device for $220 V_{\text{rms}}$ to $240 V_{\text{rms}}$. This device promises, on the one hand, direct current measurements up to $65 A_{\text{rms}}$ but also accuracies of 1 % in the accuracy class B on the

other. The guaranteed minimum measurement current is given as $250 \text{ mA}_{\text{rms}}$ by ABB. To verify the claims, a test with controllable three-phase loads and a reference power analyser are executed. As loads, three Chroma 63804 Chroma, 2025 were used. For reference measurement, a ZES Zimmer LMG671 (LMG671) (ZES Zimmer, 2025) is used. The Chroma 63804 load can dissipate up to 4.5 kW per phase, resulting in an overall electric load of up to 13.5 kW . At nominal grid voltage of $230 \text{ V}_{\text{rms}}$, this results in up to $19.56 \text{ A}_{\text{rms}}$ per phase in a symmetric load condition. The LMG671 is equipped with L60-CH-B cards for voltage and current measurement. The accuracy given by the LMG671 datasheet is better than 0.1% and therefore sufficient for evaluating the B23 meter precision with 1% accuracy. In the measurement setup, the LMG671 and B23 are connected to the Chroma loads at the same time. Power set points for the Chroma loads are set, then the system is given 10 s to stabilize. In the next step the readings of the LMG671 and B23 are acquired. For the measurements, it was decided to acquire equidistant measurements every 50 W and evaluate active power only. Two scenarios are tested.

First, the fully symmetric load of all three phases, as it is expected with motors or other large three-phase loads, is evaluated. The maximum power per phase is limited by the Chroma load to up to 4.5 kW . The results are given in Figure 5. The plot shows the three phases compared to the error margin given for the LMG671. For evaluation, the load on each phase is varied simultaneously. The load set point is given on the x-axis. The deviation in the measurement of the LMG671 compared to the B23 is calculated for each load set point and is plotted on the y-axis. The result is normalized to the LMG671 measurement and is given in percent. It can be seen that the deviation is well below 1% .

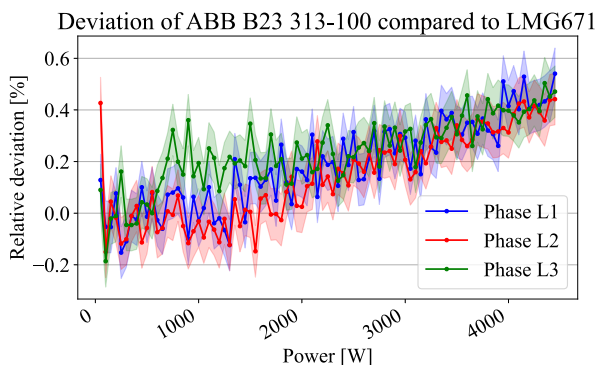


Figure 5: Accuracy of ABB B23 313-100 meter in comparison to ZES Zimmer LMG671 for a symmetric load.

The second test evaluates an asymmetric load condition. This condition appears if multiple single-phase loads are connected on one phase of the power grid. In this case, two of the Chroma loads are connected in parallel to one phase, the other phases of the Meter-X are disconnected. This test is repeated for each phase individually. The maximum power is limited by the cabling and fuses used. Therefore, the test is run up to 6.8 kW , resulting in a maximum of

$29.5 \text{ A}_{\text{rms}}$. The plot follows the schema of the first test case except that now three separate tests are compared. The results of the asymmetric test are shown in Figure 6. It can be seen that for higher load values, the B23 deviates more than 1% from the LM671. These results have to be taken into account when interpreting the measurement data of the Meter-X, but it should also be mentioned that this is a worst-case load scenario for the B23 meter.

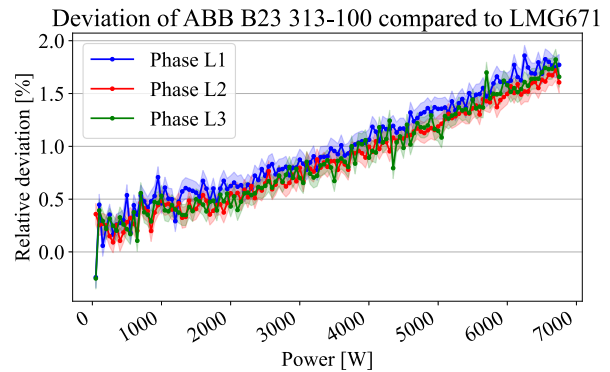


Figure 6: Accuracy of ABB B23 313-100 meter in comparison to ZES Zimmer LMG671 for an asymmetric load.

Field Test Deployments

For field testing, Meter-X was deployed in two different experimental setups for the verticals construction and manufacturing. Each experimental setup mimics the application of the metering device in a typical process in one of the verticals.

Robotics

The setup, shown in Figure 7, used a Kinova Gen 3 robotic arm with 7 degrees of freedom (DoF) (Kinova, 2025), a Robotiq 2-Finger Gripper (Robotiq, 2025), and an interface based on the Robot Operating System (ROS) for control and motion planning.

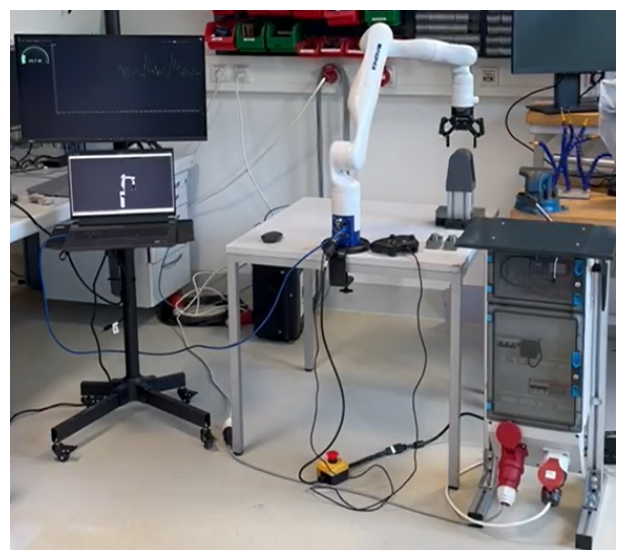


Figure 7: Setup of a pick-and-place test with Meter-X.

Customized weights (Figure 8) were used to systematically

assess energy consumption under varying payloads. The setup also included a customized holder as also shown in Figure 8 designed to be easily manipulated by the robot's gripper, with a base mass of 1.68 kg and four removable weights, each weighing 0.67 kg. When fully assembled, the total weight reached 4.37 kg.



Figure 8: Customized weights used in the demonstration.

The experiment involved repetitive pick-and-place tasks performed in a chosen loop of 99 cycles (to a few hours without interruption). During each cycle, the robot's end effector traveled between two points along two distinct paths, back and forth, following predefined trajectories. Real-time energy consumption data was collected using the Meter-X device, revealing the impact of factors such as payload mass and motion patterns on energy monitoring. The process was designed to operate continuously, regardless of the payload configuration. This flexibility allowed live adjustments to the payload, with options to leave the gripper empty, attach only the weight-holder, or add varying weights to the holder. These variations in payload conditions directly affected energy consumption, which was displayed in real time on the monitoring dashboard. For instance, it is expected that less energy consumption will occur when the robot operates with no payload, while adding the holder and incrementally increasing or decreasing weights can result in observable variations in power usage.

Construction

To gain more insight into individual consumers on the construction testbed, for the experimental setup, a common construction material lift GEDA 1200 Z/ZP was chosen. The material lift does not possess any built-in sensors for energy monitoring. Without dedicated metering, only the maximum total power consumption of the lift's transport operations could be estimated from the data sheet and the operating time. For the test, Meter-X was connected inline to the material lift's power supply as shown in Figure 9. Next, the operator sent the lift upwards to the first level and afterwards down again to the ground level. During lift operations, the power consumption of all three phases were recorded with a sampling rate of 1 s. The recorded data was visualized on a Grafana dashboard for live monitoring and stored for later offline analysis.

Results

In this section, the first results and findings are discussed separately for each vertical. As this is a proof of concept for a flexible monitoring platform, no in-depth analysis of a process has been done yet.



Figure 9: Experimental setup for the power measurement with the Meter-X device connected to the material lift.

Robotics

The results of a first test as described in the Experiment section are given in Figure 10.

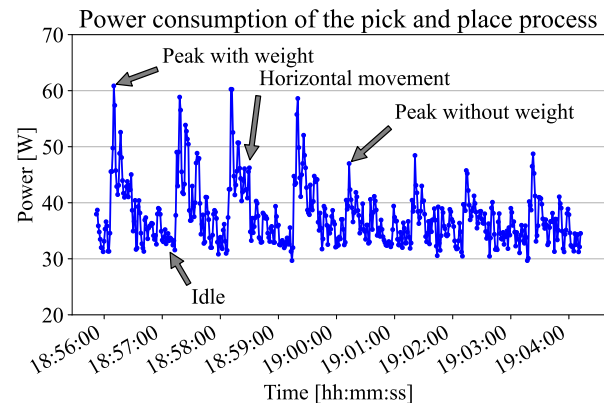


Figure 10: Power consumption for different weights.

It can be clearly seen that the maximum power peak strongly depends on the attached weight. The first four runs used a weight and the second four runs did not. The peak power with a weight of around 60 W is marked in the plot with an arrow, as is the peak power without a weight. In the trajectory, we observe the start of the lifting operation as the first power spike. The robot then moves on one height level, creating a small plateau (marked as horizontal movement). Finally, the robot arm sets the weight back on the table and stops moving for a moment (idle), observed as a low spot before the next cycle begins with another peak. Additionally, the plot reveals alternating robot paths, with higher peaks for rectilinear paths and smaller peaks for triangular paths, allowing the monitoring of trajectory patterns. For these measurements an uncertainty of less than 0.5 % is expected as derived in Figure 6.

Construction

During the test operation, the lift's recorded power consumption showed a similar trajectory for all three phases. When ascending, the lift consumed approximately 1.2 kW

per phase as shown in blue, red, and green in Figure 11 between timestamps 12:06:09 and 12:06:20. When stopping in a fixed position on the first floor, the lift does not consume significant electrical energy. When starting to descend, the power consumption of the lift peaks shortly at approximately 1.2 kW before turning negative. When negative, the three phases behave differently. Phase 1 shows the strongest peak with approximately -200 W, followed by phase 2 with approximately -155 W. The smallest negative peak was observed for phase 3 with approximately -115 W. For these measurements an uncertainty of less than 0.7 % is expected as derived in Figure 5.

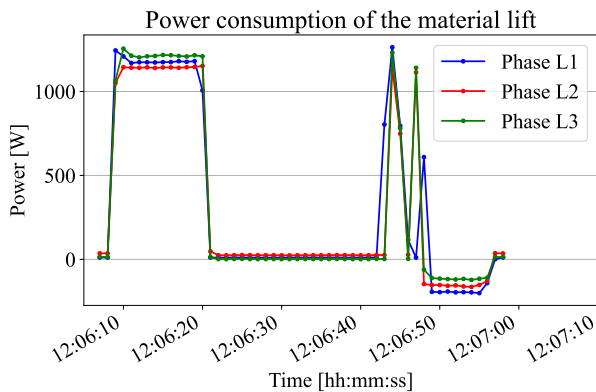


Figure 11: Power measurement with Meter-X at the construction lift. The three phases are indicated in red, green, and blue.

All measurement data displayed was published as a dataset on Zenodo Manuel Pitz (2024).

Conclusions and Outlook

The Meter-X device has been shown to be a versatile device, capable of measuring in applications with single-phase loads of less than 100 W, as well as for three-phase loads up to the 7 kW range. The evaluation of the used B23 meter has shown that this device is well-suited for low-power measurements, with better accuracy than 1 %. Furthermore, asymmetric loads have been shown to result in errors larger than 1 %. This must be taken into account when interpreting the field measurements.

The 5G connection between the construction testbed and an edge server was established successfully using a private 5G network. The measurement data was sent lossless by Meter-X from the construction testbed to the edge server and was aggregated with additional measurements from other metering points of a building. This allows for a comparison of the energy consumption while the results can be accessed easily from within the 5G network.

The evaluation of the robot arm's motion demonstrated that the Meter-X device provides sufficient accuracy to detect differences in the weight lifted by a small robotic arm in an automation scenario of a pick-and-place task. Notably, this was achieved without any modifications to the Meter-X device, which was configured for 32 A_{rms} three-phase operation.

The first test deployment of Meter-X on the construction

testbed has already provided further insight into the power consumption of the construction machinery used. Already during the test through live data monitoring and in the later data analysis, the team discovered that, while for ascending the lift consumed power as expected, for descending the power consumption of the lift was negative. Consequently, the lift feeds back energy into the power grid when it descends. This means that any descending transport does not add to the overall power consumption of construction sites. This demonstrated that the use of measuring devices such as the Meter-X can contribute to greater transparency and awareness of energy consumption on construction sites.

In future work, the device should be enhanced software-wise to allow for higher time resolution. This would enable an even more in-depth review of a process and the different process steps. In addition to energy monitoring, the edge server could be used to implement consumption-specific services such as predictive maintenance or job-site supervision. Furthermore, additional measurement campaigns in the construction and robotics should be executed and analysed. The results would show energy consumption of different types of equipment in different conditions and can allow for a more targeted optimization of operations and billing. Finally the integration of the Meter-X measurements in real time monitoring and operations control for construction and manufacturing should be done, for example the integration of energy monitoring in real time path planning and task scheduling.

Acknowledgments

This work has been carried out in the TARGET-X framework, a project funded by the Smart Networks and Services Joint Undertaking (SNS JU) under Horizon Europe. The views expressed are those of the authors and do not necessarily represent the project. The consortium is not liable for any use that may be made of any of the information contained therein.

References

- ABB (2025). B23 313-100. <https://new.abb.com/products/2CMA100170R1000/b23-313-100>. Accessed: 2025-01-28.
- A.Eberle (2025). Pq-box 300. [Online]. Accessed: 2025-04-28.
- Ahmed, I., Aris, I. B., Marhaban, M. H., and Ishak, A. J. (2016). Wireless energy monitoring in biped robot based on xbee rf module.
- Chroma (2025). Chroma 63804. https://www.chromaate.com/de/product/ac_dc_electronic_load_63800_series_157. Accessed: 2025-01-28.
- CORDIS (2025). Robotic solution to flexible production lines. Community Research and Development Information Service (CORDIS). Accessed: 2025-01-24.

- Council of European Union (2022). Directive (eu) 2022/2464 of the european parliament and of the council. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464>.
- DEOS AG (2025). Energy monitoring. <https://www.deos-ag.com/en/solutions/energy-monitoring/>. Accessed: 2025-02-11.
- EU-OSHA (2025). Advanced robotics in injection moulded and extruded plastic. Technical report, European Agency for Safety and Health at Work (EU-OSHA). Accessed: 2025-01-24.
- European Parliament (2023). Analysis exploring risks and opportunities linked to the use of collaborative industrial robots in europe. Technical Report PE 740.259, European Parliamentary Research Service (EPRS). Accessed: 2025-01-24.
- Fadhil, J., Faeq Hussein, A., Abd, L., Quadr, L., and Sabry, A. (2021). Wireless monitoring of power consumption for industrial robot during a pick and place task for predictive maintenance. *Journal of Theoretical and Applied Information Technology*, 99.
- Fluke (2025). Fluke 1732. [Online]. Accessed: 2025-04-28.
- Hou, L., Zhang, L., and Kim, J. (2019). Energy modeling and power measurement for mobile robots. *Energies*, 12(1).
- IEA (2025). Emissions in europe. International Energy Agency (IEA). Accessed: 2025-01-24.
- Kinova (2025). Gen3 robots. [Online]. Accessed: 2025-01-24.
- Li, X. and Tian, Q. (2023). How does usage of robot affect corporate carbon emissions?—evidence from china’s manufacturing sector. *Sustainability*, 15(2).
- Liu, A., Liu, H., Yao, B., Xu, W., and Yang, M. (2018). Energy consumption modeling of industrial robot based on simulated power data and parameter identification. *Advances in Mechanical Engineering*, 10(5):1687814018773852.
- Maldonado, R., Karstensen, A., Pocovi, G., Esswie, A. A., Rosa, C., Alanen, O., Kasslin, M., and Kolding, T. (2021). Comparing wi-fi 6 and 5g downlink performance for industrial iot. *IEEE Access*, 9:86928–86937.
- Manuel Pitz, Lucas Manassés Pinheiro de Souza, M. Z. (2024). Power consumption measurements at vertical testbeds. Dataset on Zenodo. <https://doi.org/10.5281/zenodo.14802053>.
- Our World in Data (2025). Greenhouse gas emissions by sector. Our World in Data. Accessed: 2025-01-24.
- Paryanto, P., Brossog, M., Kohl, J., Merhof, J., Spreng, S., and Franke, J. (2014). Energy consumption and dynamic behavior analysis of a six-axis industrial robot in an assembly system. *Procedia CIRP*, 23:131–136.
- Pitz, M., Wege, F., Eiling, N., Vogel, S., Bareis, V., and Monti, A. (2024). Automated deployment of single-board computer based grid measurement and co-simulation equipment. In *2024 Open Source Modelling and Simulation of Energy Systems (OSMSSES)*, pages 1–6.
- Robotiq (2025). Adaptive grippers: 2-finger gripper. [Online]. Accessed: 2025-01-24.
- Schneider (2025). Pm8000. [Online]. Accessed: 2025-04-28.
- Siemens (2025). P850. [Online]. Accessed: 2025-04-28.
- Spacewell Energy (Dexma) (2025). Spacewell energy platform. <https://www.dexma.com/what-is-spacewell-energy-platform-by-dexma>. Accessed: 2025-02-11.
- The Greenhouse Gas Protocol Initiative (2015). A corporate accounting and reporting standard, revised edition. <https://ghgprotocol.org/corporate-standard>.
- United Nations Environment Programme (2022). 2022 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. Technical report, Global Alliance for Buildings and Construction.
- Vásárhelyi, J., Salih, O. M., Rostum, H. M., and Benot-sname, R. (2023). An overview of energies problems in robotic systems. *Energies*, 16(24).
- WAGO (2025). Wago energy management. <https://www.wago.com/global/energy-management>. Accessed: 2025-02-11.
- Yang, X., Zhu, N., Lv, J., and Luo, S. (2024). Industrial robot applications’ effects on consumption of energy and its spatial effects. *Environment, Development and Sustainability*, TBD:TBD.
- ZES Zimmer (2025). Zes zimmer lmg671. <https://www.zes.com/de/Produkte/Praezisions-Leistungsmessgeraete/LMG671>. Accessed: 2025-01-28.
- Zhang, L. and Shen, Q. (2023). Carbon emission performance of robot application: Influencing mechanisms and heterogeneity characteristics. *Discrete Dynamics in Nature and Society*, 2023(1):4380575.