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# Describing Long-Term Electricity Demand Scenarios in the Telecommunications Industry: A Case Study of Japan

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**Abstract:** Due to the rapid expansion of information and communication technology (ICT) usage, the telecommunications industry is faced with a challenge to promote green ICT toward achieving a low-carbon society. One critical obstacle in planning long-term strategies for green ICT is the uncertainty of various external factors, such as consumers' lifestyle and technological advancement. To tackle this issue, this paper employs a scenario planning method to analyze electricity consumption in the telecommunications industry, where both changes in various external factors and energy-saving measures are assumed. We propose a model to estimate future electricity consumption of the telecommunications industry using a statistical approach. In a case study, we describe four scenarios that differ in the diffusion of ICT and the technological advancement of ICT equipment in order to analyze the electricity consumption in Japan's telecommunications industry to 2030. The results reveal that the electricity consumption in 2030 becomes 0.7–1.6-times larger than the 2012 level (10.7 TWh/year). It is also shown that the most effective measures to reduce the electricity consumption include improving the energy efficiency of IP (Internet Protocol) communication equipment and mobile communication equipment.

**Keywords:** green ICT; scenario planning; electricity consumption; telecommunications industry; statistical approach

## 1. Introduction

The usage of information and communication technology (ICT) is widely recognized as a means of improving energy efficiency to address climate change across the world [1,2]. Smart buildings, smart transportation systems and smart grids are examples of ICT applications that help to improve environmental performance in society [3]. In addition to environmental benefit, ICT devices, such as personal computers and smartphones, have enhanced convenience in our everyday lives. However, the expansion of ICT usage results in an increase in the ICT sector's share of global $CO_2$ emissions, which is projected to increase from 1.3% of global emissions in 2002 to 2.3% in 2020 [4]. Thus, green

ICT needs to be further promoted than ever to reduce $CO_2$ emissions. Here, green ICT is a concept enabling the improvement of the environmental performances of ICT (*i.e.*, direct effects of ICT) [3].

In the telecommunications industry, new technologies have been introduced to promote green ICT, such as fiber optic cables to reduce energy consumption in fixed networks and energy-efficient base stations in mobile networks [3]. The $CO_2$ emissions in the telecommunications industry stem largely from the electricity consumption of communication buildings. A communication building refers to a building containing ICT equipment (e.g., telephone switchboard) and other associated equipment (e.g., air-conditioning equipment) in order to provide telecommunication services. Given that the lifetime of ICT network infrastructure, including equipment in communication buildings, is typically 5–10 years or longer, the research question in this paper is how to plan mid- and long-term strategies to effectively reduce the electricity consumption in the telecommunications industry. One critical obstacle is the uncertainty of various external factors surrounding the telecommunications industry (e.g., technological advancement and consumers' lifestyle), which may affect the electricity consumption in the future. To the best of our knowledge, few studies have tackled the above question in ways that take into account such uncertainty, although much effort has been devoted to research on the energy savings of ICT equipment from a technological viewpoint. For example, Schlomann *et al.* [5] analyzed the technological improvement potential in the electricity consumption of ICT equipment.

To solve the above research question, this paper aims at describing scenarios to analyze a possible range of electricity consumptions by assuming a variety of uncertain external factors associated with the telecommunications industry, as well as energy-saving measures. In this paper, the boundary of interest is limited to the ICT network infrastructure owned by telecommunications companies (see Section 2.1 for details), whereas other end-user devices (such as personal computers, televisions and data centers) are outside the scope of the paper. In the process of describing scenarios, we distinguish external and internal factors of the telecommunications industry: external factors are uncontrollable by telecommunications companies (e.g., social changes), whereas internal factors are controllable by the same (e.g., energy-saving measures). We employ a scenario planning method to assume future social situations, upon which we estimate a range of the electricity consumptions in the future. We quantify the scenarios by developing the electricity demand model for the telecommunications industry (EDMoTI). The characteristic of this model is to extrapolate the electricity consumption of ICT equipment based on the correlation of the electricity consumption and various external factors. In addition, the model enables in-depth analysis of the entire electricity consumption of communication buildings using the communication building electricity demand model, which was developed in our previous study [6]. A case study demonstrates the scenario exercises of the electricity consumption in the Japanese telecommunications industry to 2030.

The rest of the paper is organized as follows. Section 2 mentions the current trends of electricity consumption in the telecommunications industry. Section 3 proposes a method for describing electricity demand scenarios in the telecommunications industry using EDMoTI. Section 4 depicts a case study of scenario analysis regarding the electricity consumption of Japan's telecommunications industry to 2030. Section 5 discusses the advantages and limitations of the proposed method based on case study results. Section 6 concludes the paper.

## 2. Current Trends and Problems in the Telecommunications Industry

### *2.1. Current Trends and Outlook of Electricity Consumption in the Telecommunications Industry*

The diffusion of ICT in many ways, such as smartphones and social networking services (SNS), has brought about changes in our lifestyles and workstyles [7]. The global IP (Internet Protocol) traffic in 2014 was increased to 59,851 petabytes per month (PB/month) [8] in accordance with the expansion of ICT services. According to Cisco, global IP traffic has increased more than five-fold in the past five years and will increase nearly three-fold over the next five years [8]. Likewise, in Japan, the total volume of download traffic by broadband subscribers as of 2012 reached 1.7 Tbps (equivalent to approximately 550 PB/month), increasing at an annual growth rate of about 20% from 2004–2012 [7].

As ICT usage is rapidly expanding, the global electricity consumption by ICT equipment is growing accordingly [9]. Figure 1 shows the electricity consumption in the Japanese telecommunications industry from 2005–2012, where the data were obtained from CSR (corporate social responsibility) reports published by major Japanese telecommunications companies [10–12]. The total electricity consumption in 2012 was 11.4 TWh/year, which was 1.1-times larger than that in 2005 (10.4 TWh/year). As described in Table 1, the services provided by the telecommunications industry are classified into five categories, (1)–(5). In 2012, the electricity consumption of mobile network accounted for 45% of the total, followed by the IP communication network (20%), the fixed-line network (18%) and office (12%). The electricity consumption of the IP communication network and mobile network beyond 2012 is projected to steadily increase, whereas that of the fixed-line network and office is likely to be stable or rather declining (see Figure 1).

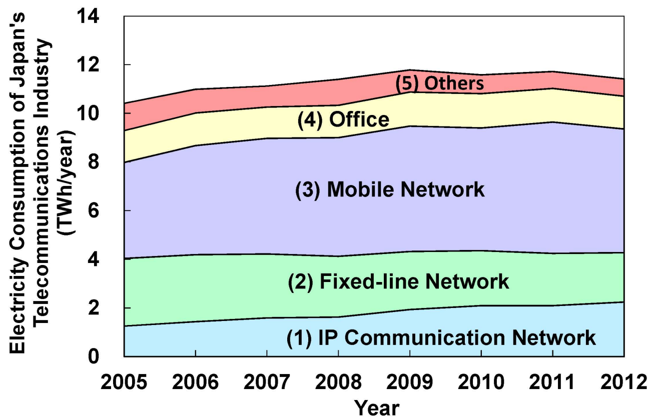


**Figure 1.** Electricity consumption in the Japanese telecommunications industry [10–12].

**Table 1.** Constituent equipment of the telecommunications industry according to provided services.

| Category | Provided Services | Constituent Equipment |
|---|---|---|
| (1) IP (Internet Protocol) communication network | • Broadband network service<br>• IP telephone service | • IP communication equipment<br>• Air conditioning equipment<br>• Power-feeding equipment |
| (2) Fixed-line network | • Fixed-line telephone service<br>• Public telephone service | • Telephone switchboard<br>• Air conditioning equipment<br>• Power-feeding equipment |
| (3) Mobile network | • Mobile telephone service<br>• Mobile data communication service | • Mobile communication equipment<br>• Air conditioning equipment<br>• Power-feeding equipment |
| (4) Office | • Maintenance and management of telecommunication networks | • Office equipment (e.g., lighting, air conditioning and office automation) |
| (5) Others | • Other services (e.g., data center) | • Diverse equipment |

Since the equipment associated with Categories (1)–(4) is installed in communication buildings, over 90% of the total electricity consumption comes from communication buildings, as seen from Figure 1. A communication building consists of two types of space: ICT equipment space and office space [6]. ICT equipment space is used to provide Services (1)–(3) in Table 1, where ICT equipment (*i.e.*, IP communication equipment, mobile communication equipment and telephone switchboard), air-conditioning equipment and power-feeding equipment are installed. On the other hand, office space has office equipment installed (e.g., lighting and air conditioning).

### *2.2. Related Work and Problems*

There are a number of studies related to electricity consumption in the telecommunications industry. Lubritto *et al.* [13] examined the relationship between the electricity consumption of mobile network systems and outdoor temperature. Malmodin *et al.* [14] assessed the electricity use related to the ICT sector and the entertainment and media sector, including end users (e.g., personal computers, televisions and data centers). Malmodin *et al.* [15] performed a life cycle assessment (LCA) of Swedish ICT networks, including end-user equipment and the IP core network. Nielsen *et al.* [16] proposed an optimization scenario in the construction of ICT networks by integrating fixed broadband access with wireless communications. Jorguseski *et al.* [17] presented an example of reducing energy consumption in wireless access networks by dynamically switching on/off base stations according to the current traffic demands. Koomey [18] estimated total power consumption by servers and associated air-conditioning equipment in the U.S. and the world. Regarding future electricity consumption in the telecommunications industry, Kuroda *et al.* [19] forecast the electricity consumption of the Japanese telecommunications industry to 2030 based on the projection of telecommunication traffic by Cisco [8].

Regardless of existing studies as shown above, it is still unclear how the entire electricity consumption in the telecommunications industry will be influenced by future changes in external factors, such as consumers' lifestyles, the ICT services provided and the energy efficiency of ICT equipment. This makes it difficult to identify what measures are effective at reducing the electricity consumption as a whole.

## **3. Methodology for Describing Electricity Demand Scenarios in the Telecommunications Industry**

### *3.1. Approach*

To help plan long-term energy-saving strategies, we describe electricity demand scenarios in the telecommunications industry. The focus of this paper is on Categories (1)–(4) in Table 1, which correspond to the electricity consumption of communication buildings, whereas Category (5) is not dominant within the overall structure in Japan (see Figure 1). We describe scenarios by applying a scenario planning method, which is intended to explore different possible futures with different trends and events to test or review of a range of plans and policy options [20]. With the aim to analyze the influences of external factors and measures on electricity consumption in the telecommunications industry, we propose a method to describe such scenarios by addressing two research tasks as follows:

(1) Developing the electricity demand model for telecommunications industry (EDMoTI) to estimate the future electricity consumption of communication buildings;
(2) Formalizing a process to describe electricity demand scenarios in the telecommunications industry using EDMoTI based on a scenario planning method [20].

Regarding Task (1), the problem is how to deal with complex causal relationships between the electricity consumption of communication buildings and various external factors (e.g., consumers' lifestyle and technological development). In order to analyze the influences of long-term social and technological changes on the electricity consumption, we propose a two-step procedure by integrating two sub-models (*i.e.*, (I) the ICT equipment electricity demand forecasting model and (II) the communication building electricity demand model). Model (I) enables analyses of the impact of the electricity consumption by social and technological changes on a business-as-usual basis. Model (II) enables analyses of the impacts of the electricity consumption when additional technological changes compared to the business-as-usual changes happen (e.g., additional improvement in the energy efficiency of ICT equipment).

In developing Model (I), we take a statistical approach to modeling the long-term electricity consumption of ICT equipment installed in communication buildings. Although there are various statistical methods available, we apply linear regression analysis, since it seems the most prevalent way to model the business-as-usual changes. That is, we assume a linear relationship between the electricity consumption of ICT equipment and explanatory variables, which are identified from among various external factors based on linear regression analysis. As described in Figure 2, we estimate the future electricity consumption of ICT equipment by extrapolating past data. Using the result of Model (I), the second step is to estimate the electricity consumption of a whole communication building by employing Model (II), which was proposed in our preceding study [6]. The electricity consumption of a communication building is calculated by adding that of ICT equipment, air-conditioning equipment and power-feeding equipment (see Table 1).

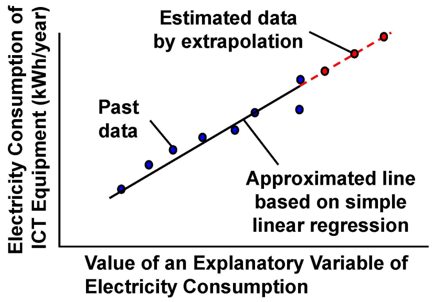


**Figure 2.** Concept of the ICT equipment electricity demand forecasting model using linear regression analysis.

Regarding Task (2), we define a process to describe electricity demand scenarios in the telecommunications industry based on our previous study [21]. The proposed process extends the scenario design procedure in [21] by integrating the usage of EDMoTI.

## 3.2. Electricity Demand Model for Telecommunications Industry

Figure 3 depicts the architecture of EDMoTI. As mentioned in Section 3.1, EDMoTI consists of two sub-models: (I) the ICT equipment electricity demand forecasting model and (II) the communication building electricity demand model. The final output of EDMoTI is the future electricity consumption of communication buildings at year *t* by aggregating the outputs of Model (II). The details of each sub-model are described below.

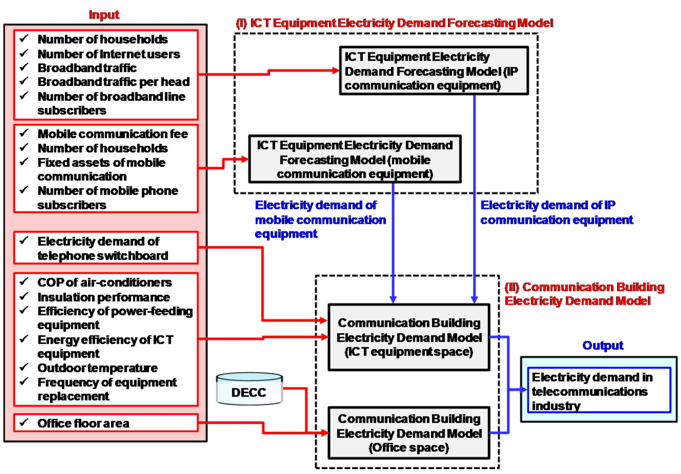


**Figure 3.** Architecture of the electricity demand model for telecommunications industry (EDMoTI). DECC, Database for Energy Consumption of Commercial Building; COP, coefficient of performance.

#### 3.2.1. ICT Equipment Electricity Demand Forecasting Model

Model (I) estimates the electricity consumption of the ICT equipment installed in communication buildings in a region at year $t$ ($F_{equip}(t)$ (kWh/year)). The basic formula of Model (I) is represented as:

$$F_{equip}(t) = A \times P(t) + B \quad (1)$$

where $P(t)$ is an explanatory variable of ICT equipment $i$ at year $t$. We identify explanatory variables $P(t)$ as external factors that meet $R^2$ >0.75 in linear regression analysis, where we use past time series data of $F_{equip}$(t) and $P(t)$. Note that $R^2$ is a coefficient of determination. Both coefficients $A$ and $B$ are determined in the same regression analysis.

Model (I) covers two types of ICT equipment, IP communication equipment and mobile communication equipment, whereas we do not model the electricity consumption of telephone switchboards, since we assume that the amount of telephone switchboards used in society will remain constant in the future. This is because, due to the rapid growth of the IP communication network and the mobile communication network in the world, fixed-line networks seem saturated and unlikely to expand in the future. The extracted explanatory variables for IP/mobile communication equipment are shown on the top-left side in Figure 3 (see Section 3.3 for details).

#### 3.2.2. Communication Building Electricity Demand Model

Model (II) calculates the electricity consumptions of ICT equipment space and office space separately, as we assume that they are independent of each other [6]. Relevant to ICT equipment space, Model (II) covers three types of ICT equipment: IP communication equipment, mobile communication equipment and telephone switchboard. The calculation method for each space is described below.

- Calculating the electricity consumption of ICT equipment space:

The basic concept of Model (II) is to estimate the annual electricity consumption of ICT equipment space per floor area in communication building $i$ at year $t$ ($e_{ict\_space}(i, t)$ (kWh/m$^2$/year)) as follows:

$$e_{ict\_space}(i,t) = e_{equip}(i,t) + e_{air}(i,t) + e_{feed}(i,t) \quad (2)$$

where $e_{equip}(i, t)$, $e_{air}(i, t)$ and $e_{feed}(i, t)$ are the electricity consumptions of ICT equipment per floor area (kWh/m$^2$/year), air-conditioning equipment per floor area (kWh/m$^2$/year) and power-feeding equipment per floor area (kWh/m$^2$/year), respectively. Letting $N$ be the number of communication buildings in the region being studied, $F_{ict\_space}(t)$ the electricity consumption of ICT equipment space in communication buildings in the region ($i$ = 1, 2, . . . , $N$) and $A_{ict\_space}(i)$ the floor area of ICT equipment space in communication building $i$, the following equation is obtained:

$$\begin{aligned} F_{ict\_space}(t) &= \sum_{i=1}^{N} \left(e_{ict\_space}(i,t) \times A_{ict\_space}(i)\right) \\ &= \sum_{i=1}^{N} \left\{ \left(e_{equip}(i,t) + e_{air}(i,t) + e_{feed}(i,t)\right) \times A_{ict\_space}(i) \right\} \\ &= \sum_{i=1}^{N} \left\{ E_{equip}(i,t) + \left(e_{air}(i,t) + e_{feed}(i,t)\right) \times A_{ict\_space}(i) \right\} \end{aligned} \quad (3)$$

where $E_{equip}(i, t)$ (kWh/year) is the annual electricity consumption of ICT equipment installed in communication building $i$ at year $t$ ($E_{equip}(i, t) = e_{equip}(i, t) \times A_{ict\_space}(i)$).

When we calculate the value of $F_{ict\_space}(t)$ in the future by connecting Equation (1) with Equation (3), we estimate $E_{equip}(i, t)$ as follows. Assuming that the rate of changes in the electricity consumption from the initial year $t_0$ to arbitrary year $t$ is the same among all communication buildings, we estimate temporal changes in $E_{equip}(i, t)$ in proportion to those in $F_{equip}(t)$, that is,

$$E_{equip}(i,t) = E_{equip}(i,t_0) \times \frac{F_{equip}(t)}{F_{equip}(t_0)} \tag{4}$$

where both $F_{equip}(t)$ and $F_{equip}(t_0)$ are obtained using the regression equation of Equation (1). Hence, if $E_{equip}(i, t_0)$ is given, $F_{ict\_space}(t)$ is obtained by plugging Equation (4) into Equation (3).

According to our previous study [6], $e_{air}(i, t)$ and $e_{feed}(i, t)$ are calculated as follows. First, we calculate $e_{air}(i, t)$ based on the exhaust heat from ICT equipment and the heat transmission from outside air into communication building $i$.

$$e_{air}(i,t) = \frac{e_{equip}(i,t) + Q(i,t)}{COP(i,t)} \tag{5}$$

where $Q(i,t)$ (kWh/m$^2$/year) and $COP(i, t)$ are the yearly heat transmission amount per floor area at year $t$ and the average yearly coefficient of performance (COP) of air-conditioning equipment at year $t$, respectively. $Q(i,t)$ is given by:

$$Q(i,t) = \frac{U(i) \times S(i) \times (T_{out}(i) - T_{in}(i)) \times 8760(h/year)}{A_{ict\_space}(i)} \tag{6}$$

where $U(i)$ (kW/K·m$^2$), $S(i)$ (m$^2$), $T_{out}$ (K) and $T_{in}$ (K) are the heat transmission coefficient of communication building $i$, the gross area of the envelope of communication building $i$, outdoor temperature and indoor temperature, respectively.

Second, we calculate $e_{feed}(i, t)$ by the following equation:

$$e_{feed}(i,t) = \eta \times (e_{equip}(i,t) + e_{air}(i,t)) \tag{7}$$

where $\eta$ is the loss coefficient of power-feeding equipment. Using Equations (5) and (7), Equation (3) is converted to:

$$F_{ict\_space}(t) = \sum_{i=1}^{N} \left\{ \frac{(1 + COP(i,t)) \times E_{equip}(i,t) + Q(i,t) \times A_{ict\_space}(i)}{COP(i,t)} \right\} \times (1+\eta) \tag{8}$$

Although $E_{equip}(i, t)$ is given by Equation (4), the value of $E_{equip}(i, t)$ may become smaller because of the improvement of the energy efficiency of ICT equipment. It should be noted that $E_{equip}(i, t)$ in Equation (4) includes business-as-usual improvement, since we derive Equations (1) and (4) using regression analysis with past data, which already involve historical improvement in the energy efficiency of ICT equipment. Letting $\gamma(t)$ be the additional energy efficiency improvement of ICT equipment as of year $t$ compared to business-as-usual, we express the annual electricity consumption of ICT equipment taking into account additional technological improvement of ICT equipment as:

$$E'_{equip}(i,t) = E_{equip}(i,t) \times \gamma(t) \tag{9}$$

Finally, the following equation is obtained by substituting $E_{equip}(i, t)$ in Equation (8) with $E_{equip}{'}(i, t)$ in Equation (9):

$$\begin{aligned} F_m(t) &= \sum_{i=1}^{N} \left\{ \frac{(1 + COP(i,t)) \times E'_{equip}(i,t) + Q(i,t) \times A_{ict\_space}(i)}{COP(i,t)} \right\} \times (1+\eta) \\ &= \sum_{i=1}^{N} \left\{ \frac{(1 + COP(i,t)) \times E_{equip}(i,t) \times \gamma + Q(i,t) \times A_{ict\_space}(i)}{COP(i,t)} \right\} \times (1+\eta) \end{aligned} \tag{10}$$

- Calculating the electricity consumption of office space:

We calculate the electricity consumption of office space by multiplying the office floor area ($m^2$) and average monthly electricity consumption of an office building ($kWh/m^2/month$), which refers to the Database for Energy Consumption of Commercial Building (DECC) [22]. We calculate the annual electricity consumption of office space ($kWh/m^2/year$) as the sum of electricity consumption from January–December.

### *3.3. Deriving the Formula of the ICT Equipment Electricity Demand Forecasting Model in the Japanese Context*

We derived formulae of Model (I) (see Section 3.2.1), specifically for IP communication equipment and mobile communication equipment, in the Japanese context. For this purpose, we carried out linear regression analysis between various external factors and the electricity consumption of IP/mobile communication equipment (TWh/year) in the period of 2005–2012 (see Figure 1). External factors as candidates of explanatory variables were chosen based on available statistical data in Japan, which included ICT white papers [7,23], population [24], GDP (gross domestic product) [25] and the number of mobile phone subscribers [26].

Table 2 summarizes extracted explanatory variables that meet $R^2$ >0.75. Note that other tested variables, which do not meet $R^2$ >0.75, are listed in Table A1 (see the Appendix). The number of households has a high correlation with the electricity consumption of IP/mobile communication equipment. In contrast, GDP is less correlated with electricity consumption. The formulae in Table 2 are used in the case study in Section 4.

**Table 2.** ICT equipment electricity demand forecasting model in Japan.

| | Explanatory Variables | $R^2$ | Coefficient | |
|---|---|---|---|---|
| | | | A | B |
| IP communication equipment | | | | |
| 1 | Number of national households (thousand) | 0.976 | $1.8 \times 10^{-4}$ | −8.0 |
| 2 | Number of broadband subscribers (thousand) | 0.971 | $3.8 \times 10^{-5}$ | −0.22 |
| 3 | Number of Internet users (thousand) | 0.964 | $5.1 \times 10^{-5}$ | −3.6 |
| 4 | Broadband traffic (Gbps) | 0.962 | $4.1 \times 10^{-4}$ | 0.56 |
| 5 | Broadband traffic per subscriber (bps/subscriber) | 0.955 | $1.7 \times 10^{-5}$ | 0.37 |
| Mobile communication equipment | | | | |
| 1 | Mobile communication fee (JPY/household/year) | 0.912 | $4.5 \times 10^{-5}$ | −0.78 |
| 2 | Fixed assets of mobile communication (billion JPY) | 0.846 | $4.6 \times 10^{-4}$ | 1.8 |
| 3 | Number of national households (thousand) | 0.771 | $1.8 \times 10^{-4}$ | −6.5 |
| 4 | Number of mobile phone subscribers (thousand) | 0.760 | $1.7 \times 10^{-5}$ | 0.93 |

### *3.4. Procedure for Undertaking Scenario Analysis of Electricity Consumption*

With the aim to systematically describe electricity demand scenarios in the telecommunications industry using EDMoTI, we define a procedure in four steps by adjusting the scenario planning method [21] as follows:

1. Problem setting: The scenario designers explicitly define the objective of scenario analysis being undertaken (*i.e.*, what should be achieved using the scenario analysis?) and a region and time horizon of interest.
2. Extracting key drivers: The scenario designers extract key drivers to delineate a scenario structure. The scenario designers organize a workshop in constructing a causal network in order to understand the relationship between external and internal factors of electricity consumption in the telecommunications industry by utilizing a brainstorming technique (e.g., PEST (political, economic, social and technological) analysis [27] and the KJ method [28]). Based on the causal network, the two-axis method [20] is applied to generate four contrasting scenarios by placing a major factor influencing electricity consumption (*i.e.*, key driver) on each of two axes. The two

key drivers chosen should be "high impact, high uncertainty", to ensure that the four quadrants defined by their intersection are clearly differentiated.

3. Describing scenario storylines: The scenario designers set each of the four quadrants as a sub-scenario, in which the scenario designers define the scenario titles and describe/narrate the storylines of each sub-scenario.
4. Describing sub-scenarios with EDMoTI: The scenario designers detail the storylines of the four sub-scenarios. In this step, each sub-scenario is quantified to estimate future electricity consumption. More concretely, in each sub-scenario, the scenario designers assume the values of the input parameters in Figure 3 to be consistent with the storyline described in Step 3. Then, the scenario designers estimate the future electricity consumption of IP/mobile communication equipment using Model (I), followed by estimating a whole communication building using Model (II).

## 4. Case Study: Describing Electricity Demand Scenarios in Japan's Telecommunications Industry

In this section, we described electricity demand scenarios in the Japanese telecommunications industry along with the four-step procedure mentioned in the previous section.

### *4.1. Problem Setting*

The main objective of this scenario exercise was to clarify what external factors and energy-saving measures have a large impact on future electricity consumption in the telecommunications industry. The scenarios here were mainly designed by university researchers working on scenario studies, who are not experts in ICT. The period covered was from 2012–2030, while the targeted region was the Japanese telecommunications industry. One reason for choosing this period was that it becomes much more difficult to foresee a longer term future (e.g., 2050), as ICT itself and relevant standards and regulations would be drastically changed from the present.

### *4.2. Extracting Key Drivers*

The scenario designers constructed a causal network of the electricity consumption in ICT equipment space. Figure 4 shows part of the causal network. It was found that the whole structure can be divided into three blocks: electricity consumption, ICT equipment and ICT service demand. As a result, the scenario designers identified consumes' lifestyles and energy-saving technology as key drivers, because both were connected to many other external factors and, therefore, seemed the most influential on the electricity consumption.

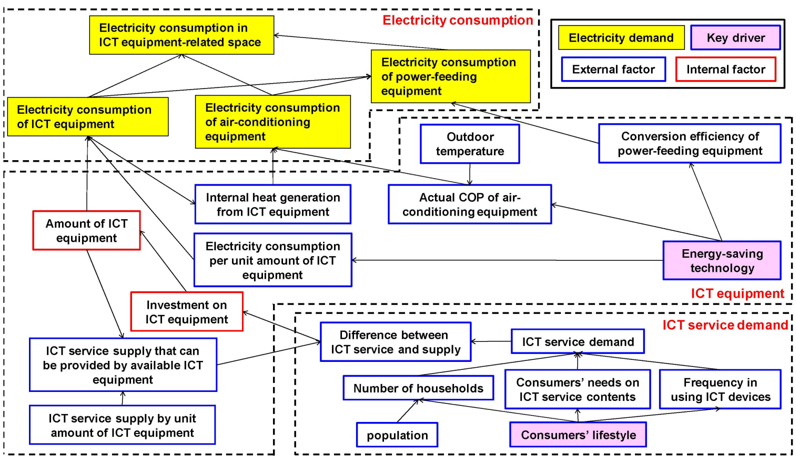


**Figure 4.** Causal network of the electricity consumption in ICT equipment space (not exhaustive).

### *4.3. Describing Scenario Storylines*

Figure 5 shows the resulting four quadrants, each of which represents a sub-scenario or a possible future of Japan's telecommunications industry. The scenario designers named the scenario titles as follows: (A-1) lower consumption scenario, (A-2) baseline scenario, (B-1) technology-oriented society scenario and (B-2) energy-consuming scenario. They were differentiated in terms of the pace of technological advancement and the ICT diffusion level caused by consumers' lifestyles. Scenario (A-2) was regarded as business-as-usual. In contrast, Scenarios (A-1) and (B-1) assumed a faster pace of energy-saving technology advancement than the current pace because of investment and governmental policies on energy savings. Scenarios (B-1) and (B-2) assumed a higher level of ICT diffusion than the current level, where people were assumed to be shifting to ICT-oriented lifestyles using various types of devices, which might include autonomous vehicles [29] and wearable cameras.

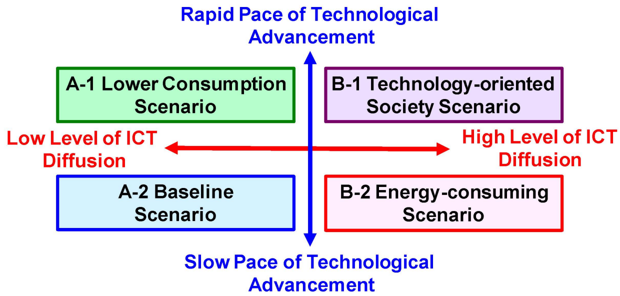


**Figure 5.** Four quadrants of the scenario storylines.

### *4.4. Describing Sub-Scenarios with Simulations of Electricity Consumption*

Consistent with the underlying assumption in Figure 5, the scenario designers assumed specific conditions of the input parameters of EDMoTI as shown in Table 3. Common assumptions across the sub-scenarios included:

- The number of households in Japan was assumed to decrease to 51,231 thousand in 2030 from 52,854 thousand in 2012 [24];
- The COP of air-conditioning equipment was assumed to be 2.57 in 2012 when the outdoor temperature is 35 °C and the load factor is 100%, respectively [30];
- The monthly electricity consumption data of a set of communication buildings, in the period of April 2012–March 2013, were used to represent the Japanese telecommunications industry. These data were analyzed in our previous study [6]. Here, the buildings were located in the eastern area of Japan. Based on these buildings, the distribution of the floor areas of ICT equipment and office spaces was assumed. Also, the outdoor temperature of each building was set according to which prefecture the building was located;
- Average monthly outdoor temperatures of prefectural capitals [31] were used to assume outdoor temperature, while indoor temperatures of all communication buildings were set at 24 °C;
- The electricity consumption of the telephone switchboard was assumed to gradually decline because of the replacement of old equipment with newer and more energy-efficient ones.

Figure 6 shows the electricity consumption in the four sub-scenarios. The solid line of each sub-scenario represents the mean estimate or averaged electricity consumption. The range in each sub-scenario, which is expressed as dotted lines, means the difference in response to the formula of Model (I) (see Table 2). For example, Figure 7 expresses the range of the electricity consumption of IP communication network in Scenario B-2, where the upper and lower bounds were determined by broadband traffic and the number of households, respectively. Note that the "mean estimate" line in Figure 7 is drawn as the simple arithmetic average of all of the estimates. According to Figure 6, the results in 2030 ranged from 7.7 TWh/year (A-1) to 17.0 TWh/year (B-2), which reached 0.72 (A-1), 1.59-times (B-2) larger than the 2012 level (10.7 TWh/year). While the electricity consumption in A-2, B-1 and B-2 in 2030 was higher than that in 2012, the electricity consumption in Scenario A-1 decreased from 2012.

**Table 3.** Scenario assumptions (not exhaustive).

| Parameter | Value | | Remarks |
|---|---|---|---|
| | 2012 | 2030 | |
| Number of households (thousands) | 52,854 | 51,231 | The number of households was assumed to decrease according to [24]. |
| Average yearly electricity consumption per office floor area (kWh/m$^2$/year) | 132 | 65.8 (A-2, B-2)<br>52.6 (A-1, B-1) | The data in 2012 were calculated using the floor areas of a set of the communication buildings [6] and the average electricity consumption of office buildings provided by DECC [22]. The data in 2030 were assumed by referring to external literature [32]. |
| Office floor area (thousand m$^2$) | 1,020 | | The office floor area to 2030 was assumed the same across the entire period [10–12]. |
| Broadband traffic (Gbps) | 1905 | 10,110 (A-1, A-2)<br>50,710 (B-1, B-2) | The broadband traffic in 2030 was assumed by linearly extrapolating past data (2005–2012) for A-1 and A-2, while increasing as projected in [8] for B-1 and B-2. |
| Energy efficiency improvement of ICT equipment in 2030 compared to business-as-usual $\gamma(t)$ | n/a | 1 (A-2, B-2)<br>0.87 (A-1, B-1) | The energy efficiency of ICT equipment in A-2 and B-2 was assumed to improve on a business-as-usual basis from 2012, while that in A-1 and B-1 was improved more by referring to [33]. The ICT equipment being considered here was IP and mobile communication equipment. |
| Electricity consumption of telephone switchboards in Japan (TWh/year) | 1.125 | 0.944 (A-2, B-2)<br>0.510 (A-1, B-1) | The electricity consumption of telephone switchboards in 2030 in A-2 and B-2 was the case in which all of the switchboards were replaced with the state-of-the-art equipment available as of 2012 [10–12]. In A-1 and B-1, on the other hand, continuous improvement in the energy efficiency of switchboard was assumed from 2012–2030. The replacement period was 9 years, as designated by law. |
| Conversion efficiency of power-feeding equipment η | 82% | 82% (A-2, B-2)<br>88% (A-1, B-1) | The conversion efficiency of power-feeding equipment in A-2 and B-2 was assumed constant from 2012 [10–12], while continuous improvement was assumed in A-1 and B-1 [34]. |
| Average COP improvement of air-conditioning equipment compared to the 2012 level | 1 | 1 (A-2, B-2)<br>1.45 (A-1, B-1) | The COP in 2030 in A-1 and B-1 was assumed as the state-of-the-art performance available as of 2012 [30], while that in A-2 and B-2 was the same in 2012. The replacement period was 12 years, as designated by law. |
| Heat transmission coefficient of communication buildings $U(i)$ (W/(K·m$^2$)) | 0.39 (wall)<br>0.42 (roof) | | The data were assumed with reference to [35]. |

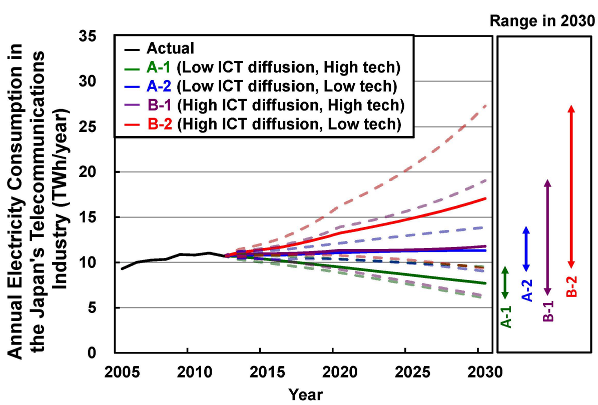


**Figure 6.** Electricity consumption to 2030 in each scenario.

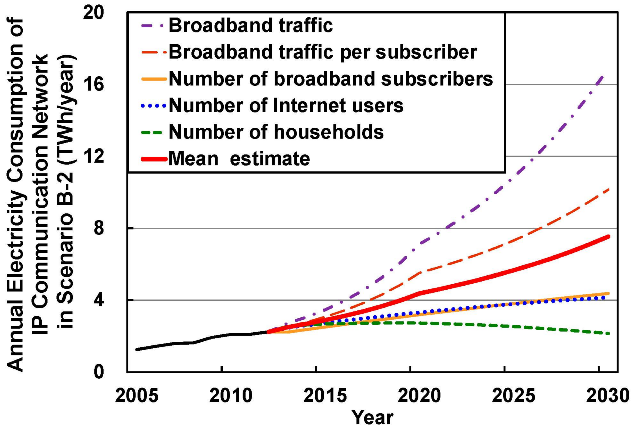


**Figure 7.** Electricity consumption of IP communication network in Scenario B-2.

Now, we focus on Scenario B-2 to discuss how to reduce the electricity consumption in the most energy-consuming future. Figure 8 shows the breakdown of the electricity consumption in Scenario B-2 by equipment. Air-conditioning equipment occupied the largest portion in 2030, accounting for 28%. Both IP communication equipment and mobile communication equipment accounted for 24% in 2030. In particular, IP communication equipment was doubled from 12% in 2012. The electricity consumption of telephone switchboards was almost halved in 2030 (6%) from 2012 (10%) because of equipment replacement.

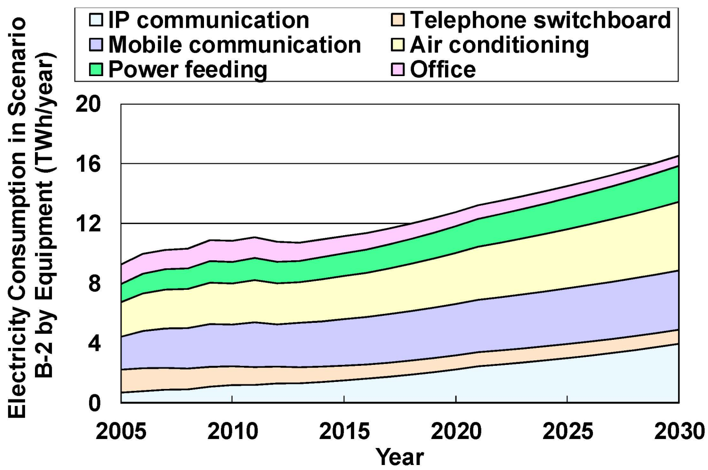


**Figure 8.** Electricity consumption in Scenario B-2.

To explore effective measures for energy savings, a sensitivity analysis was conducted.

Table 4 lists the five most influential parameters on the electricity consumption. The sensitivity here refers to the difference in electricity consumption due to a 10% change in the parameter divided by the original electricity consumption in Scenario B-2. According to the result in Table 4, the most effective measures included improving the energy efficiency of IP/mobile communication equipment. Therefore, faster replacement of such equipment with more energy-efficient ones would be an effective action. In addition, introducing air-conditioning equipment with higher COP was also effective at reducing the electricity consumption.

**Table 4.** Sensitivity analysis of the electricity consumption in Scenario B-2 (5 most influential parameters).

| No | Parameter | Sensitivity to 10% Change in Each Parameter | |
|---|---|---|---|
| | | Electricity Consumption in 2030 (TWh/year) | Difference Divided by Reference (%) |
| | Reference (Scenario B-2) | 17.0 | - |
| 1 | Energy efficiency of IP communication equipment | 16.3 | 4.7% |
| 2 | Energy efficiency of mobile communication equipment | 16.3 | 4.5% |
| 3 | COP of air-conditioning system | 16.6 | 2.4% |
| 4 | Broadband traffic | 16.7 | 2.0% |
| 5 | Conversion efficiency of power-feeding equipment | 16.8 | 1.5% |

## 5. Discussions

EDMoTI enabled analyzing the impacts of changes in both social factors (e.g., broadband traffic) and technological factors (e.g., energy efficiency of ICT equipment) on future electricity consumption in the telecommunications industry. However, there are several limitations in our model. First, we chose the simplest method (*i.e.*, linear regression) to model the business-as-usual changes. Since future electricity consumption in the telecommunications industry obviously involves non-linear phenomena, the applicability of the model thus needs to be further tested through several ways, such as conducting more case studies and interviewing ICT experts. Moreover, continuous effort is necessary in collecting pertinent time series data to enhance the validity of the developed model. Nevertheless, we believe that our attempt is available as a benchmark approach for future research. Second, although Model (I) assumed the same amount of telephone switchboards from 2012–2030, the amount might decrease in the future as customers switch to mobile and IP phones from fixed-line phones. Therefore, one future issue is to extend Model (I) to further analyze the future electricity consumption of telephone switchboards. To do this, it is necessary to gather relevant data, such as the number of fixed-line phone subscribers.

The scenario description procedure proposed in this paper successfully helped to describe four distinct sub-scenarios in the case study. Different from merely using simulations, our approach was to combine a scenario planning method and mathematical models (*i.e.*, EDMoTI). This approach was advantageous in systematically analyzing a possible range of electricity demand in the future while ensuring consistency within the scenario involving social situations and technological parameters (see Sections 4.3 and 4.4). Although the case study in Section 4 chose the two axes of ICT diffusion and technological advancement (see Figure 5), choosing other axes and describing alternative scenarios would be meaningful to undertake in-depth scenario analysis.

Key messages from the scenario exercise are summarized in two points: (1) the electricity consumption in 2030 is likely to increase from 2012 unless technological advancement on energy savings is accelerated (see Figure 6); and (2) proactive replacement is recommended to reduce electricity consumption, particularly for IP communication equipment, mobile communication equipment and air-conditioning equipment according to the sensitivity analysis in Table 4 Regarding (2), we should take into account the environmental impact of ICT equipment in its product lifecycle, since there is a trade-off between the energy savings due to faster replacement and the energy consumption in the manufacturing process of new ICT equipment. Furthermore, cost-effect analysis remains a future issue, since the sensitivity analysis did not take into account the economic aspect.

## 6. Conclusions

We proposed a method for describing electricity demand scenarios in the telecommunications industry in order to help plan mid- and long-term strategies for energy savings. By employing a scenario planning method to assume future social situations, we formalized a procedure to describe the scenarios. We quantified the scenarios by developing the electricity demand model for telecommunications industry (EDMoTI). A scenario exercise was carried out regarding electricity consumption of Japan's telecommunications industry to 2030. The results revealed that the electricity consumption in 2030 was 0.7–1.6-times larger than the 2012 level (10.7 TWh/year). It was also shown that the most effective measures to reduce the electricity consumption included improving the energy efficiency of IP/mobile communication equipment and air-conditioning equipment. Future work includes further verification of the proposed model.

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**Author Contributions:** Yusuke Kishita and Yasushi Umeda developed the ICT equipment electricity demand forecasting model and the method for describing scenarios in the telecommunications industry. Moreover, they were mainly responsible for executing the case study in Section 4. Yohei Yamaguchi and Yoshiyuki Shimoda developed the communication building electricity demand model and tested the validity of the model. Minako Hara, Atsushi Sakurai, Hiroki Oka and Yuriko Tanaka contributed to this work in collecting various data to carry out the case study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix

**Table A1.** Tested variables that do not meet $R^2 > 0.75$.

| | Variables | $R^2$ | Coefficient | |
|---|---|---|---|---|
| | | | A | B |
| | IP communication equipment | | | |
| 1 | Investment in fixed-line network (billion JPY/year) | 0.397 | $-2.3 \times 10^{-3}$ | 3.3 |
| 2 | Value of fixed assets of fixed-line network (billion JPY) | 0.389 | $-2.0 \times 10^{-3}$ | 3.6 |
| 3 | Personal computer ownership rate (%) | 0.105 | $-1.8$ | 2.4 |
| 4 | GDP per capita (USD/capita in 2011, purchasing power parity (PPP)) | 0.000 | $5.6 \times 10^{-6}$ | 0.80 |
| | Mobile communication equipment | | | |
| 1 | Length of mobile phone calls (second/subscriber/day) | 0.551 | $5.5 \times 10^{-3}$ | 3.9 |
| 2 | Mobile traffic per subscriber (bps/subscriber) | 0.307 | $1.5 \times 10^{2}$ | 2.6 |
| 3 | Mobile traffic (Gbps) | 0.290 | $1.1 \times 10^{3}$ | 2.6 |
| 4 | Number of mobile phone base stations (thousand) | 0.090 | $-7.4 \times 10^{8}$ | 3.1 |
| 5 | GDP per capita (USD/capita in 2011, PPP) | 0.000 | $4.8 \times 10^{7}$ | 2.7 |

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