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# Appropriate Technology-Based AMI Deployment in Multi-Dwelling Units

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**Abstract:** Digital technologies, especially information and communication technologies, paved the way for social welfare by providing efficient and effective means for services. In the energy sector, advanced metering infrastructures (AMIs) are essential for providing various services through information measurement. In this article, we focus on the deployment of an AMI in multi-dwelling units where automated meter reading (AMR) infrastructures are installed. In particular, we explore whether the AMR should substitute the AMI with few alterations, while ensuring desirable accuracy. To determine the adequacy of technology, information measurement performance, service performance, and implementation cost are used as the indicators. Through a case study using real data recorded in Korea, we quantitatively estimate that AMR-based information measurement can exhibit adequate performance and performance degradation of less than 1% in a service environment utilizing AMI with a low-cost investment. We also discuss several technologies and implementation issues in the upcycling of AMR for more reliable service. This study provides a guide for when configuring an information measurement system for a new energy service.

**Keywords:** advanced metering infrastructure; automated meter reading; measurement; remote metering; smart meter; energy-as-a-service



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## 1. Introduction

Digital technology has contributed to the evolution of modern society through social welfare by providing efficient and effective means for various services. Energy systems have also been digitalized [1]. Energy systems are important social infrastructure and considered as ubiquitous resources in modern society. Users are generally not concerned about where the energy is sourced from because it is provided to them by another party. Therefore, the role of users remains as customers. However, the recent digitalization in the energy sector, combined with innovative technologies, such as photovoltaic (PV), electrical energy storage (EES), and electric vehicles (EVs), has helped customers gain awareness in this regard. Using this information, they can compare various energy providers and determine how much PV or EES should be installed to reduce their electricity bills. It can also determine how the excess energy can be traded to the neighbors for better prices. All of this has been made possible through the use of the digitalized infrastructure.

Digitalized energy systems tend to evolve into service systems that can be called energy-as-a-service (EaaS) [2]. Distributed energy resources (DER) and dynamic pricing are key enablers of the EaaS business models. EaaS providers can deploy a combination of assets, such as solar PV, EES, smart devices, and smart meters to optimize energy consumption and provide demand response services to system operators.

Advanced metering infrastructure (AMI), including smart meters, is another key component that enables EaaS based on energy digitalization [3]. AMI supports real-time energy metering and energy transactions. The global market size of smart meters is estimated as USD 20.7 billion in 2020 and is expected to increase to USD 28.6 billion by 2025, at a compound annual growth rate of 6.7% [4]. As investments in AMI account for 51% of the smart grid investment grant (SGIG) project funded in 2012 [5], AMI is considered an essential component for electricity charges under various tariffs or pricing systems. The AMI has been widely installed in regular homes and had a global penetration rate of 14% in 2019. In the US and China, this rate was 70% in 2019 and 44% in EU-28 in 2018 [6].

On the contrary, the AMI for multi-dwelling units in urban areas is ambiguous. In countries with a high population density and high land prices, one of the trends in building construction is a multi-dwelling unit [7]. A multi-dwelling unit consists of individually owned small offices or housings located in the building. The building supports a minimum of common utility services such as aisles, elevators, and a lobby. Therefore, they have different ownership depending on the space in a building [8]. In some countries, power utilities directly provide electricity to individuals in multi-dwelling units. In some others, power utilities provide electricity up to the entry point of a building, and sub-meters installed by the building operator are used for charging; this is more common in urban multi-dwelling units [9].

Various AMI structures, such as efficient metering data collection and transmission [10–13], smart metering using Internet of Things (IoT) [14,15], and distributed communication architectures have been suggested [16–19]. Niyato and Wang introduced the cooperative transmission for the meter data collection in smart grid [10]. They proposed a two-hop cooperative transmission network architecture of a wireless network to cover the multiple energy communities. Potdar et al. discussed the progress in the field of big energy data covering several data management aspects, such as data collection, data preprocessing, data integration, data storage, data analytics, data visualization, and decision-making [11]. Secure data sensing and communication have presented a new set of issues related to open research of big data management in smart grids. Wen et al. presented a survey on smart meter big data compression and compared compression methods for smart meter big data [12]. The data acquisition to achieve an acceptable balance between efficiency and the loss ratio is suggested as a major challenge in the practical applications. Recioui and Grainat reviewed data and communication infrastructure for data exchange in smart grids [13]. It is shown that the wireless communication systems are a suitable and efficient solution for data transmission in smart grids. Lloret et al. proposed an integrated IoT architecture for smart meter networks to be deployed in smart cities [14]. They showed that the proposed IoT architecture can increase the benefits for both the customers and the utilities. Tightiz and Yang investigated the communication requirements of the smart grid and introduced IoT protocols and their specifications [15]. By analyzing the characteristics of the IoT protocols, they highlighted the weak points of these practices making them fail to acquire the holistic guidelines in utilizing proper IoT protocol that can meet the smart grid environment interaction requirements. Jiang and Qian presented a distributed communication architecture that implements smart grid communications in an efficient and cost-effective way [16]. The proposed distributed architecture can manage and analyze data locally leading to reduced cost and burden on communication resources. Xu et al. proposed two practical solutions as parts of incremental network design to improve the communication robustness of the existing communication architectures for AMI [17]. These solutions solve a network connectivity problem in access networks of an AMI considering both the communication architecture for the overall network reliability improvement and the network deployment cost minimization. Ahsan and Bais propose a smart home distributed architecture involving home sensors that communicate directly to a smart gateway installed within the home [18]. It is predicted that the future smart grid will contain applications like time-critical wide area measurement and control systems and the distributed architecture that can perform time-sensitive calculations. Choi proposed a hierarchical distributed architecture that combines the advantages of both hierarchical and distributed architectures [19]. A hierarchical architecture provides large-scale information acquisition, communications, processing, and control for cooperative energy management in homes and grids through cloud computing, while a distributed architecture provides autonomous decision-making capability with agent-based intelligence through edge computing. In these studies, the AMI is a key element of communication networks for data measurement and transmission. However, the environments in multi-dwelling units have not been adequately considered, since they are different from the conventional AMIs that are installed outdoors under severe weather conditions.

Many multi-dwelling units use an automated meter reading (AMR) infrastructure that supports remote meter reading, although it does not support two-way communication. In several cases, there is a notion that the infrastructure must be upgraded from AMR to AMI to support energy monitoring and real-time pricing. However, the decision tends to be made without sufficient critics. In this case, upgrading from AMR to AMI cannot guarantee a sufficient return on investment, considering the limited services based on AMI. The higher the cost, the slower the deployment of AMI because of the limited budget.

This study starts with the following question.

- What is an appropriate technique for collecting information for energy service in a multi-dwelling unit environment?

As mentioned above, installing the latest AMI is technically a suitable choice. However, it is expensive. Moreover, newly constructed buildings comprise less than 2% of the total floor area annually [20]. AMR has been installed in numerous conventional buildings. Therefore, the question that motivates this study can be revised as *whether AMR can substitute AMI while ensuring desirable accuracy and with few alterations*. If the aforementioned assumption is true, then the existing AMR can be used to support real-time pricing for a short period of time without a high investment. Moreover, to check the suitability of AMR for energy service as an appropriate technique, we set the information measurement performance, energy price error, and implementation cost as comparative indicators. By numerical analysis using the real data set measurement in Korea, we verify the feasibility of using an AMR instead of a high-tech AMI.

The rest of this paper is organized as follows: In Section 2, the AMI metering architecture is described, and in Section 3, the method for checking the appropriate technique is discussed. In Section 4, measurement studies and discussions using the real data set are presented. In Section 5, the conclusions of the paper are presented.

## 2. AMI Metering Architecture

The basic architecture of AMI includes smart meters, a data collection unit (DCU), a server, and communication networks, as shown in Figure 1.

The metering data are collected from the smart meter to the DCU, and then the data are sent to the metering data server. The AMI systems are usually designed with the assumption that the smart meters and communication networks are installed outdoors and experience extremely severe weather conditions, such as hot, cold, and humid. In addition, the communication networks that do not use wireless technology are exposed in public areas, which may weaken network security allowing physical access to the network.

Various different network technologies are adopted to implement AMI, and they have their own strengths and weaknesses. Power line communication is one of the preferred technologies by various power companies, but the quality of communication varies depending on the situation [21]. Using a wired communication line can be secure, but costly and difficult to maintain, whereas a wireless network facilitates easy maintenance, but the communication quality and cost are the factors that need to be considered [22].

Indoor AMRs or AMIs are usually installed for multi-dwelling units through wired communication lines because the installation is inexpensive, and maintenance is relatively easy. Further, the wires cannot be tapped easily because the network infrastructure is regularly maintained by building operators, resulting in relatively stable communication.

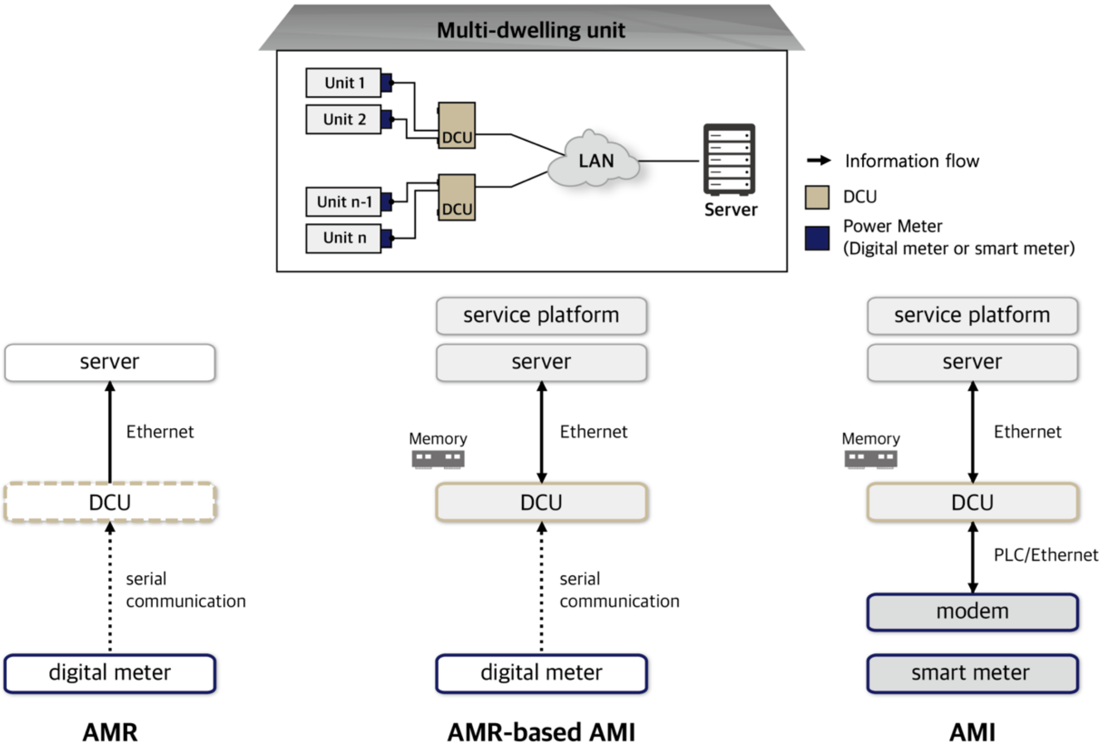



**Figure 1.** Comparison of a generic AMR, AMR-based AMI, and smart meter-based AMI architecture for multi-dwelling units.

AMR systems that were installed before AMI are usually based on serial communication, such as RS485. The meter data are collected via data collection units using a polling mechanism in sequence. This means that even though there can be a certain amount of delay in reading the meter data, the data collection is stable. On the contrary, outdoor AMIs require additional features to acquire the required communication stability, such as time synchronization and profile saving for avoiding communication loss.

Figure 1 shows the typical structures of an AMR, an AMR-based AMI, and the new smart meter-based AMI. In AMR, DCU simply performs digital meter reading according to the request of the server without using intelligence. In the AMR-based AMI, DCU performs meter reading from digital meters in a more intelligent manner using an existing serial communication network. Since both the AMR and the AMR-based AMI use serial communication networks, power consumption of multi-units is measured through sequential polling. The main difference between the AMR and the AMR-based AMI is whether the DCU has a memory or not, as shown in the first and second system architecture in Figure 1. In the AMR-based AMI, the DCU uses memory to reduce the risk of data loss. Therefore, the server supports the metering of data-based services through the addition of a service platform. In AMI, a full communication network is upgraded, and the digital meters are changed to smart meters using modems that support advanced communication methods, such as power line communication (PLC) or Ethernet. Unlike AMR or AMR-based AMI, in AMI, a two-way communication network is configured between DCU and smart meter as shown in the third system architecture in Figure 1. Moreover, compared to the digital meters, the smart meters provide more information, such as power factor, peak power consumption, as well as active/reactive power consumption. Here, the power factor representing the efficient use of electricity is calculated from the relationship between active and reactive powers. Using the information, advanced energy services, such as demand response, can be operated in AMI.

## 3. Method

The main purpose of the remote meter reading is to provide various energy services through the online monitoring of consumer energy consumption patterns. The AMR-based power consumption measurement, which is generally performed every hour, increases the predictability of grid operation in terms of utility, and provides an opportunity to reduce electricity bills by presenting an appropriate rate to the users through time-based rate programs such as time-of-use (ToU) pricing. With the development of smart grids and energy services based on short measurement intervals, that is, 5 or 15 min, there has been a demand to replace the AMR with a smart meter. Therefore, this study uses information measurement performance, service performance, and implementation cost as indicators for the selection of appropriate technology.

### *3.1. Information Measurement Performance*

Figure 2 compares the differences between the smart meter-based and AMR-based power consumption measurements. The smart meter has a built-in memory for data measurement. Therefore, it transmits a value suitable for the time for multiple access and retransmission, as shown in Figure 2a. However, the AMR is a memoryless system for data measurement. In addition, the sequential polling method is used for data transmission in multiple access environments in the case of AMR. In the polling sequence, the AMR transmits a value at the time when the request is received. Depending on the number of measurement units, the sequential measurement generates an accumulated delay, including transmission delay and multiplexing delay, as shown in Figure 2b. Due to this delay, a measurement error occurs between the actual power consumption and the measured value.

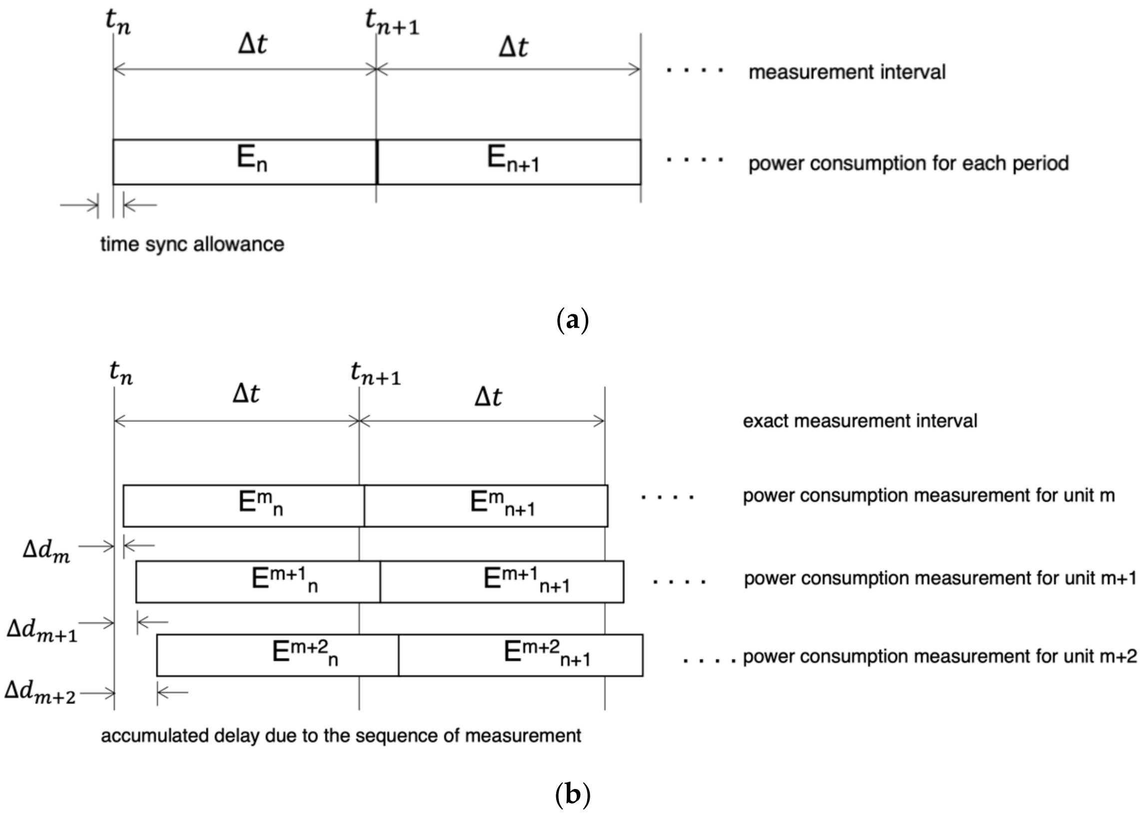



**Figure 2.** Comparison of a generic AMR, AMR-based AMI, and smart meter-based AMI architecture for multi-dwelling units; (**a**) smart meter-based power consumption measurement; (**b**) AMR-based power consumption measurement.

Let $t_n$ and $\Delta t$ be the start time of the n-th measurement time and the power consumption measure time interval, respectively. The actual power consumption measurement of unit $m$ at the n-th measurement time is calculated as

$$E_n^m = \int_{t_n}^{t_n+\Delta t} p_t^m dt, \tag{1}$$

where $p_t^m$ is the power consumption of unit $m$ at time $t$. However, the AMR-based power consumption measurement is affected by the accumulated delay $\Delta d_m$. Therefore, the power consumption of unit $m$ measured by the AMR is

$$\hat{E}_n^m = \int_{t_n+\Delta d_m}^{t_n+\Delta d_m+\Delta t} p_t^m dt. \tag{2}$$

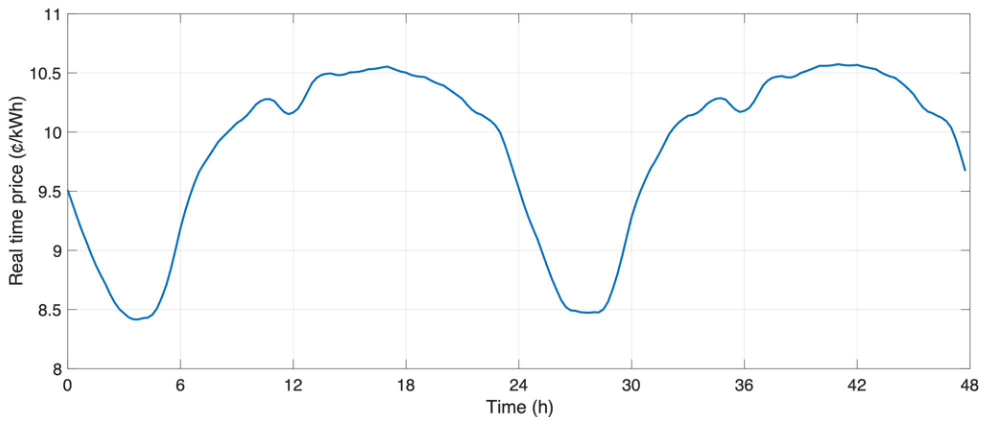
Using Equations (1) and (2), the information measurement performance is determined as the mean absolute percentage error (MAPE) between the actual power consumption measurement and the power consumption measurement with accumulated delay,

$$\begin{aligned} f_1(\Delta t, \Delta d_m, p_t^m) &= \mathbb{E}\left\{\left|\frac{E_n^m - \hat{E}_n^m}{E_n^m}\right|\right\} \times 100 \\ &= \mathbb{E}\left\{\left|\frac{\int_{t_n}^{t_n+\Delta t} p_t^m dt - \int_{t_n+\Delta d_m}^{t_n+\Delta d_m+\Delta t} p_t^m dt}{\int_{t_n}^{t_n+\Delta t} p_t^m dt}\right|\right\} \times 100 \\ &= \mathbb{E}\left\{\left|\frac{\int_{t_n}^{t_n+\Delta d_m} p_t^m dt - \int_{t_n+\Delta t}^{t_n+\Delta d_m+\Delta t} p_t^m dt}{\int_{t_n}^{t_n+\Delta t} p_t^m dt}\right|\right\} \times 100. \end{aligned} \tag{3}$$

From Equation (3), the parameters to determine the information measurement performance are the fluctuation of the power consumption as well as the measurement time interval and the accumulated delay.

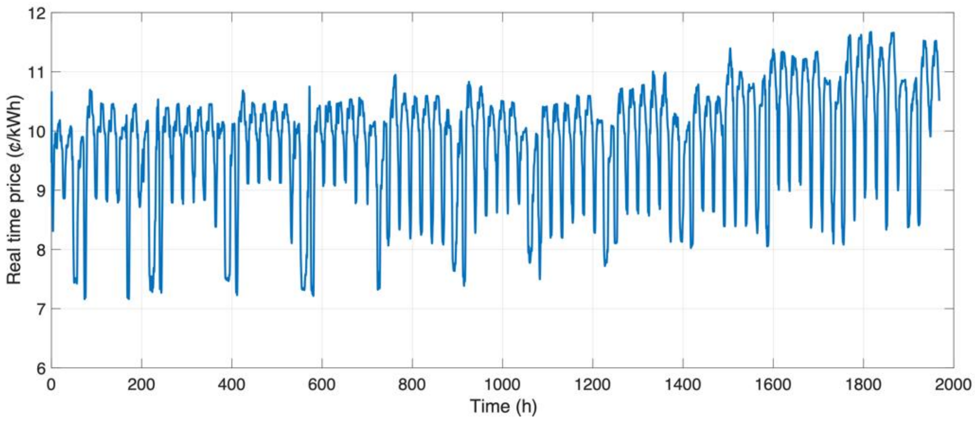
### *3.2. Service Performance*

The purpose of the information measurement is to provide new energy services, such as dynamic pricing. Dynamic pricing, such as ToU, and real-time pricing is time-based rate pricing as shown in Figure 3. Figure 3a,b shows the short and long period price changes, respectively. Therefore, the information measurement error affects the service performance presented as the electricity bill.




**(a)**

**Figure 3.** *Cont.*




(**b**)

**Figure 3.** Example of real-time pricing recorded in Korea; (**a**) real-time price over two days; (**b**) real-time price for three months.

Similar to the information measurement performance, the service performance is determined as the MAPE between the actual electricity bill and the electricity bill,

$$f_2(\Delta t, \Delta d_m, p_t^m, c_t) = \mathbb{E}\left\{\left|\frac{\int_{t_n}^{t_n+\Delta t} c_t p_t^m dt - \int_{t_n+\Delta d_m}^{t_n+\Delta d_m+\Delta t} c_t p_t^m dt}{\int_{t_n}^{t_n+\Delta t} c_t p_t^m dt}\right|\right\} \times 100, \quad (4)$$

where $c_t$ is the electricity price at time $t$. The information measurement performance is determined by the power consumption difference during the mismatching interval according to the accumulated delay. However, in the case of the service performance, the value is accumulated during the measurement time interval. Therefore, to determine the service performance, price volatility should be added in addition to the information measurement performance.

### *3.3. Implementation Cost*

In multi-dwelling unit environments where indoor AMRs or AMIs are already installed, additional network equipment needs to be installed and upgraded in order to configure new smart meter-based AMI architecture, as shown in Figure 1. These system reconfigurations require high costs. Particularly, the replacement of AMRs with multi-function smart meters requires a considerable amount of investment [5]. Therefore, the implementation cost is affected as an indicator for the selection of appropriate technology.

The implementation cost includes the cost of (1) installation of smart meter and modem, and (2) upgradation of DCU and server,

$$\begin{aligned} f_3(c^{\text{meter}}, c^{\text{modem}}, \quad & c^{\text{DCU}}, c^{\text{server}}) \\ & = M \times c^{\text{meter}} + M \times c^{\text{modem}} + \tfrac{M}{30} \times c^{\text{DCU}} + c^{\text{server}}, \end{aligned} \quad (5)$$

where $M$ is the number of units, and it is assumed that a DCU accumulates the data of 30 units.

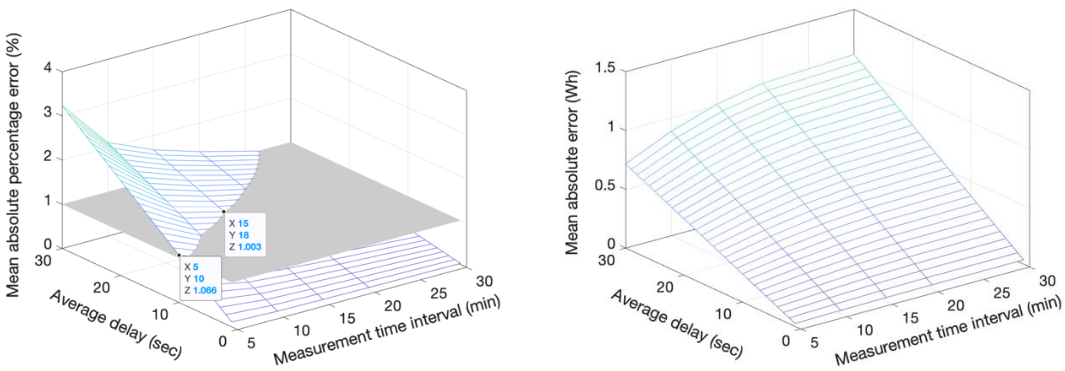
## 4. Results and Discussion

To present the appropriate technology review criteria between the AMR and smart meter, a performance analysis of the AMR-based sub-metering network, which is currently used for multi-dwelling unit metering in Korea, was performed.

Korea Electric Power Corporation, an electric power utility in Korea, uses AMR to acquire eight types of information, including unit ID, measurement time, active power, and reactive power. Each information has a 4-byte data format, and the transmission data at one time has a data length of 64 bytes with an error-correcting code and added data encryption. In the case of a smart meter, it reads additional information, such as the maximum power consumption and volt-ampere power, and has a maximum data length of 640 bytes [23]. Communication between meters and a data acquisition unit configured for the meter reading of a multi-dwelling unit is composed of a wired network based on RS-485. The 9600-bps mode is set as a default to guarantee communication [24]. Considering the data length, transmission speed, and interruption time, the cumulative delay increases by approximately 0.1 s each time the number of units increases.

### 4.1. Information Measurement Performance Analysis

Figure 4 shows the information measurement performance of the AMR-based power consumption measurement according to the measurement interval and delay. This is the average result obtained by measuring the data of 20 households for three months in Korea. The MAPE in Figure 4a and mean absolute error (MAE) in Figure 4b are the errors relative to the actual value and the absolute error, respectively. The MAPE and MAE increased with the delay, which, as a result, increased with the measurement error. Further, as the measurement interval decreased, the MAPE increased, but the MAE decreased. It was found that the shorter the measurement interval was, the lesser was the power consumption variability over time. Accordingly, the MAE was reduced. However, in this case, as the measured value decreased, the proportional influence of the error, which is the MAPE, increased. The gray plane in Figure 4a represents 1% MAPE, which is the maximum tolerance of the remote meter reading device. This result shows that in the case of a multi-dwelling unit environment in Korea, the AMR-based power consumption measurement can be performed for measuring more than 300 units for a 30-min measurement interval and approximately 180 units for a 15-min measurement interval. For metering in a multi-dwelling unit environment, one DCU is installed per 100–200 units [25].




(**a**) (**b**)

**Figure 4.** Information measurement performance in AMR-based power consumption measurement; (**a**) mean absolute percentage error of the measurement data; (**b**) mean absolute error of the measurement data.

To show how the information measurement performance is decided, Pearson's linear correlation coefficient (PLCC) is checked between power consumption characteristics and information measurement performance [26]. Mean, standard deviation, and related standard deviation of the power consumption measurement are used as the characteristics. As shown in Table 1, PLCC has little change depending on the average delay and is affected by the measurement time interval. The information measurement performance is determined by the fluctuation of the power consumption in Equation (3). The delay is a short time for the effect of fluctuation to appear, and the measurement time interval is sufficient. Moreover, the mean and standard deviation of the power consumption have a negative correlation to MAPE. This is because the MAPE is calculated as the relative value, as shown in (3). Therefore, the MAPE is correlated to the related standard deviation of the power consumption, and the relationship becomes stronger as the measurement time interval increases. This also shows that the information measurement performance is determined by the influence of fluctuations. The MAE of the information measurement performance is the absolute value. Therefore, the value is directly related to the mean and standard deviation of the power consumption. Particularly it has a high correlation to standard deviation as the measurement time interval increases. These results indicate that the fluctuation of the power consumption is the dominant factor to determine the information measure performance.

**Table 1.** PLCC between power consumption characteristics and information measurement performance according to information measurement environments.

| Time Interval | Average Delay | MAPE | | | MAE | | |
|---|---|---|---|---|---|---|---|
| | | Mean | Std. | Related Std. | Mean | Std. | Related Std. |
| 5 min | 1 s | −0.347 | −0.308 | 0.206 | 0.700 | 0.661 | −0.227 |
| | 10 s | −0.361 | −0.320 | 0.219 | 0.700 | 0.662 | −0.226 |
| | 20 s | −0.372 | −0.330 | 0.229 | 0.701 | 0.663 | −0.225 |
| 15 min | 1 s | −0.495 | −0.418 | 0.364 | 0.784 | 0.790 | −0.135 |
| | 10 s | −0.494 | −0.417 | 0.364 | 0.784 | 0.790 | −0.134 |
| | 20 s | −0.493 | −0.416 | 0.363 | 0.783 | 0.790 | −0.132 |
| 30 min | 1 s | −0.423 | −0.244 | 0.461 | 0.844 | 0.899 | −0.114 |
| | 10 s | −0.423 | −0.245 | 0.460 | 0.844 | 0.899 | −0.113 |
| | 20 s | −0.424 | −0.245 | 0.461 | 0.843 | 0.900 | −0.111 |

*4.2. Service Performance Analysis*

Figure 5 shows the service performance in AMR-based power consumption measurement by applying the system marginal price as the real-time pricing in Korea [27]. As shown in Figure 4a, the result of the service performance is similar to the information measurement performance, as shown in Figure 4a. This is due to two reasons. First, the time-based electricity price is determined by the state of the power system, such as generations and transmission, to serve the energy demand at each time. However, the state of the power system does not change rapidly. Therefore, when the measurement interval is as short as 20 min, the electricity price is constant. Second, when the measurement interval is as long as 30 min, the influence of the price change is marginal because the information measurement error is small.

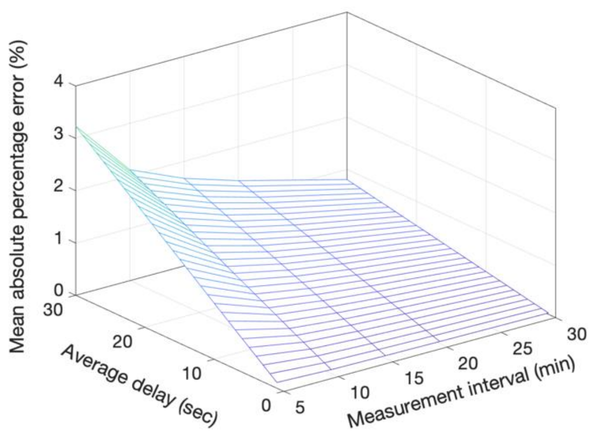



**Figure 5.** Service performance in AMR-based power consumption measurement.

To show how the service performance is determined, Figure 6 presents the pricing error of AMR-based power consumption measurement according to the real-time price change. The right and left axes of Figure 6 express the real-time price, and pricing error, respectively, according to the measurement error in the case of a 15-min measurement interval and 20-s average delay. Similar to the measurement time, in the case of a pricing error at each measurement time, the MAPE has an error of approximately 1%. However, as shown in Figure 6, the effect of the error on the monthly bills is negligible, as positive and negative pricing errors are offset. Moreover, the pricing error is sparkled only at the moment when the real-time price is converted and is marginal in the rest of the section. The information measurement performance and service performance in Figures 4 and 5 indicate that AMR can be used and therefore replacement with a smart meter is not required.

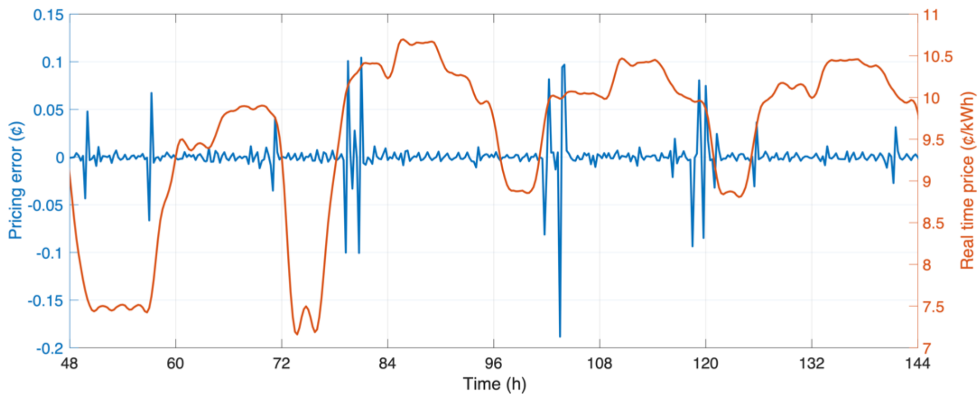



**Figure 6.** Pricing error of AMR-based power consumption measurement according to the real-time price change.

### *4.3. Implementation Cost Analysis*

The implementation costs for the two architectures are compared in this section based on the actual field costs [28,29]. Therefore, due to the effectiveness of the existing AMR system, new smart meters and communication modems are not required, which significantly reduces the total cost. In the case study of 3000 household multi-dwelling units, smart meters and modems accounted for more than 70% of the total cost, as presented in Table 2. The DCU upgrade and server installation/upgrade costs are the same in both cases. The server cost includes the cost of an uninterruptible power supply (UPS), and a high-availability server configuration setup for five-min-based metering services.

**Table 2.** Cost analysis for AMI installation in a multi-dwelling unit with 3000 households.

| | **AMR-Based** | **New AMI** |
|---|---|---|
| Smart meter | Not required | USD 35 × 3000 houses |
| Modem | Not required | USD 25 × 3000 houses |
| DCU upgrade | USD 500 × 100 clusters | USD 500 × 100 clusters |
| Server upgrade | USD 20,000 × 1 set | USD 20,000 × 1 set |
| Installation & Labor | Not required | USD 20 × 3000 houses |
| Total | USD 70,000 | USD 310,000 |

The cost analysis result indicates that by using the existing AMR system, 343% more AMIs can be deployed with the same budget while satisfying the minimum requirements. This suggests that the appropriate technology can contribute by reducing deployment delay among households in multi-dwelling units. Alternatively, the saved budget can be used to accelerate or educate tenants to develop the service using metering in the energy sector. In particular, in the early stage of AMI deployment, there are no clear business models specialized for AMI, except for the time-of-use based tariff.

## 5. Conclusions

Cost efficiency is an important factor for the acceleration of the AMI deployment, while satisfying the minimum requirements. To meet the minimum requirements, the technical and implementation issues should be addressed. This paper investigated the feasibility of the AMR-based power consumption measurement system. The information measurement performance, service performance and implementation cost are used as the indicators to select the appropriate technology for power consumption measurement in multi-dwelling unit environments. Experimental results using the real data sets recorded in Korea show that the AMR-based power consumption measurement system has the performance reduction for the information measurement and service compared to the measurement using the smart meter-based AMI system. However, the performance degradation is marginal at less than 1% with low implementation cost. It indicates that the AMR-based power consumption measurement system is a suitable technology to provide the current time-based pricing service. As a result, the proposed method benefits both utility and customers by reducing costs and deployment delays while providing enough performance when they already have AMR.

To improve the reliability of the service that uses the AMR-based system, additional issues are required to be resolved. First, the missing data is a critical issue because the meters used in the AMR systems do not have memories, as mentioned in Section 2. This can be complemented by the load profile estimation when data between the AMR meter and DCU are missing. Missing data due to communication failure problems between the DCU and server can be managed by using or adding memory storage in the DCU. Second, the measurement delay is another issue that occurs when a service is performed using the AMR systems. As presented in Section 3, the delay causes a service price error. Delay is a time asynchronous problem that arises from the difference between the actual time and the information time used for service utilization. Fortunately, energy information is periodic. The measurement delay can be reduced by applying nonintrusive load monitoring and/or time synchronization approaches.

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