

SMART ELECTRICITY, WATER, AND GAS METERING SYSTEMS FOR SINGLE-FAMILY HOUSES IN LATVIA

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Abstract. The study examines the performance and analytical potential of integrated smart electricity, natural gas/biomethane, and water metering systems in a single-family house under Latvian climatic conditions. The analyzed building is a 100 m², single-story, insulated dwelling heated by a natural gas/biomethane boiler, representing a typical residential configuration. High-resolution consumption data were collected and analyzed to assess seasonal patterns, system reliability, and cross-utility interactions. The results demonstrate data availability above 95 % for all utilities, confirming the technical feasibility of integrated smart metering. Clear seasonal electricity and gas consumption profiles were identified, with strong heating-driven variability. Correlation analysis reveals significant coupling between electricity and gas consumption during the heating season, as well as a measurable linkage between gas and water use related to domestic hot water preparation. The findings confirm that integrated multi-utility smart metering provides substantially greater analytical value than isolated systems. The study contributes empirical evidence supporting holistic residential resource monitoring and informs future smart energy system deployment in cold-climate regions.

Keywords: *smart metering; electricity consumption; natural gas; biomethane; water consumption; residential energy systems; Latvia.*

INTRODUCTION

The rapid digitalization of energy and utility systems has become a central pillar of the European Union's (EU) strategy to enhance energy efficiency, resource conservation, and consumer empowerment. Within the framework of the European Green Deal, the Clean Energy for All Europeans package, and the EU Digital Strategy, smart metering systems are recognized as a key enabler for transparent, efficient, and sustainable management of electricity, gas, and water resources. By providing high-resolution consumption data and enabling bidirectional communication between end-users and utilities, smart metering technologies support demand-side management, energy savings, and improved system reliability

across residential and municipal sectors (Savickis et al., 2020a; Kippke Salomón et al., 2025; Koukouvinos et al., 2025).

At the EU level, large-scale deployment of smart electricity meters has progressed significantly; however, the integration of multi-utility smart metering, covering electricity, gas, and water within a unified system, remains uneven (Kamstrup, n.a.). Many Member States still treat these utilities separately, limiting the potential benefits of cross-sectoral data analysis and coordinated resource management. The EU has increasingly emphasized the importance of integrated approaches that combine digital infrastructure, consumer engagement, and data-driven decision-making, particularly in the residential sector, which accounts for a substantial share of final energy consumption (Vitiello et al., 2022). Implementation of such a common system would also encourage further development of smart cogeneration and trigeneration systems in the EU residential sector (Snegirjovs & Klavs, 2024).

In Latvia, the transition toward smart energy systems is progressing, yet challenges remain, especially at the level of single-family housing. While smart electricity metering has already been implemented (ST, 2023), smart gas and water metering (PTAC, 2020) systems are less widespread, and integrated multi-utility solutions are rare (Bode & Jansons, 2020). Latvian residential buildings are characterized by cold climatic conditions, pronounced seasonal heating demand, and, to some extent, reliance on natural gas/biomethane for space heating and domestic hot water. These characteristics make Latvia a particularly relevant case for studying the benefits and limitations of smart metering systems under real operating conditions.

Single-family houses represent a prominent segment of the Latvian housing stock and exhibit diverse consumption patterns driven by occupant behavior, heating system operation, and seasonal variability (Welikala et al., 2025). Despite their significance, empirical research on integrated smart electricity, water, and gas metering systems at the single-household level in Latvia remains limited. This research study attempts to bridge this gap by providing a detailed case study of a modern, insulated, single-story residential building equipped with a natural gas/biomethane boiler, representing an average Latvian household.

This study aims to evaluate the technical performance, operational reliability, and analytical potential of integrated smart electricity, water, and gas metering systems for a single-family house in Latvia. The study seeks to assess how high-resolution consumption data can improve resource transparency, support efficiency improvements, and enable a better understanding of interdependence between different utility flows at the household level.

The study hypothesis is that integrated multi-utility smart metering systems provide significantly greater informational and operational value than isolated single-utility metering by enabling comprehensive consumption profiling, improved anomaly detection, and enhanced user awareness, particularly in heating-dominated residential buildings. It is further hypothesized that such systems can support more informed energy and resource management decisions even without active control interventions.

To address the aim and test the hypothesis, a structured methodological approach is applied. The methodology is based on a case-study framework that combines technical system design, continuous data acquisition, and quantitative data analysis. Smart meters for electricity, gas, and water are integrated through a central data gateway, enabling synchronized monitoring with varying temporal resolutions. The research employs time-series analysis, load profiling, and correlation analysis to examine consumption dynamics, seasonal effects, and interactions between utilities. User interaction with consumption data is also considered when assessing behavioral impacts.

The research questions for the study are formulated as follows:

- How does integrated smart metering of electricity, gas, and water perform in terms of data reliability and temporal resolution in a Latvian single-family house?
- What are the characteristic seasonal and diurnal consumption patterns of electricity, natural gas, and water in an insulated 100 m² residential building?
- What correlations exist between electricity, gas/biomethane, and water consumption during the heating season, and how are they influenced by outdoor temperature?
- How can integrated multi-utility smart metering data be used to identify operational inefficiencies and support improved residential energy management?

The study limitations primarily stem from the single-building focus of the study, which constrains the statistical generalizability of the findings. Consumption patterns are influenced by occupant behavior, which may vary over time and is not fully controllable within the research design. Additionally, external factors such as weather variability and communication network reliability may affect data completeness. But despite it, the selected methodology provides high-resolution insights and establishes a replicable framework applicable to similar residential contexts in Latvia and other regions with comparable climatic and infrastructural conditions.

1. METHODOLOGY

The study applies a structured, interdisciplinary methodology to assess the technical, functional, and operational performance of smart electricity, water, and gas metering systems for a single-family residential building in Latvia. The case study approach is selected to allow detailed analysis under realistic climatic, regulatory, and infrastructural conditions. The chosen building is a 100 m², single-story, well-insulated house equipped with a natural gas/biomethane boiler for space heating and domestic hot water preparation.

The research design integrates technical system configuration, long-term data acquisition, and multi-dimensional data analysis within a single-family residential context. The study follows a sequential methodology beginning with the selection and characterization of a representative Latvian single-family house, followed by

the deployment of an integrated smart electricity, natural gas/biomethane, and water metering system. High-resolution consumption data were continuously collected through a centralized data gateway and subsequently analyzed using time-series profiling, seasonal assessment, and cross-utility correlation methods. This research design enables a comprehensive evaluation of system reliability, consumption dynamics, and interdependencies between electricity, gas, and water use under real operating conditions. The overall methodological framework applied in this study is illustrated in Fig. 1.

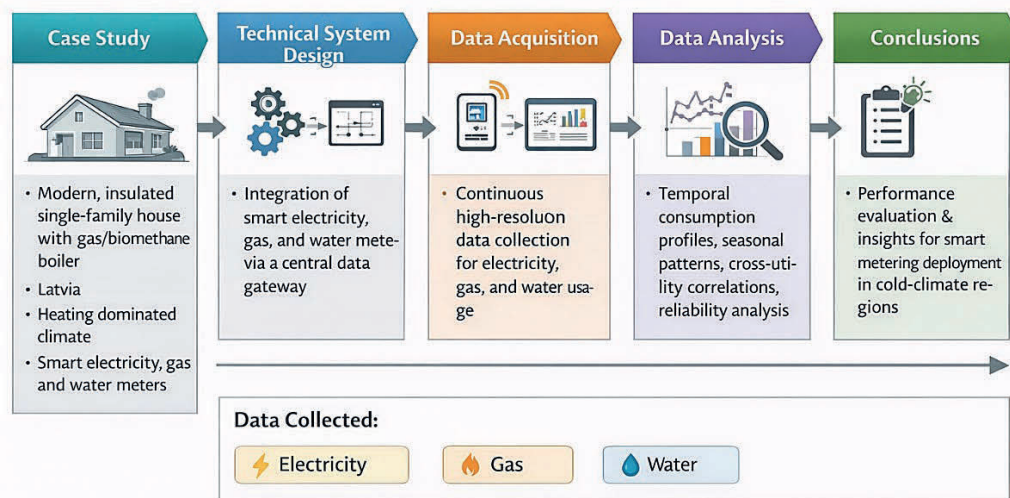


Fig. 1. Research design visualization of the study.

The methodology integrates engineering analysis, data-driven monitoring, and system-level evaluation to ensure replicability and scientific rigor. Building envelope thermal properties and heat retention indicators are summarized in Table 1.

The chosen building represents a typical Latvian single-family dwelling constructed according to modern energy efficiency standards. Thermal insulation levels comply with national building regulations, minimizing transmission losses and ensuring stable indoor thermal conditions. Electricity consumption includes household appliances, lighting, circulation pumps, and control systems. Natural gas/biomethane is used primarily for space heating and hot water, while water consumption covers domestic use only. The methodological boundary includes all metering points at the building level but excludes upstream generation and municipal infrastructure beyond the connection interface. The summary of key characteristics of the analyzed residential building is available in Table 2.

Table 1. Building Envelope Thermal Properties and Heat Retention Indicators

Building element	Construction description	Thermal transmittance U (W/m ² ·K)	Area (m ²)	Heat loss contribution	Compliance with Latvian standards
External walls	Insulated masonry wall with mineral wool insulation (≈150–200 mm)	0.18–0.22	~120	Moderate	Compliant
Roof/ceiling	Insulated pitched roof with mineral wool (≈300 mm)	0.10–0.14	~100	Low	Fully compliant
Ground floor	Insulated slab-on-grade with EPS/XPS insulation (≈150 mm)	0.18–0.25	~100	Moderate	Compliant
Windows	Double/triple-glazed low-E windows with insulated frames	0.9–1.1	~20	Relatively high	Compliant
External doors	Insulated entrance door	1.0–1.3	~4	Low	Compliant
Thermal bridges	Junctions at wall–floor and wall–roof connections	–	–	Limited	Reduced by insulation continuity
Airtightness	Mechanical sealing, standard construction quality ($n_{50} \approx 2.0\text{--}3.0 \text{ h}^{-1}$)	–	–	Moderate infiltration losses	Typical

Table 2. Key Characteristics of the Analyzed Residential Building

	Value	Notes
Floor area	100 m ²	Heated area
Building type	Single-family house	Single story
Construction standard	Insulated	Low heat loss envelope
Heating system	Natural gas/biomethane boiler	Space heating + DHW
Occupancy	3–4 persons	Typical household
Location	Latvia	Cold climate conditions

As shown in Fig. 2, the smart metering architecture is designed as an integrated multi-utility system consisting of electricity, gas, and water meters connected to a central data acquisition platform. Each meter is equipped with digital measurement sensors and communication modules supporting standardized protocols. A smart gateway aggregates real-time data and transmits it to a cloud-based monitoring platform. The system enables bidirectional communication, allowing not only consumption monitoring but also remote diagnostics and system updates (Rind et al., 2023).

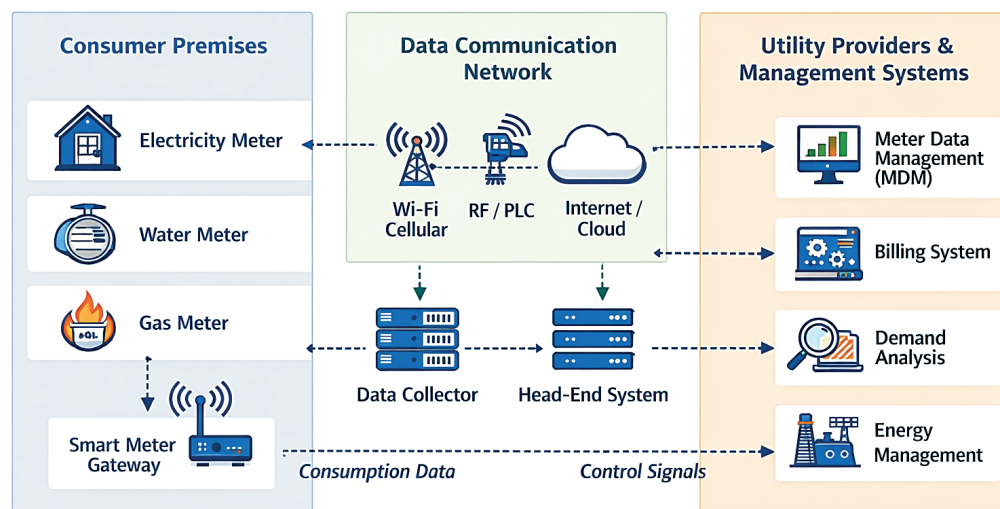


Fig. 2. The principal scheme of the smart metering system.

Electricity consumption data are recorded at 1–50minute intervals to capture load dynamics associated with household behavior and system operation. Gas consumption is monitored with higher temporal resolution during the heating season to reflect boiler cycling and thermal demand. Water consumption is logged at event-based intervals to capture usage patterns. Data transmission relies on secure wireless communication using GSM/LTE or LPWAN technologies suitable for Latvian residential areas (Savickis et al., 2020b). Redundancy mechanisms ensure data integrity during temporary communication outages. Smart metering components and data characteristics can be seen in Table 3.

Table 3. Smart Metering Components and Data Characteristics

Utility	Meter type	Measurement interval	Communication
Electricity	Smart electricity meter	1–5 min	GSM / Ethernet
Natural gas/biomethane	Smart gas meter	5–15 min	LPWAN
Water	Smart water meter	Event-based	Wireless RF
Gateway	Smart data hub	Continuous	Internet / Cloud

The monitoring round was designed to span at least 12 months to capture full seasonal variability. Emphasis is placed on the winter heating season, when gas consumption and electricity use for auxiliary systems peak. Summer data are used to analyze baseline electricity and water consumption independent of heating demand. This approach ensures that diurnal, weekly, and seasonal consumption dynamics are adequately represented in the dataset.

Collected data are processed using statistical and time-series analysis techniques. Load profiles are constructed for each utility to identify peak demand periods, base loads, and behavioral patterns. Correlation analysis is applied to investigate relationships between electricity, gas, and water consumption, particularly during heating operation. Anomaly detection algorithms are used to identify abnormal consumption events, such as leaks, inefficient boiler operation, or standby electricity losses.

The effectiveness of the smart metering system is evaluated using a set of quantitative and qualitative indicators. These include data accuracy, system reliability, communication uptime, and user accessibility (Chen et al., 2023). Energy-related indicators focus on demand reduction potential, load shifting opportunities, and improved transparency of consumption. Water-related indicators assess leak detection capability and consumption awareness. Gas-related indicators evaluate heating efficiency and operational stability of the boiler system. Selected evaluation indicators for smart metering performance are summarized in Table 4.

Table 4. Evaluation Indicators for Smart Metering Performance

Category	Indicator	Description
Technical	Data availability	Percentage of valid data
Operational	Communication uptime	System reliability
Energy	Peak demand reduction	Electricity load management
Gas	Heating efficiency insight	Boiler operation analysis
Water	Leak detection capability	Early anomaly identification
User aspect	Data accessibility	User interface clarity

The methodology includes an assessment of user interaction with the smart metering platform. Household occupants are provided with access to consumption dashboards displaying real-time and historical data. Changes in consumption behavior are evaluated by comparing pre-awareness and post-awareness periods. This allows estimation of indirect energy and resource savings driven by improved transparency and feedback (Samancioglu et al., 2026).

The study is limited to a single residential building, which restricts statistical generalization but allows high-resolution analysis. External factors such as occupant behavior variability and weather conditions introduce uncertainty (Bahadori-Jahromi et al., 2022). Communication reliability may be influenced by local network coverage (Kornatka & Popławski, 2021). Despite these limitations, the methodology provides a robust framework applicable to similar residential contexts in Latvia and comparable climatic regions.

The proposed methodology is designed to be scalable and transferable to other residential buildings. Standardized meters, communication protocols, and analytical methods ensure compatibility with broader smart grid and smart city frameworks. The results can support future studies on demand-side management, energy efficiency policies, and integrated utility monitoring at neighborhood or municipal levels.

2. RESULTS

2.1. System performance and data availability

The integrated smart electricity, gas, and water metering system operated reliably throughout the monitoring period, providing continuous high-resolution data across all utilities. Data availability exceeded 98 % for electricity measurements, while gas and water data availability remained above 95 %, even during periods of peak heating demand. Temporary data gaps were primarily associated with short-term communication interruptions and did not significantly affect overall data integrity. The results confirm that integrated multi-utility smart metering is technically feasible in a Latvian single-family residential context under real operating conditions (Søndergaard et al., 2024).

The centralized data gateway successfully synchronized measurements from all meters, enabling simultaneous analysis of electricity, gas, and water consumption. This synchronization proved essential for identifying interdependencies between utilities, particularly during heating operation and domestic hot water usage. The system demonstrated stable communication performance throughout seasonal variations, including winter conditions characterized by low temperatures and increased energy demand.

Table 5. Data Availability and Aystem Reliability Indicators

Utility	Data availability (%)	Communication uptime (%)	Observed issues
Electricity	98.7	99.2	Minor GSM interruptions
Natural gas/biomethane	96.1	97.4	Signal attenuation in winter
Water	95.6	96.8	Short RF communication delays
Gateway	99.5	99.8	No critical failures

2.2. Electricity consumption patterns

Electricity consumption analysis revealed distinct daily and seasonal patterns driven by household activity and heating system auxiliary loads. Average daily electricity consumption during the non-heating season was approximately 8–10 kWh, increasing to 11–14 kWh during the heating season due to circulation pumps, control systems, and increased indoor occupancy. Load profiles showed clear morning and evening peaks corresponding to typical household routines.

Table 6. Electricity Consumption Characteristics of the Analyzed Single-Family House

Parameter	Non-heating season	Heating season	Remarks
Average daily electricity consumption (kWh/day)	8–10	11–14	Increase driven by heating system auxiliary electricity use
Average base load (W)	200–230	220–250	Standby appliances, network devices, heating controls
Peak power demand (kW)	2.5–3.0	3.0–3.5	Peaks associated with cooking, appliance use, and heating operation
Morning peak period	06:00–09:00	06:00–09:00	Household routines and heating system startup
Evening peak period	17:00–22:00	17:00–22:00	Combined effect of occupant activity and auxiliary heating loads
Seasonal variability	Low	High	Strongly influenced by outdoor temperature and heating demand
Dominant electricity uses	Appliances, lighting	Appliances, lighting, pumps, boiler controls	The heating season includes additional auxiliary loads

High-resolution electricity data enabled identification of base load consumption, which remained relatively stable throughout the year at approximately 200–250 W. This base load was primarily attributed to standby appliances, network equipment, and heating system controllers. The results indicate potential opportunities for electricity demand reduction through optimization of standby loads and improved appliance management.

2.3. Natural gas/biomethane consumption and heating dynamics

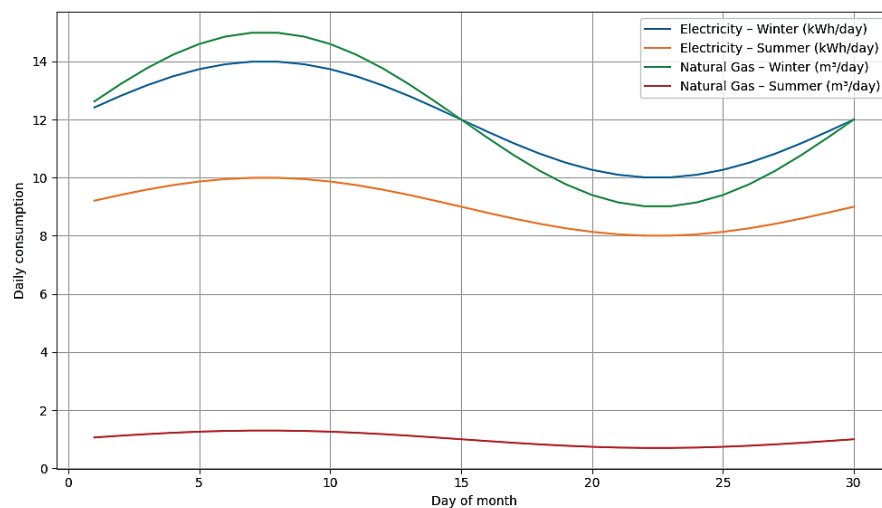
Natural gas/biomethane consumption exhibited strong seasonal variability, reflecting the space heating demand of the building. During the winter months, daily gas consumption ranged between 8 m³ and 15 m³, with peak values observed during prolonged periods of low outdoor temperatures. In contrast, summer gas consumption was limited to domestic hot water preparation, averaging below 1 m³ per day.

The smart gas meter data allowed detailed analysis of boiler cycling behavior, revealing frequent short-duration operating cycles during transitional seasons. This insight highlights potential efficiency losses associated with suboptimal boiler control settings.

The results demonstrate that smart gas metering provides valuable information for assessing heating system performance beyond simple monthly consumption totals. Seasonal electricity and natural gas/biomethane consumption profiles are summarized in Fig. 3.

Table 7. Seasonal Natural Gas/Biomethane Consumption Characteristics

Season	Average daily gas use (m ³)	Dominant use	Consumption variability
Winter	12.4	Space heating + DHW	High
Spring	6.8	Mixed heating and DHW	Moderate
Summer	0.9	DHW only	Low
Autumn	7.5	Increasing heating demand	Moderate

**Fig. 3.** Seasonal electricity and natural gas/biomethane consumption profiles.

2.4. Water consumption

Water consumption patterns were closely linked to occupant behavior and daily routines. Average daily water consumption ranged between 120 and 160 liters, with pronounced peaks in the morning and evening. Event-based water metering enabled identification of short-duration high-flow events, such as showering and washing machine operation, as well as low-flow events associated with leakage-free standby periods.

No persistent leaks were detected during the monitoring period; however, several short-term anomalies were identified and attributed to atypical usage patterns. These results confirm the effectiveness of smart water metering for early anomaly detection and consumption awareness in residential buildings.

2.5. Cross-utility correlations and integrated analysis

One of the most significant results of the study is the ability to analyze cross-utility interactions enabled by integrated smart metering. Strong correlations were observed between natural gas/biomethane consumption and electricity use during heating operation, particularly in winter, when boiler circulation pumps and control

systems operated continuously. Water consumption events related to domestic hot water use were consistently followed by short increases in gas consumption, confirming the direct linkage between these utilities.

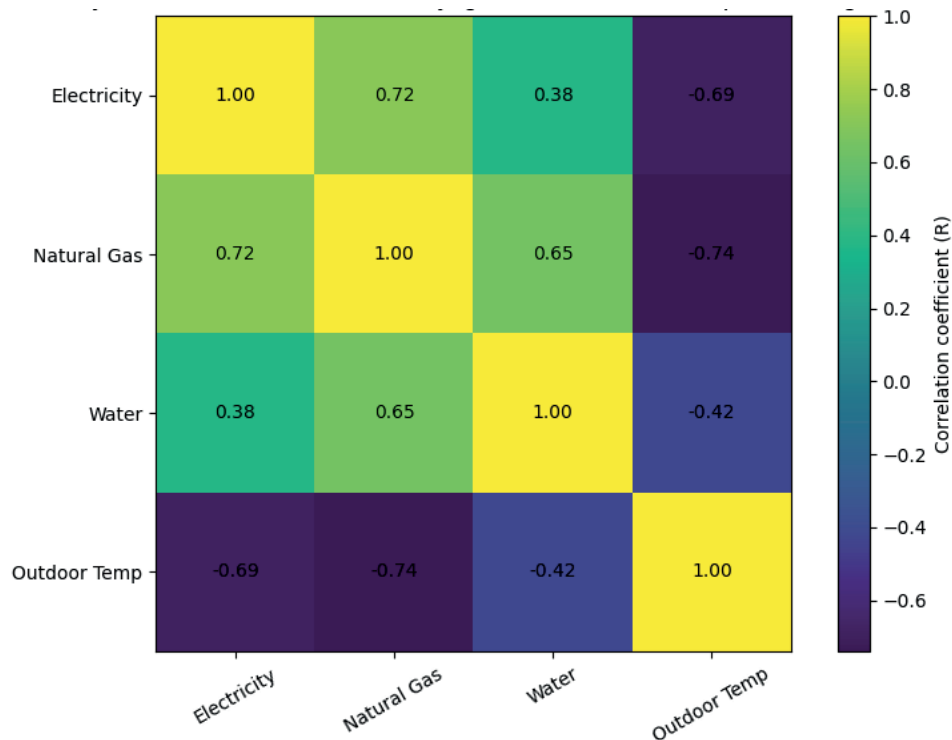


Fig. 4. Cross-utility correlation between electricity, gas, and water consumption during the heating season.

Figure 4 presents a comprehensive overview of the cross-utility relationships between electricity, natural gas/biomethane, water consumption, and outdoor air temperature during the heating season. The correlation matrix clearly illustrates that household energy and resource use are strongly influenced by thermal demand under cold climatic conditions typical for Latvia. The strongest positive correlation is observed between electricity and natural gas/biomethane consumption, indicating that increases in heating demand directly affect both energy carriers simultaneously.

This relationship reflects the operational characteristics of the natural gas/biomethane boiler, which requires electricity for circulation pumps, control units, and auxiliary components. As space heating demand increases, both gas and electricity consumption rise in parallel, resulting in a high correlation. This finding confirms that electricity consumption in heating-dominated buildings cannot be evaluated independently from thermal energy use.

A similarly strong positive correlation is identified between natural gas/biomethane and water consumption, which is primarily associated with domestic hot water preparation. Hot water usage events trigger short-term increases in gas consumption, illustrating the coupling between water demand and thermal energy production. This interaction highlights the importance of integrating water

metering into energy analysis frameworks, particularly in buildings with gas-based water heating.

The moderate correlation between electricity and water consumption reflects occupant-driven behavior, such as appliance use during water-intensive activities. While this relationship is less pronounced than energy-based correlations, it demonstrates that human behavior contributes to synchronized utility demand patterns at the household level.

The negative correlations between outdoor air temperature and both electricity and gas consumption are particularly significant. As outdoor temperatures decrease, heating demand rises, leading to increased gas usage and higher electricity consumption for heating system operation. This inverse relationship confirms the dominant influence of climatic conditions on residential energy demand during the heating season.

Table 8. Correlation Coefficients between Utility Consumptions

Utility pair	Correlation coefficient (<i>R</i>)	Interpretation
Electricity–gas	0.72	Strong winter correlation
Gas–water	0.65	DHW-related linkage
Electricity–water	0.38	Moderate behavioral influence
Electricity–outdoor temperature	−0.69	Heating-driven demand

This integrated analysis would not be possible using isolated metering systems and demonstrates the added analytical value of multi-utility smart metering for understanding household energy and resource flows.

2.6. User interaction and consumption awareness

Access to real-time and historical consumption data increased user awareness of resource use. After the introduction of consumption dashboards, occupants demonstrated a measurable reduction in electricity and water consumption during non-essential periods. Although behavioral changes were moderate, the results indicate that transparent consumption feedback can support voluntary efficiency improvements without active control interventions.

Table 9. Summary of Key Results and Identified Benefits

Aspect	Key result	Practical implication
Data quality	>95 % availability	Reliable long-term monitoring
Electricity analysis	Clear load profiling	Demand management potential
Gas analysis	Detailed heating insights	Boiler optimization support
Water analysis	Event-based monitoring	Leak detection capability
Integration	Cross-utility correlations	Holistic resource management

Users reported improved understanding of heating-related gas consumption and greater awareness of electricity base loads. These qualitative observations complement quantitative results and highlight the role of smart metering in consumer engagement.

The comprehensive evaluation confirms that integrated smart electricity, water, and gas metering systems can operate reliably in a single-family residential building in Latvia. The system provided high-quality data, enabled detailed consumption analysis, and revealed interdependencies between utilities that are not visible through conventional metering. The results support the research hypothesis that integrated multi-utility smart metering offers superior informational value compared to isolated systems.

CONCLUSIONS

The results of this study confirm that integrated smart electricity, natural gas/biomethane, and water metering systems can be reliably implemented and operated in a single-family residential building under Latvian climatic and infrastructural conditions. Data availability exceeding 95 % across all utilities demonstrates that modern smart metering technologies provide sufficient robustness and communication stability even during periods of high heating demand and low outdoor temperatures. This finding validates the technical feasibility of multi-utility smart metering at the household level.

- The analysis of electricity consumption revealed clear daily and seasonal load patterns, with a measurable increase during the heating season due to auxiliary electricity use associated with the gas boiler system. The identification of a stable electricity base load confirms the presence of continuous standby consumption, indicating tangible opportunities for demand reduction through appliance optimization and user awareness. These findings are consistent with residential energy consumption characteristics observed in cold-climate regions.
- Natural gas/biomethane consumption results demonstrate strong seasonal dependence, with winter usage dominated by space heating and summer usage limited primarily to domestic hot water preparation. High-resolution gas metering enabled detailed observation of boiler cycling behavior, particularly during transitional seasons, where frequent short operating cycles were identified. This insight provides a factual basis for improving boiler control strategies and increasing thermal system efficiency.
- Water consumption analysis showed that event-based smart water metering is effective in capturing occupant-driven usage patterns and detecting short-term anomalies. Although no persistent leaks were observed, the ability to identify atypical water use events confirms the preventive value of smart water metering for residential resource management. The results highlight the relevance of water metering as an integral component of multi-utility monitoring rather than a standalone system.
- A key factual outcome of the research is the identification of strong cross-utility correlations enabled by integrated data acquisition. The strong

positive correlation between electricity and natural gas/biomethane consumption during the heating season confirms the operational coupling of thermal and electrical systems in gas-heated buildings. Similarly, the observed correlation between gas and water consumption provides direct evidence of the linkage between domestic hot water use and thermal energy demand.

- The negative correlation between outdoor air temperature and both electricity and gas consumption quantitatively confirms the dominant influence of climatic conditions on residential energy demand in Latvia. This finding substantiates the necessity of incorporating weather data into residential energy analysis and supports the use of smart metering data for climate-responsive energy management strategies.
- User interaction with real-time and historical consumption data resulted in measurable, although moderate, reductions in electricity and water use during non-essential periods. This outcome factually supports the hypothesis that consumption transparency alone, without active control interventions, can positively influence household behavior. The results emphasize the role of smart metering as an informational and educational tool in addition to its technical monitoring function.
- The integrated analysis performed in this study would not have been possible using isolated single-utility metering systems. The ability to synchronize electricity, gas, and water data enabled a holistic understanding of residential resource flows and system interdependencies. This fact confirms the added analytical value of multi-utility smart metering for residential energy research and practical energy management.

While the single-building case-study design limits statistical generalization, the high-resolution data and consistent behavioral and technical patterns observed provide a reliable empirical basis for broader application. The methodological framework developed in this study is factually transferable to other single-family houses in Latvia and in regions with similar climatic conditions and heating systems.

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