Asynchronous Sensor Systems as the Next Generation of Urban Monitoring Systems for Resource Consumption, Air Pollution, and Meteorological Parameters

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Abstract. The aim of this study is to examine the feasibility of establishing urban monitoring systems to support the energy transition. To achieve this aim, the following tasks were addressed: analyzing the limitations of traditional synchronous Advanced Metering Infrastructure (AMI) systems; demonstrating the advantages of shifting to asynchronous systems—which utilize a unified technology and set of rules to collect granular data not only on resource consumption but also on weather conditions and indoor/outdoor air pollution, with adjustable granularity for each parameter; and identifying the initial step in deploying urban monitoring systems—the international ASMI pilot project—while outlining its goals, objectives, and expected outcomes. Key results include moving away from complex "smart meters" in favor of extremely simple, low-cost sensors; standardizing data transmission protocols across all monitored parameters; and reducing the costs associated with establishing and operating the monitoring system. The significance of these results lies in the fact that lower costs and enhanced data value pave the way for a new market—a market for urban resource consumption and environmental data—thereby attracting private-sector investment and laying the groundwork for future research involving artificial intelligence, the directions of which are outlined in the article.

***Keywords*:** asynchronous sensor monitoring system, ASMI, data granularity, monitored parameter sensors, resource consumption, energy transition, urban data market.

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Sisteme de senzori asincroni: următoarea generație de sisteme de monitorizare urbană a consumului de resurse, a poluării aerului și a parametrilor meteorologici

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Rezumat. Scopul acestui studiu este de a examina fezabilitatea construirii unor sisteme urbane de monitorizare care să furnizeze date pregătite pentru aplicații de inteligență artificială privind consumul de resurse, parametrii meteorologici și poluarea aerului în interiorul și exteriorul clădirilor, în sprijinul tranziției energetice. Pentru atingerea acestui scop au fost realizate următoarele sarcini: au fost analizate limitările sistemelor sincrone convenționale de tip Advanced Metering Infrastructure (AMI); a fost descrisă o infrastructură alternativă de monitorizare senzorială asincronă (ASMI), bazată pe tehnologia brevetată Smart Monitoring, prin arhitectura senzor-ruter-centru de monitorizare și principiul de achiziție a datelor bazat pe eveniment; au fost comparate avantajele și principala limitare a abordării ASMI cu sistemele sincrone și cu metodele NILM (Non-Intrusive Load Monitoring); a fost conturat un prim pas practic către implementare, un proiect-pilot internațional numit ASMI, cu obiectivele și rezultatul așteptat. Cele mai importante rezultate arată că abordarea asincronă permite un protocol unificat de colectare pentru parametri eterogeni, un nivel de detaliere reglabil independent pentru fiecare variabilă, o simplificare și reducere a costului senzorilor, o comunicare unidirecțională senzor-ruter care elimină accesul la distanță la senzor, și o scalabilitate practic nelimitată, cu prețul unei limitări reziduale în dezagregarea consumului pe aparate individuale, comparativ cu NILM. Semnificația rezultatelor constă în demonstrarea faptului că reducerea costului senzorilor, împreună cu un protocol unificat de transmisie, poate face monitorizarea urbană viabilă economic pentru investitorii privați, deschizând o nouă piață a datelor despre consum și mediu. Aceasta creează o bază pentru cercetări bazate pe inteligență artificială în domeniul climei, sănătății și reabilitării fondului locativ, în acord cu prioritățile din cel de-al șaselea ciclu de evaluare IPCC și din programul Orizont Europa al UE.

***Cuvinte-cheie*:** sistem asincron de monitorizare senzorială, ASMI, granularitatea datelor, senzori ai parametrilor controlați, consum de resurse, tranziție energetică, piața urbană a datelor.

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Асинхронные сенсорные системы – следующее поколение городских систем мониторинга потребления ресурсов, загрязнения воздуха и метеорологических параметров

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Аннотация. Целью работы является рассмотрение возможности построения городских систем мониторинга в интересах энергетического перехода. Для достижения этой цели были решены следующие задачи: проанализированы ограничения традиционных синхронных систем учета ресурсов (AMI); показаны преимущества перехода к асинхронным системам, позволяющим по единой технологии и единым правилам собирать детализированные данные не только о потреблении ресурсов, но и о параметрах погоды и загрязнении воздуха внутри и вне помещений, с регулируемой для каждого параметра степенью детализации; определен первый шаг в развертывании городских систем мониторинга - международный пилотный проект ASMI - с указанием его целей, задач и ожидаемого результата. Наиболее важными результатами являются: отказ от сложных «интеллектуальных счетчиков» в пользу предельно простых и дешевых сенсоров; унификация протокола передачи данных для всех видов контролируемых параметров; снижение затрат на создание и эксплуатацию системы мониторинга. Значимость полученных результатов состоит в том, что снижение затрат и повышение ценности собираемых данных открывают возможность формирования нового рынка - рынка данных о потреблении ресурсов и параметрах окружающей среды в городе, что способствует привлечению частного бизнеса в эту область и создает основу для дальнейших исследований с применением искусственного интеллекта, направления которых перечислены в статье.

***Ключевые слова*:** асинхронная сенсорная система мониторинга, ASMI, детализация данных, сенсоры контролируемых параметров, потребление ресурсов, энергетический переход, городской рынок данных.

INTRODUCTION

The rapid advancement of artificial intelligence (AI) has underscored its transformative potential in driving the energy transition toward a net-zero greenhouse gas emissions economy [1].

A recent European Union report [2] highlights the global enhancement of data quality, consistency, and collection methods as a top scientific research priority. The report notes that "harnessing the vast volumes and diverse types of environmental data collected daily to extract meaningful insights presents a profound challenge. There is a growing consensus that AI can play a pivotal role in advancing modeling and forecasting capabilities for highly intricate systems, including the complex interactions between climate, biodiversity, and society" (pp. 21–22).

Similarly, in the "Knowledge Gaps and Research Priorities Report" [3], the authors of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) observe that breakthroughs in neural network architectures unlock unprecedented opportunities for climate comprehension (Cluster 7, p. 52). Utilizing neural networks enables the quantitative evaluation of cross-influences among a vast array of monitored parameters whose interdependencies were previously mathematically intractable. Consequently, they explicitly call for rigorous research into obtaining highly granular demand-side data on end-user resource consumption.

The report further emphasizes that cities will act as critical vectors for advancing the climate agenda and serve as primary battlegrounds in mitigating climate change during the energy transition (Cluster 7, p. 52). To address this, a dedicated Special Report on Climate Change and Cities [4] is scheduled for the IPCC's 7th assessment cycle, focusing on urban environment observation and modeling tools designed to monitor and evaluate discrete sectors and unaccounted variables.

Expanding the nomenclature of monitored parameters while enhancing their granularity will provide deep insights into demographic consumption patterns. This will significantly improve the accuracy and fidelity of predictive models undergirding climate policy, thereby fostering a systemic approach to decarbonization and enabling the formulation of targeted climate interventions. Furthermore, these data-driven insights will establish a foundation for designing optimization, repurposing, and modernization strategies for the residential housing stock, aligning with the SER (Sufficiency, Efficiency, Renewables) framework [5, 6].

Notably, the European Union's "Horizon Europe" Work Programme [7] has opened targeted funding streams specifically for research addressing these urgent priorities.

Deploying artificial intelligence fundamentally depends on solving the data acquisition problem, specifically securing sufficiently granular datasets for the targeted parameters. Overcoming this barrier requires dedicated instrumentation, namely specialized monitoring architectures. Recognizing this, the World Meteorological Organization (WMO), upon launching the Systematic Observations Financing Facility (SOFF) [8] in 2021, heavily emphasized the need for structural mechanisms that incentivize private capital

investments in meteorology and resource conservation.

This paper confines its scope to exploring the architectural feasibility of constructing urban asynchronous sensor monitoring systems and evaluating their structural advantages over conventional synchronous paradigms. The parameters under consideration encompass residential resource consumption, weather metrics, and air pollution indices.

ASYNCHRONOUS SENSOR SYSTEMS AS A TOOL FOR THE ENERGY TRANSITION

Conventional monitoring infrastructures for resource consumption, meteorology, and air pollution operate as synchronous Advanced Metering Infrastructure (AMI) systems [9]. In these architectures, data retrieval from utility meters and environmental sensors occurs at pre-established, uniform time intervals, commonly referred to as the polling interval. The architectural concept of AMI was originally formalized by the U.S. Department of Energy to classify data acquisition systems utilizing "smart" electricity meters [10].

In such frameworks, a system "event" is defined strictly by the expiration of the designated polling interval. The system responds by logging the meter readings alongside the corresponding timestamp, archiving the aggregated values, and transmitting the payload to a centralized monitoring hub.

Importantly, these operations execute routinely even when zero resource consumption occurs. To manipulate data granularity within an AMI framework, one must modify the polling frequency. However, this introduces substantial structural complexity into the meter design, requiring robust network-wide time synchronization, continuous self-diagnostic routines, and sophisticated anti-tampering mechanisms. Consequently, the manufacturing cost of "smart" meters escalates, which inflates overall AMI capital investments and inflates long-term operational costs.

The advent of AMI architectures generated considerable optimization expectations, particularly regarding the rapid scaling of a commercial marketplace for highly detailed electricity consumption data. For instance, in 2009, Google unveiled its Google PowerMeter platform [11], designed to aggregate detailed home energy analytics and incentivize consumer conservation behavior. Projections implied that widespread global adoption of smart meters would yield up to a 15% reduction in electricity demand. Nevertheless, by September 2011, Google decommissioned the platform, citing an inability to achieve scalable adoption—a clear indication that initial projections for smart meter proliferation were overly optimistic [12].

However, the most formidable barriers stem from rigid interdisciplinary and institutional silos. Monitoring infrastructures for electricity, water, gas, and thermal energy are typically developed as disparate, proprietary, and isolated systems engineered by separate utility providers for their own specific operational goals. Meteorological and air quality tracking networks are similarly siloed within their respective regulatory agencies. This structural fragmentation leads to redundant capital expenditures, inflates maintenance costs, eliminates any realistic path to financial self-sustainability, and ultimately deters private sector investment.

To resolve these inherent deficiencies, bridge interdisciplinary divides, enhance data utility through flexible granularity management, and lower overall system costs, a series of investigations were conducted. The resulting solution entails abandoning synchronous architectures entirely in favor of an asynchronous approach, culminating in the development of Smart Monitoring technology [13]. This technology enables the implementation of an Asynchronous Sensor Monitoring Infrastructure (ASMI), a methodology protected by a U.S. invention patent [14].

Transitioning from a synchronous to an asynchronous framework circumvents many of the engineering bottlenecks that plague AMI systems when capturing high-granularity parameter fluctuations. Within an ASMI framework, a system event triggers if and only if the monitored parameter shifts by a predefined delta (Δ P). The system's response is limited to logging the exact timestamp of the event and its sequential index number. Here, data granularity is managed simply by calibrating the magnitude of Δ P. Crucially, if the parameter remains static (e.g., during periods of zero resource consumption), no event is triggered, and no data processing or transmission resources are consumed. The divergent event-trigger mechanisms of AMI and ASMI frameworks are graphically contrasted in Figure 1.

To decrease deployment and maintenance costs, ensure seamless scalability, and maintain rigorous security, routers are integrated into an ASMI architecture as an intermediary abstraction layer between the localized edge sensors and the centralized Monitoring Center. The systemic architecture of an ASMI configuration is illustrated in Figure 2.

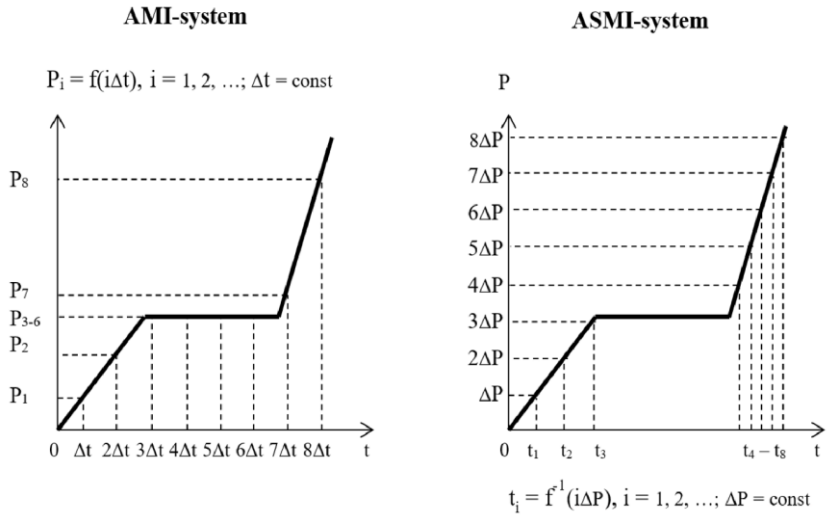


Fig. 1. Event trigger mechanisms in AMI versus ASMI frameworks.

The ASMI ecosystem comprises three primary components:

Monitored Parameter Sensors: Distributed across residential multi-family complexes, these devices are deployed either indoors or outdoors depending on the specific variables being tracked.

Routers: Installed within common building areas outside individual apartments, these mains-powered devices are positioned to ensure every edge sensor falls within radio range of at least one router.

Central Monitoring Center: A centralized computing infrastructure that aggregates and processes all data packets forwarded by the router field.

Sensors constitute the most numerous components within the ASMI framework. Consequently, their design complexity and unit production cost dictate the economic viability of the entire system. For this reason, the development of Smart Monitoring technology prioritized minimizing sensor edge-intelligence and eliminating redundant on-board functions.

The primary function of the router is to capture incoming sensor transmissions, append an accurate arrival timestamp, and forward the enriched data packet to the Monitoring Center. Communication from sensors to routers is standardized across all parameter classes via a unified Pi-protocol. This link is strictly unidirectional (uplink only, from sensor to router), with the sensor acting as the sole initiator. The router remains agnostic to sensor types, logging all intercepted packets from any device within radio range before bulk-forwarding them to the Monitoring Center, where data demultiplexing and sorting take place. The router-to-sensor ratio is estimated between 1:25 and 1:50.

The spatial distribution of sensors and routers within a typical multi-family residential building is diagrammed in Figure 3.

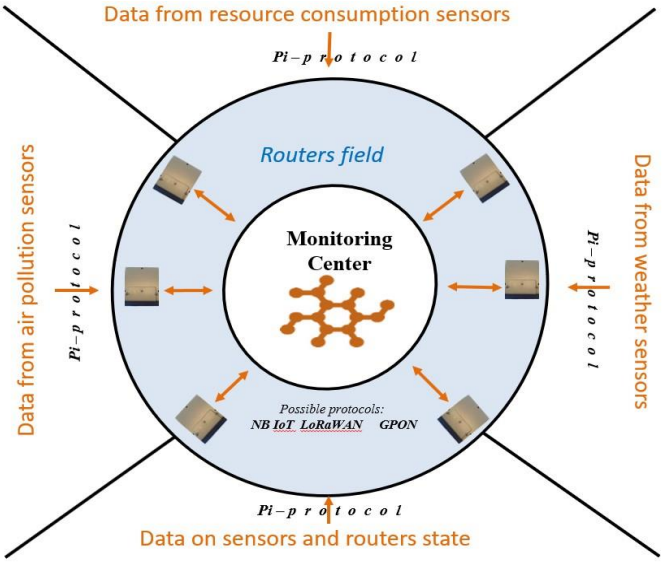


Fig. 2. ASMI system architecture

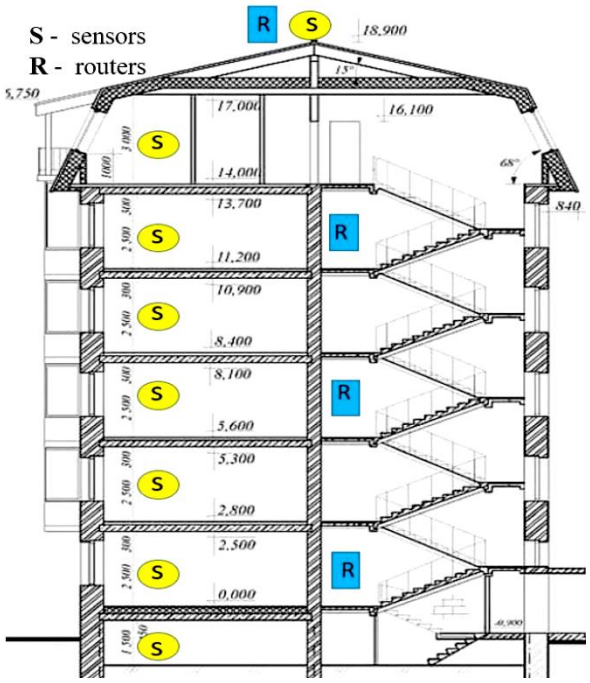


Fig. 3. Spatial deployment configuration of sensors and routers within a multi-family residential building.

KEY ADVANTAGES OF ASMI SYSTEMS

The central Monitoring Center, operating in tandem with the distributed urban router network, establishes a robust transport layer that remains completely decoupled from the underlying data semantics. The Center maintains relational databases detailing registered sensors, installation coordinates, tracked variables, assigned Δ P thresholds, and router topological nodes. As incoming packets arrive from the router field, they undergo processing and are committed to persistent storage for downstream applications. A comprehensive architectural breakdown of the ASMI pipeline is available in [13].

The advantages of ASMI systems include the following:

• **Unified Architectural Paradigm:** Monitoring across all heterogeneous variables is executed via a singular, harmonized technological stack.

• **Dynamic Granularity Control:** Granularity configurations are decoupled and tailored for individual parameters, enforcing sensor transmissions only upon a ΔP threshold violation.

• **Minimalist Sensor Design:** The structural complexity of the edge sensors—the most mass-produced hardware components—is drastically reduced.

• **Redundant Interception Topology:** Routers optimistically capture payloads from all proximal sensors within their radio range, enhancing data transmission reliability.

• **Unidirectional Security Isolation:** Implementing an uplink-only communication path completely insulates edge sensors from external network-borne exploits or unauthorized access.

• **Harmonized Communication Protocol:** Utilizing a unified Pi-protocol simplifies system orchestration and eliminates the need to recertify sensors as legal metrology instruments when router-to-center transmission interfaces are upgraded.

• **License-Free Spectrum Utilization:** Sensor-to-router links exploit open, license-exempt frequency bands.

• **Seamless Scalability:** The system architecture scales efficiently across arbitrary geographical scales.

The range of urban parameters monitored by ASMI frameworks includes, but is not limited to: residential utility consumption (electricity, potable water, hot water, thermal energy, natural gas); indoor and outdoor air quality indices (carbon monoxide, nitrogen oxides, hydrocarbons, particulate matter, heavy metals, CO_2, ambient radiation levels); and meteorological variables (ambient temperature, relative humidity, barometric pressure, wind velocity, and direction).

LIMITATIONS OF ASMI SYSTEMS

Despite its structural benefits, the ASMI framework possesses one notable limitation, particularly concerning electricity consumption monitoring. Historically, the concepts of AMI and "smart metering" were explicitly conceived for electrical grids before being extended to other utility domains.

Hart's pioneering invention [15] established a dedicated research domain known as Non-Intrusive Load Monitoring (NILM) [16-21]. NILM provides a methodology for analyzing aggregated electrical load profiles captured at a single point of measurement (voltage and current) and disaggregating the total load into discrete appliances. As Hart observed, the activation or deactivation of an electrical appliance injects a distinct power transient signature into the network. Resolving these signatures allows for appliance identification and the quantification of its specific energy draw.

While these insights facilitate appliance profiling, lifecycle tracking, and consumer behavioral modification, signature recognition requires sophisticated mathematical algorithms. When deploying this method at scale across urban centers, significant financial bottlenecks arise due to the high cost of the high-frequency data acquisition hardware required.

In a standard ASMI system, capturing these precise activation and deactivation timestamps is theoretically possible but requires a drastic reduction in the ΔP threshold. This adjustment causes a compounding increase in transmitted packet volume. To mitigate this bottleneck, a specialized data granularity algorithm was engineered for ASMI frameworks, enabling appliance event detection without inflating network traffic.

AVENUES FOR FUTURE RESEARCH

The comprehensive and highly granular datasets generated by this integrated monitoring infrastructure significantly expand information density. This unlocks broad opportunities for advanced research across several domains, including but not limited to:

1. **AI-Driven Environmental and Climatological Interdependency Analyses:**

• Generating highly localized weather and climate forecasts to formulate recommendations on adjusting regional fuel and energy balances.

• Predicting macro-environmental shifts, including air pollution dispersion patterns and radiological contingencies.

• Detecting, localizing, and modeling the propagation dynamics of natural disasters or industrial infrastructure failures to evaluate potential systemic damage.

2. **Advanced End-Use Edge Disaggregation and Behavioral Modeling:**

• Identifying specific household appliances and mapping their corresponding energy efficiency ratings.

• Disaggregating total utility draw down to individual household appliances.

• Constructing longitudinal operational histories for residential appliances (tracking consumption, maintenance, and efficiency degradation).

• Generating automated, tailored recommendations to guide consumers toward higher-efficiency appliance alternatives.

• Inferring actual occupancy rates within residential units to analyze localized demographic density shifts and urban migration dynamics.

• Streamlining utility billing infrastructure and providing optimal multi-tariff scheduling strategies for consumers.

3. **Residential Infrastructure Modernization and Efficiency Auditing:**

• Empirical quantification of efficiency classes for individual units and entire multi-family buildings.

• Formulating target interventions to improve structural energy performance profiles.

• Conducting empirical post-intervention audits to verify the efficacy of resource-conservation initiatives.

4. **Socio-Behavioral Incentive Engineering:**

• Developing specialized AI frameworks and applications to encourage resource-conscious behaviors, tailored to specific demographic, gender, and age cohorts.

5. **Data Marketplace Business Modeling:**

• Designing commercial frameworks to capture private investment and sustain a new commercial data market.

6. **Epidemiological Correlation Studies:**

• Investigating the direct impacts of localized urban microclimates and air pollution variations on public health metrics.

THE FIRST STEP TOWARD URBAN MONITORING INFRASTRUCTURE DEPLOYMENT

As an inaugural step toward realizing comprehensive urban monitoring, it is critical to

initiate a foundational research initiative dedicated to constructing a functional ASMI prototype (demonstrator). Utilizing Smart Monitoring technology, this prototype will validate the unified acquisition of multi-parameter data at scale. We designate this initiative as the **ASMI Project**.

Scope of Investigation: The urban ecosystem, specifically focused on monitored parameters including: the quantity of resources consumed in apartment building units (electricity, cold and hot water, thermal energy, gas); indoor and outdoor air pollution indicators (carbon monoxide, nitrogen oxides, hydrocarbons, dust, heavy metals, CO2, radiation levels, etc.); and meteorological parameters (air temperature and humidity, atmospheric pressure, wind speed and direction, etc.).

To ensure robust execution, the project should establish a transnational consortium comprising leading research institutes and manufacturing enterprises.

The **ASMI Project** will focus on the following key operational objectives:

• Engineering, manufacturing, and certifying experimental sensor and router units embedded with *Smart Monitoring* logic via consortium manufacturing partners.

• Securing international patent protections for the developed sensor and router hardware.

• Deploying a foundational Monitoring Center prototype in Moldova.

• Establishing interoperable National Monitoring Center nodes within all participating member states.

• Instrumenting target pilot facilities across participant states and binding them to their respective National Monitoring Centers.

• Drafting regulatory and standardized frameworks to govern the implementation of Smart Monitoring systems within energy transition strategies.

• Formulating architectural guidelines for scaling the ASMI framework up to macro-urban dimensions.

• Engineering data exchange interfaces compatible with the WMO's Global Basic Observing Network (GBON).

The primary deliverable of this project will be an operational, end-to-end ASMI prototype natively interfaced with the GBON network. This prototype will be technically and regulatorily primed for large-scale industrial replication. The data assets generated by this infrastructure will serve as a catalyst for downstream research and application development supporting the energy transition.

SOCIETAL READINESS AND DEPLOYMENT VIABILITY

The argument for widespread societal readiness for ASMI deployment rests on several key observations:

1. **Familiarity with Residential Metering:** Urban populations universally accept residential resource metering as a standard prerequisite for utility access. The recent deployment of telemetry-enabled smart meters has encountered minimal public resistance. Consequently, replacing legacy meters with significantly lower-cost sensor hardware can be effectively positioned as a logical upgrade to next-generation intelligent monitoring.
2. **Structured Rollout Pathways:** Deployment can follow established maintenance cycles. New construction projects can integrate the complete sensor suite natively, while existing housing stock can be retrofitted with sensors as older meters hit their mandatory calibration expirations. Routers can be installed concurrently, establishing a foundational urban transport network to which additional environmental and weather sensors can be added over time.
3. **Plug-and-Play Orchestration:** Integrating a new sensor node requires only local physical installation followed by digital registration within the Monitoring Center database.
4. **Value-Added Consumer Services:** End-users gain immediate access to an extensive suite of novel, data-driven analytical services.

CONCLUSION

The authors anticipate that ASMI systems will emerge as a powerful tool for accelerating the energy transition by:

• Providing co-located, unified monitoring of resource streams, localized weather conditions, and indoor/outdoor atmospheric pollution.

• Enabling dynamic control over data granularity, thereby maximizing information utility.

• Significantly lowering capital expenditures and ongoing operational costs for monitoring infrastructures.

Combined, these factors create strong incentives for establishing a commercial data market, unlocking private capital investments in resource conservation and predictive environmental analytics.

It should be noted that the development of urban observation infrastructures and the monetization of high-granularity environmental and resource consumption data are also being actively investigated within other research domains. For instance, [22] introduces a hierarchy of urban sensor monitoring—

spanning from the individual to the city-wide level—and demonstrates the role of open sociotechnical data acquisition frameworks in aligning community- and municipal-level actions. The transition to asynchronous ASMI systems proposed in this paper advances this field by introducing a unified, data-agnostic collection protocol alongside a cost-effective hardware solution that lowers the barrier to entry for operators of such observation infrastructures. Furthermore, according to market forecasts [23], the global IoT sensor market underpinning these frameworks continues to expand at an accelerated pace, thereby confirming the timeliness and economic viability of the proposed approach.

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