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Consumption Monitoring System for Demand Base Energy Supply Innovation - Prototyping EMAK (Energy Management Data Center) at ZalaZONE

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Witnessing the importance of energy efficiency and sustainability, there is a definite need for modular, standard-component-driven, vendor-independent energy management systems. A system with real-world scenarios capable of driving practical experiences and incorporating AI enhancements would serve as a base for Energy Community platforms that can include even small energy consumers and producers. A multi-year R&D pilot project was established to create a unique Energy Community model using the industrial environment at ZalaZONE, the Hungarian Vehicle Proving Ground in Zalaegerszeg. The main novelty of the project and the study is the unique setup of parallel R&D work from the academic and practitioner's view and the unique data per second of online, real-time data collection methodology and structure. The EMAK platform uses micro transactional data processing enabled to collect, aggregate, and analyse data every second, build more efficient consumption, and balance models with machine learning enhancements. The onsite research includes three buildings (five building parts) with 200 sensors, 5 data aggregators, energy meters, internal and external heat and humidity meters, and weather stations, measuring electricity consumption, heat, humidity, wind, sun radiation, and more environmental data. That network and the backbone software set measure, aggregate, display, and monitor 867 data points, transmitting 8,600,000 data points daily. Although the project lasts till 31st December 2025, the work has already contributed to several key findings within the ecosystem.

1. Introduction

Energy is a driving force globally, supporting residential life and industrial operations and serving as a key element of economic development (Liu et al., 2022). The main components of total energy consumption include electricity, transportation, heating, cooling, and industrial processes (Ritchie et al., 2020). According to Statista data, global primary energy consumption has increased from 397.28 EJ in 2000 to 604.04 EJ in 2022, with only 2 y (2009 and 2020) showing negative year-over-year growth (Statista, 2024a). Global consumption is projected to grow, reaching 760 EJ by 2050 (Statista, 2024b). As there is no infinite resource, and energy consumption is critical, sustainability in the energy sector has the highest priority. The significance of this topic is highlighted by the increasing number of high-rated publications examining the relationship between energy consumption and sustainability. As of June 1, 2024, a Scopus search using the Advanced Query: "TITLE-ABS-KEY (energy AND consumption AND sustainability)" for documents on this subject yielded 20,787 results, highlighting the growing academic interest and research focus. In the last decade, the number of publications in this field has grown at an average year-on-year rate of 21 %, as shown in Table 1. This growth rate is based on a linear forecast for 2024, extrapolated from the figures for the first five months.

There is no debate that, for sustainability reasons, a global energy transition must be achieved, specifically through the decarbonisation of energy systems (Goldthau et al., 2020). Although academic and business research and applied technologies aim to create comprehensive energy measurement and management systems, there are a few instances of seemingly successful installations (Zia et al., 2018).

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Table 1: Publications based on Scopus result list, performed on 1st June 2024, source: authors' edit

Year	Documents	YoY Change
2024*	4,490	40 %
2023	3,209	29 %
2022	2,482	17 %
2021	2,115	28 %
2020	1,654	26 %
2019	1,310	16 %
2018	1,134	7 %
2017	1,060	15 %
2016	922	12 %
2015	823	15 %
2014	715	base

However, significant challenges remain, such as vendor lock-ins (Ahmad et al., 2016), the creation of suitable hardware-software solution combinations (Guldner et al., 2018), and the secure transmission (Potlapally et al., 2003), storage and analysis of large volumes of data (Mathew et al., 2015). To establish a demand-based energy supply system, it is essential first to measure usage through a consumption monitoring system (Srithapon and Månsson, 2023).

This study introduces a significant, several-year-lasting real-life R&D project at a unique location, ZalaZONE, the Hungarian Vehicle Proving Ground in Zalaegerszeg, Hungary. ZalaZONE offers extensive scenario-based onsite probing and testing opportunities for the world's largest automotive and vehicle-type production companies. With a significant and growing energy demand and plans for installing green energy (solar, wind, biomass), and later creating an Energy Community system, ZalaZONE identified the need for an appropriate Energy Management System. After several months of preparation, it was concluded that the market does not offer a system that can ensure rapid and online data accessibility, scalability of the hardware and software system, and a cost-effective response to include existing infrastructure elements into the whole platform. The potential impact of this project on the energy management and industrial sectors is significant.

2. Literature Review

Scopus has nearly 21,000 academic works in its database for the keywords energy, consumption, and sustainability. Since this paper focuses on the practical realisation of an energy consumption monitoring system, the literature review was narrowed to the most relevant results. For the keyword "energy consumption monitoring*" as of 1st June 2024, the following results were found in Google Scholar: 6.840 results, Scopus: 451 results, Web of Science: 265 results. Academic literature predominantly covers overviews (Rathor and Saxena, 2020) and strategies (Mariano-Hernández et al., 2021), with some papers detailing special working systems like home energy systems (Zafar et al., 2020). The direct cost associated with energy overuse is substantial, but several other impact elements can also be identified (Xiang et al., 2022). Another significant approach is the social cost of carbon (SCC), predicting how today's CO_2 emissions will affect future economic outcomes (Rode et al., 2021). Implementing and actively using energy-efficiency measures can significantly result in long-term reductions in electricity usage, mainly when these measures do not rely only on human factors (Clark et al., 2019). The proper energy usage model can lead to significant energy savings and pollution reduction (Neveux et al., 2013). Based on the latest set of high-relevance publications, the five main characteristics of a modern energy consumption monitoring system have been recognised as follows in Table 2:

Table 2: Main characteristics of a modern energy consumption monitoring system, authors' edit

Characteristics	No. of Scopus articles
a) User-friendly customisable interface	823
b) Real-time data collection and analysis	784
c) Big Data reporting, analysis and prediction capabilities	450
d) Customizable alerts and notifications	202
e) Interoperability and Open Access	115

a) User-friendly customisable interface. In addition to professionals, standard users from facility management or business levels must understand and interpret the results produced and visualised by the energy consumption system (Fletcher and Malalasekera, 2016). Therefore, the system must feature an easy-tonavigate and customisable interface (Trejo-Perea et al., 2013). For instance, a dashboard with visual aids such as graphs and charts can effectively summarise energy usage results and trends.

b) Real-time data collection and analysis. The system offers real-time data transfer, enabling immediate monitoring of energy consumption and establishing a demand-based energy supply approach. Such online and sufficiently managed functionality helps identify and manage usage patterns, examine potential inefficiencies, and provide actionable decision points (Francisco et al., 2020).

c) Big Data reporting, analysis and prediction capabilities. Due to the large and continuously collected data, classical cloud-based Big Data recording, management, and storage capabilities are essential for energy consumption systems (Cakir et al., 2021). Leveraging raw and aggregated data enables precise, self-learning analysis and enhances predictive capabilities, leading to more accurate and seamless forecasting (Zhou and Yang, 2016).

d) Customizable alerts and notifications for autonomous manageability. System administrators and given users can define notifications and alerts for different measures, time periods, and matching or mismatching set thresholds. This functionality recognises unusual consumption activities and patterns, allowing for a proactive approach to managing and reducing energy waste and providing near-real-time support (Alrikabi et al., 2020).

e) Interoperability and Open Access. The system should be capable of interconnecting with a standard range of hardware and software elements, creating a platform view of energy consumption (Starace et al., 2022). Management should extend beyond access levels to import and export data and information. This ensures further development possibilities using Open-Access technologies (Collin et al., 2017).

While the existing literature has a growing coverage of both the theoretical and some practical aspects of energy consumption monitoring systems, there is a notable research gap in academically examining, analysing, and publishing the results and future usability of such pilot systems, which includes all the five above listed modern energy monitoring system features. According to the authors' research and knowledge, this is the first study academically following and showcasing such an R&D project in detail, even from the planning and execution phase of the activities.

3. Project and Method Overview – EMAK

After a comprehensive review of current literature, an extensive search, and using the authors' latest knowledge, ZalaZONE, the Hungarian Vehicle Proving Ground, is the pioneering Vehicle Proving Ground globally to plan, develop, and implement a complex energy management system for its own operations. The EMAK system, as the pivotal backbone for the energy consumption measurement platform, is strategically designed to enhance and expand ongoing innovative research and development within the domains of the circular economy and Energy Community modelling. ZalaZONE Energy Management System is being developed as part of a dedicated research and development project to establish an Energy Community pilot in a real-world operational setting. This initiative targets integrating renewable energy sources, continuous energy consumption monitoring, circular economy principles, Energy Community operations, and the incorporation of Building Information Modelling (Valinejadshoubi et al., 2021). ZalaZONE, functioning as an established Innovation Ecosystem, is dedicated to creating and advancing a sustainable model in collaboration with the ZalaZONE Industrial Park and various industrial and governmental stakeholders (Hary et al., 2023). Initiated on February 1, 2023, the project is scheduled for completion by December 31, 2025. The main physical parts of EMAK are shown in Figure 1.

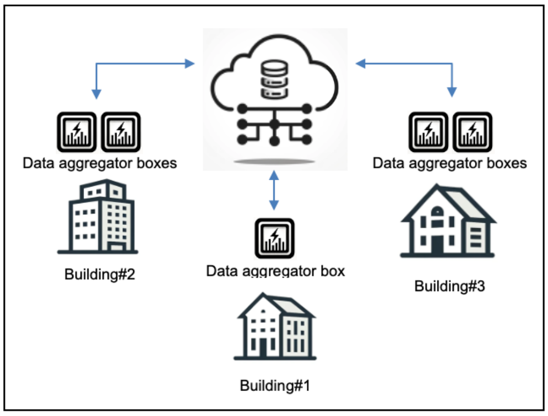

Figure 1: EMAK simple structure, source: authors‘ edit

The construction of the physical Smart Grid infrastructure is organised into three primary stages, culminating in a Community Energy Consumption type system for internal energy usage and cost management. All those efforts were implemented to integrate innovative technology solutions into a working live model to enhance energy efficiency and sustainability within the operational framework. The energy consumption monitoring system includes sensors, data transfer communication methods, central data aggregator boxes, and a central cloud infrastructure managing the operations of the central software solution, storing and aggregating the data, and providing the resources for the web-based visualisation and control applications.
Decided to run a practitioner and academic initiative within the EMAK project, the planning period included not only the logical and physical review of existing architectural and engineering documentation for selected buildings and energy consumption units but also It has also focused on setting up a research environment where data are retrieved, gathered, analysed also for further scientific works and initiatives. To maximise the results the systems can produce, the following directives were implemented:
a) Include at least three different types of buildings in the measurement pool
b) Measurement of equipment and machines that at least add up to 80 % of the electricity consumption
c) Measure in every main area the internal heat and humidity, and external heat, humidity, pollution, sun power
d) Ensure that all system components are capable of data per second collection
e) Ensure that all communication connections are capable of online, real-time data transaction
g) Ensure that data structure supports Big Data and AI (machine learning) data processing and analysis.

To meet the above criteria, the project team has created different scenarios and evaluations for the optimal utilisation of constrained resources. At the same time, the main aim remained the same from the project initiation: to enhance the overall efficiency and effectiveness of the future Energy Community system. The design and construction work plan for installing the sensors, data acquisition boxes, and communication units has been set up to minimise structural intervention. This approach served three purposes. The first goal was to optimise the allocation of resources; the second goal was to minimise potential external dependencies; and the third was to optimise the maximum coverage of available data collection. The principal aim was to increase the total efficiency of the installation process. Following the multistage design process and finalisation of the placement plan, several issues were uncovered during the onsite installation, which will be summarised as lessons learned in the conclusion section. Despite all the challenges, the project deadlines were maintained, and the first phase of the EMAK prototype was completed and delivered on time.

Table 3: Midterm results from EMAK operations, authors' edit

Platform's informative data	Possible and examined root causes
a) One building's HVAC system energy consumption levels are following the outside temperature value lines with a very low latency	Thermal insulation problems Issues with the extended window surface sun protection Issues with the programming of the thermometers
b) Despite the same thermo setup, given building shows high temperature and low temperature in different zones at the same time	Human behaviour experience (open windows even after closing) HVAC's built-in programming is not capable to offer sufficient balancing of performance in a certain setup
c) Unutilized usage of electricity consumers	Human behaviour experience (unused equipment left on, lighting left on after closing)
d) Untypical and unknown drop of the network during data sending and retrieval	Third-party equipment installation and operational setup creating radio signal interferences

4. Results and discussion

Using the integrated platform of installed sensors, this system placed data aggregator boxes, communication networks, local firmware, and central control software, collects, transmits, aggregates, and displays data from 200 measured sensors across 867 data points. This robust setup processes approximately 6,000 data items per minute and accumulates around 8,640,000 data points daily. According to the project plan, the primary internal data collection pilot period will extend until the third quarter of 2024. As this is a specialised prototype operation, starting from the initial receipt of live data, this period is dedicated to understanding the operational elements of the system, identifying and addressing any deficiencies or areas for improvement, and documenting operational characteristics. The definite plan was to collect as many insights about the system's performance as possible to ensure its reliability and scaleability before further deployments. Processing and interpreting such

a large volume of data with AI tools provides an excellent opportunity to discover, confirm, or refute operational correlations, uncover and investigate non-trivial relationships, and draw conclusions (Himeur et al., 2021).
Even in the currently running project phase, there were several findings revealed that would have remained undiscovered without the system's data, detailed in Table 3. As shown in the information provided by the platform, some indicated measurements and situations generated immediate attention at operational and management levels. Having such occurrences, the related technical teams have created a root cause analysis and examined the validity of the possible issues. Given the platform's extended reporting and visualisation capabilities, having a data-per-second base collection and monitoring system with customisable visuals and reporting capabilities helps identify non-trivial connections between usage and consumption. When backed up with machine learning capabilities beyond optimisation of energy management utilisation, such a system has a strong potential to discover further non-trivial misusages, non-standard operational patterns, and third-party issues.

5. Conclusion

The significance of the ongoing research work with the EMAK R&D project is very promising, seeing how it definitely serves scientific and business purposes simultaneously. That mixture of both worlds offers a joint and strengthened cooperation between market players and the university environment, of which success has already been proven via the midterm results presented formerly. The current status, documented performance, and experiences with the implementation and operations of the EMAK system demonstrate significant proven opportunities not only for actual beneficial results but for future extension and serve as a base for similar projects. It is an essential element of the process that the experiment has been built upon to incorporate the most relevant innovation capabilities and features that the field of energy consumption systems and Energy Communities has recently represented. By the time of this research, the collected data from the 200 sensors have achieved a number of almost 2,000,000,000 energy metrics and environmental data, enabling the project team to reveal trivial and non-trivial relationships and root causes like building and construction challenges, operational challenges, human behaviour experiences, and equipment issues. The results indicate that establishing a foundational model backed up by Big Data analytical capabilities within the framework of a future Energy Community platform is achievable in a relatively short period using commercially available components. The future implementation of advanced AI algorithms will highly contribute to the system's ability to provide actionable insights, optimise energy usage, and predict future consumption.
The research's practical limitations come from the project scope and coverage. EMAK is constructed to include only three buildings (having a total of five different building parts) within a given area, with a given set of 200 sensors and data processing capabilities, and this study only contains the first phase results. Big Data and AI analysis procedures will only start in the second phase, which is expected to discover more interconnected operational, technical, and human opportunities to improve and implement in order to optimise energy management practices. For future research, the potential usage and future extension possibilities of Smart Grid technologies and the Energy Community model should be investigated further by combining theory and practice.

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