Energy Efficiency in Japan: Developments in the Business and Household Sectors, and Implications for Carbon Neutrality

Kosuke Aoki, Jouchi Nakajima, Masato Takahashi, Tomoyuki Yagi, and Kotone Yamada

Recently the efforts toward decarbonization are spreading both in Japan and abroad. In this paper, we examine the developments in Japan's energy intensity, a measure of energy efficiency, and their background at the aggregate and sectoral levels. The main results are as follows. Energy efficiency in Japan improved considerably between the 1970s and the 1980s, mainly due to the progress in energy-saving technical changes in the business sector. Although the pace of improvement decelerated on the whole from the 1990s to the first half of the 2000s, Japan's energy efficiency has returned to a moderate improving trend, particularly in the household sector, in recent years. Our estimate using a simple model of the household sector shows that the recent improvement in aggregate energy efficiency may reflect households' purchases and utilization of energy-saving goods produced by the business sector. Further efforts are expected to be made in each sector to achieve carbon neutrality.

Keywords: Climate change; Carbon neutrality; Energy efficiency; Technical change
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I. Introduction

Recently, there has been a growing interest in climate change globally. In Japan, efforts have been made to reduce greenhouse gases, such as CO2 emissions, toward achieving carbon neutrality by 2050. Such efforts to address climate change may widely affect various economic agents in Japan and abroad for a long time, since energy consumption and the resultant greenhouse gas emissions are closely related to each entity's economic activity. Working toward decarbonization may also change the industrial structure considerably. Therefore, it is crucial to pay close attention to climate change in considering Japan's economic developments.

In discussing the progress of decarbonization thus far, Kaya (1990), the Intergovernmental Panel on Climate Change (IPCC, 2000), Kurachi *et al.* (2022), and others assess changes in the amount of CO2 emissions from the perspective of energy sources and energy saving. CO2 emissions per real GDP are measured by multiplying "CO2 emission intensity (carbon intensity)," i.e., CO2 emissions per energy consumption, by "energy intensity (energy efficiency)," i.e., energy consumption per real GDP. Therefore, it is necessary to lower carbon intensity or increase energy efficiency to reduce CO2 emissions. Carbon intensity may change due to shifts in the power source structure, such as a shift from thermal power generation to solar or wind power generation. On the other hand, energy efficiency is likely to change owing to various efforts by each economic entity. For example, in the business sector, firms can improve their energy efficiency of the production process at their factories or develop final products that operate efficiently with low energy inputs. If households use such energy-efficient final products, energy efficiency improves at the aggregate level. This consideration suggests that firms producing energy-using goods contribute to developments in energy efficiency at the aggregate level through two channels: the energy efficiency of the production process and that of the products themselves.

This paper reviews developments in Japan's energy efficiency and discusses their background. Most previous studies on energy efficiency focus on the business sector. For instance, Nomura (2021) measures Japan's energy efficiency over more than the last fifty years and indicates that it has improved in the manufacturing sector. Hamamoto (2006) and Norsworthy and Malmquist (1983) analyze the major industries in the manufacturing sector and argue that environmental regulations of the government promote research and development (R&D) in firms and, in turn, contribute to an improvement in productivity. Morikawa (2011) indicates that the higher the population density of the area, the higher the energy efficiency of the nonmanufacturing sector, and points out that enhancing infrastructure in urban areas contributes to reducing environmental burden and promoting economic growth simultaneously.

Meanwhile, considering the recent increase in use of energy-efficient products such as eco-friendly automobiles and home appliances, it is essential to pay attention to developments in energy efficiency not only in the business sector (production sector)—in which such products are manufactured—but also in the household sector, in which these products are mainly used. To the best of our knowledge, few studies have focused on such efficiency in the household sector. Moreover, none of them are based on theoretical models.[1] This paper studies the changes in Japan's energy efficiency at the aggregate and sectoral levels and analyzes the recent developments in such efficiency in the business and household sectors using theoretical models and actual data. On the basis of this analysis, the paper discusses what kinds of efforts Japan needs to make to achieve a low-carbon society.

The remainder of this paper is organized as follows. Section II summarizes the developments in the energy efficiency in Japan and discusses their background. Sections III and IV examine the energy efficiency of the business and household sectors, respectively, based on simple theoretical models and empirical analyses. Section V concludes.

II. Energy Efficiency in Japan

Japan's energy intensity, a measure of energy efficiency, has followed a declining trend, indicating an improvement in efficiency in the long run, albeit with considerable fluctuations. Specifically, it improved substantially from the 1970s to the 1980s, but the pace of improvement decelerated significantly from the 1990s to the 2000s. It has recently improved again, although the pace has been moderate (Chart 1). Looking at it by sector, the improvement from the 1970s to the 1980s can be explained by the developments in the manufacturing sector. In contrast, the progress in recent years can be attributed to the household sector (Charts 2 and 3).[2]

This section analyzes developments in energy efficiency and their background in detail by phase. In doing so, we decompose changes in Japan's overall energy efficiency into the contribution of each sector to changes in efficiency.

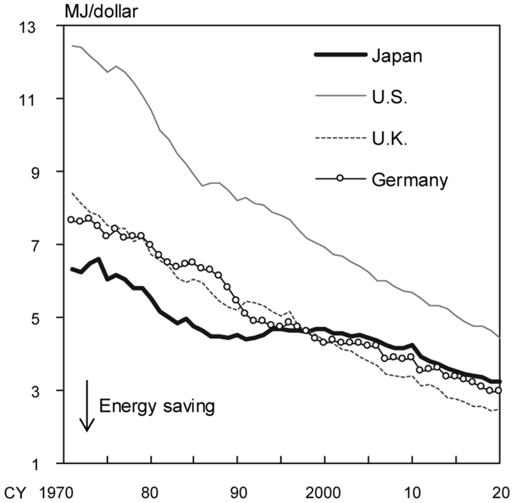
A. Phase I: From the 1970s to the 1980s

Japan's energy efficiency improved considerably from the 1970s to the 1980s, when the two Oil Shocks occurred (Phase I). There are three possible factors for improving energy efficiency in this phase.

First, changes in the industrial composition seem to have contributed to the improvement in energy efficiency at the aggregate level in Phase I (Chart 3). During this period, an increasing number of firms in the manufacturing sector shifted from a

1. Nomura (2018), one of the few studies that refers to energy efficiency of the household sector, points to the widespread use of energy-saving products in this sector as a factor for the increase in Japan's energy efficiency, in addition to the improvement in such efficiency in the business sector.
2. Energy efficiency at the aggregate level is often calculated by dividing the amount of energy supply or energy consumption by GDP. In decomposing the factors for changes in energy efficiency, we use the *General Energy Statistics* compiled by the Agency for Natural Resources and Energy for the amount of final energy consumption in the numerator. The household sector includes passenger vehicles for household use. As for the denominator, GDP for the household sector is based on the consumption of households in the expenditure side of gross domestic product, and GDP for the manufacturing and transport sectors are based on gross domestic product by economic activity (hereafter referred to as manufacturing sector GDP and transport sector GDP, respectively). Note that the former is on a fiscal year basis, while the latter is on a calendar year basis, due to statistical constraints. The intensity of "other sectors" is calculated as follows: energy consumption of all sectors excluding the manufacturing, transport, and household sectors/(GDP minus manufacturing sector GDP minus transport sector GDP minus consumption of households). It is worth noting that the denominator contains some overlap as we use GDP by economic activity and the expenditure side of GDP.

Chart 1　Energy Intensity (Energy Efficiency) at the Aggregate Level



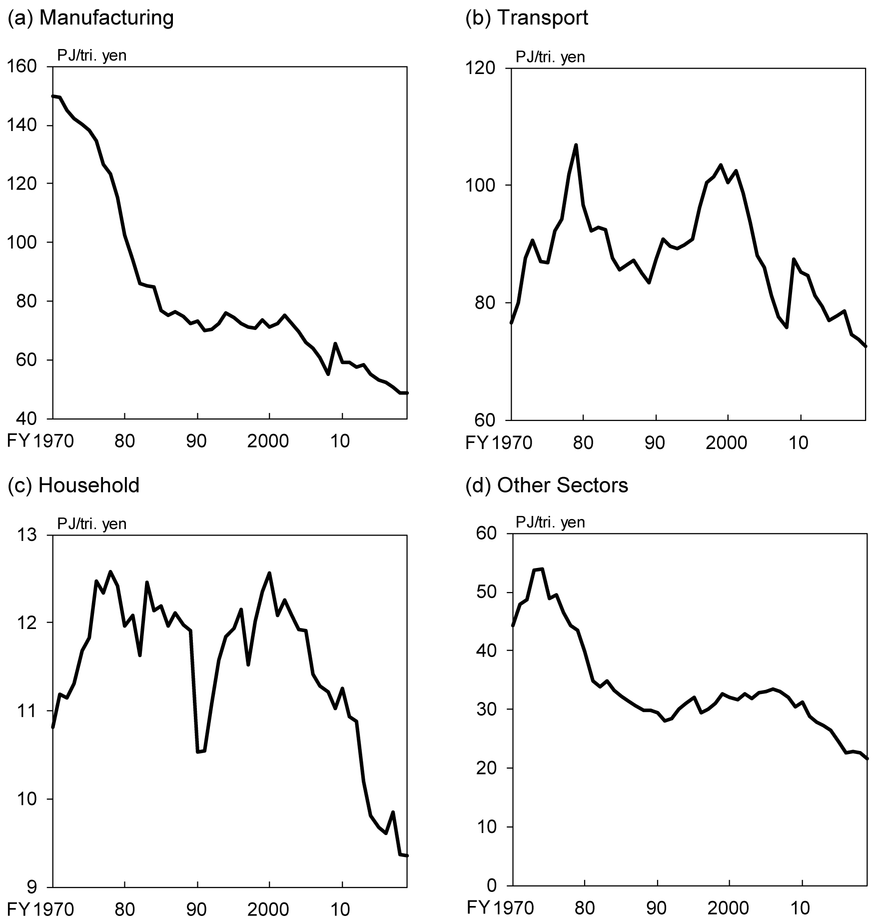
Note: MJ indicates megajoule, a unit of energy.
Source: Kurachi *et al.* (2022).

less energy-efficient material industry to a more energy-efficient processing industry (Chart 4). Moreover, as the economy matures, the share of the nonmanufacturing sector (services sector), of which the amount of energy consumption is relatively small, rose, and this also appears to have led to the improvement in energy efficiency at the aggregate level.

Second, an improvement in energy efficiency in the manufacturing sector appears to have brought about the progress in aggregate-level efficiency (Charts 2 and 3). In response to the severe pollution in Japan and abroad in the 1960s, regulations on emissions from factories and automobiles were introduced, and firms were required to comply with them. Hamamoto (2006) and Norsworthy and Malmquist (1983) point out that this response to environmental regulations promoted the energy-saving technical change in firms. In addition, the two Oil Shocks seem to have stimulated the development of energy-saving technology. Hassler, Krusell, and Olovsson (2012) and Popp (2002) argue that the surge in energy prices during the Oil Shocks promoted energy-saving technical change and innovation.

As part of the process of regulating the automobile industry, amendments to the Clean Air Act (so-called Muskie Act) were enacted in 1970 in the United States. The amendments required automakers to reduce nitrogen oxide (NOx) emissions from automobiles significantly. In Japan, motor vehicle emission control (so-called the Japanese Muskie Act) was established in 1978. Ito and Urashima (2013) argue that, while opposition from major automobile companies prevented the Muskie Act from coming into force in the United States, Japanese automakers invented new engines that satisfied the new regulations, which in turn led to the enhancement of Japan's international competitiveness. In addition, in response to environmental problems during rapid economic

Chart 2 Energy Intensity (Energy Efficiency) by Sector



Note 1: The energy consumption in the household sector is calculated as the sum of that in the "residential sector" and that of "passenger vehicles for household use" in the *General Energy Statistics*, while that in the transport sector is calculated by subtracting that of "passenger vehicles for household use" from that in "transport sector." PJ indicates petajoule, a unit of energy.

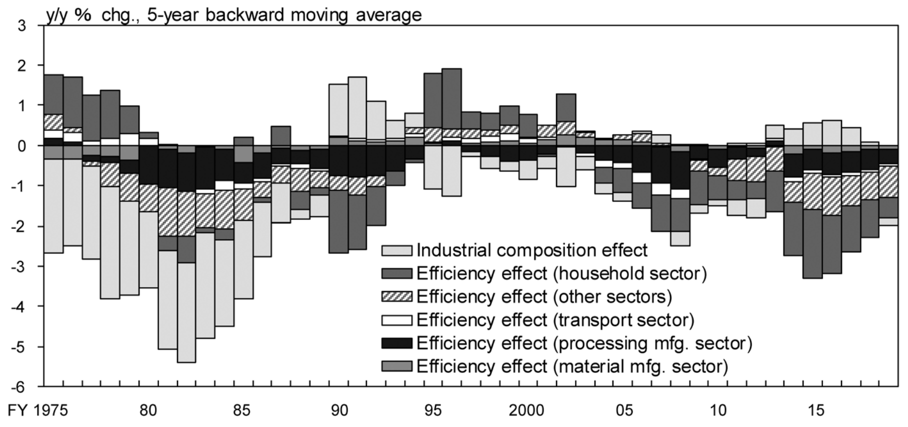
Note 2: Note that the calculation method for the *General Energy Statistics* was changed in fiscal 1990, and for this reason, there is a discontinuity in the data, particularly for the household sector.

Sources: Agency for Natural Resources and Energy; Cabinet Office, Government of Japan.

growth, the government prompted firms to shift to cleaner production technology in the chemical industry. This is likely to have resulted in an improvement in energy efficiency. These cases, as indicated by Edamura (2020), may have confirmed the "Porter hypothesis," which suggests that appropriately designed environmental regulations can promote technical change and boost productivity.

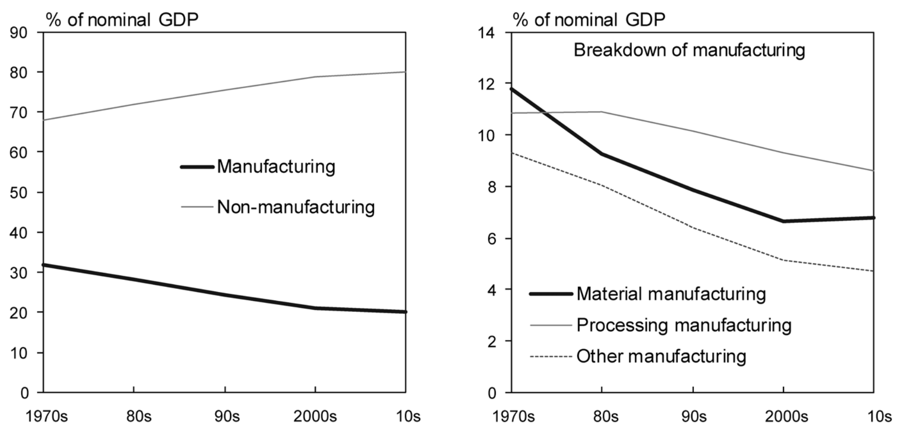
Third, energy efficiency also appears to have improved in the nonmanufacturing sector. This improvement was attributed to the fact that energy saving was promoted in offices and other places, triggered by the Oil Shocks (Agency for Natural Resources and Energy [2021]).

Chart 3 Drivers of the Changes in the Aggregate Energy Efficiency in Japan



Note: See footnote 2 in the main text and the notes of Chart 2 for details on the calculation method of energy efficiency as well as the definition of energy consumption in each sector. The decomposition is carried out using the GDP of each sector as weights.
Sources: Agency for Natural Resources and Energy; Cabinet Office, Government of Japan.

Chart 4 Changes in Industrial Composition



Note: In the right chart, material manufacturing refers to “pulp, paper and paper products,” “chemicals,” “petroleum and coal products,” “non-metallic mineral products,” “basic metal,” and “fabricated metal products;” processing manufacturing refers to “general-purpose, production and business oriented machinery,” “electronic components and devices,” “electrical machinery, equipment and supplies,” “information and communication electronics equipment,” and “transport equipment.”
Source: Cabinet Office, Government of Japan.

B. Phase II: From the 1990s to the First Half of the 2000s

In Phase II, ranging from the 1990s to the first half of the 2000s, the pace of improvement in the aggregate-level energy efficiency decelerated substantially, driven mainly by a slowdown in the pace of improvement in energy efficiency in the manufacturing sector (Charts 1–3). Although Japan's energy efficiency improved faster than in other developed countries in Phase I, mainly owing to its strict emission regulations introduced ahead of these countries, such improvement came to a pause in Phase II. The Agency of Natural Resources and Energy (2021) reports that little progress was made in improving energy efficiency in the manufacturing sector because crude oil prices had been stable at a low level since the second half of the 1980s. Meanwhile, new regulations were introduced, and moves to comply with them were seen mainly in European countries.

Phase II is also characterized by a deceleration in the pace of improvement in energy efficiency in "other sectors," which includes the nonmanufacturing sector. In addition, the energy efficiency of the household sector deteriorated through around 2000, albeit with somewhat significant fluctuations.[3] In these sectors, efficiency improvements may not have progressed as well as in the manufacturing sector, as crude oil prices were stable at a low level. It is possible that such a slowdown in the pace of improvement in energy efficiency was also attributed to stagnation in economic activity following the collapse of the bubble economy.[4] In the nonmanufacturing sector, progress in office automation led to an increase in energy consumption, likely to have resulted in a decrease in energy efficiency.

C. Phase III: Since the Second Half of the 2000s

Energy efficiency in Phase III (from the second half of the 2000s onward) has improved again, albeit at a moderate pace compared with Phase I (Charts 1–3). Looking at it by sector, the pace of improvement of energy efficiency in the manufacturing sector has been relatively moderate. In contrast, such efficiency in the household sector has increased substantially, which has led to an improvement in energy efficiency at the aggregate level. Although the production process in the manufacturing sector has seen a deceleration in its pace of improvement in energy efficiency, the production and sales of energy-efficient automobiles (eco-friendly automobiles) and home appliances (eco-friendly home appliances) have risen; thus, energy efficiency in the household sector has improved in the process of consuming and using final products.[5] In addition, energy efficiency in the nonmanufacturing sector has been enhanced due to the widespread use of energy-saving air conditioners and other products.

It is interesting to note that the driving force for the improvement in the aggregate-

3. Note that the calculation method for the *General Energy Statistics* was changed in fiscal 1990, and for this reason, there is a discontinuity in the data, particularly for the household sector. For details, see Agency for Natural Resources and Energy (2021).
4. Nakamura, Kaihatsu, and Yagi (2019) and Yagi, Furukawa, and Nakajima (2022) outline economic growth and developments in productivity in Japan.
5. In this regard, the Act on Rationalizing Energy Use was revised in 1998, and energy-saving standards based on the top-runner method were introduced for automobiles and home appliances. This requires that the performance of the product with the best energy consumption efficiency (top runner) among those commercialized at a certain point in time be met by other products by a target year several years ahead, and has been seen as contributing to the development of products with superior energy efficiency.

level energy efficiency changed from such efficiency in manufacturing processes of products in the business sector to that of using products in the household sector (improvement in the energy efficiency of consumer goods). The following sections examine the background to changes in energy efficiency using simple models at the sectoral level (the business and household sectors).

III. Energy Efficiency in the Business Sector

A. Model

In the previous section, we confirmed that (i) the energy efficiency of the business sector (particularly the manufacturing sector) improved through the 1980s, (ii) this improvement stalled from the 1990s to the first half of the 2000s, and (iii) thereafter the energy efficiency has improved moderately again. Hicks (1932) claims that changes in the relative prices of inputs promote the kind of innovation through which firms can save an input that has become relatively expensive. According to this idea, a rise in energy prices leads to "energy-saving technical change."

We explain this idea in more detail using a simple model. Consider the following production function of a representative firm with three inputs (capital, labor, and energy):

$$Y = F\left(K, L, E_f\right) = \left[(A_K K)^{1-\sigma} + (A_L L)^{1-\sigma} + \left(A_E E_f\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}, \tag{1}$$

where Y is output, K is capital input, L is labor input, E_f is energy input (by a firm), A_K and A_L are capital and labor productivity, respectively, and A_E is productivity in energy use.[6] σ (> 0) denotes the degree of substitution between the inputs. Equation (1) reduces to the Cobb-Douglas production function in the limit of $\sigma \to 1$. Let P_K, w, and P_E be the input prices of capital, labor, and energy, respectively. Then, the cost-minimization problem can be written as:

$$\min_{K,L,E_f} P_K K + wL + P_E E_f,$$
$$s.t.\ F\left(K, L, E_f\right) = Y. \tag{2}$$

The Lagrangian is:

$$\mathcal{L}\left(K, L, E_f, \lambda\right)$$
$$= P_K K + wL + P_E E_f + \lambda\left\{Y - \left[(A_K K)^{1-\sigma} + (A_L L)^{1-\sigma} + \left(A_E E_f\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}\right\}. \tag{3}$$

The first-order conditions of cost minimization are obtained as follows:

$$P_K = \lambda\left[(A_K K)^{1-\sigma} + (A_L L)^{1-\sigma} + \left(A_E E_f\right)^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} \cdot (A_K K)^{-\sigma} \cdot A_K, \tag{4}$$

6. In order to distinguish between the energy input of firms and households, the energy input of firms is denoted as E_f with the subscript f denoting firms, whereas the energy input of households is denoted as E_h with the subscript h denoting households in Section IV.

$$w = \lambda\left[(A_K K)^{1-\sigma} + (A_L L)^{1-\sigma} + \left(A_E E_f\right)^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} \cdot (A_L L)^{-\sigma} \cdot A_L, \tag{5}$$

$$P_E = \lambda\left[(A_K K)^{1-\sigma} + (A_L L)^{1-\sigma} + \left(A_E E_f\right)^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} \cdot \left(A_E E_f\right)^{-\sigma} \cdot A_E. \tag{6}$$

With these conditions, the share of energy in the total cost can be expressed as:

$$\frac{P_E E_f}{P_K K + wL + P_E E_f} = \frac{1}{\left(\frac{P_K/A_K}{P_E/A_E}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{w/A_L}{P_E/A_E}\right)^{\frac{\sigma-1}{\sigma}} + 1}. \tag{7}$$

Equation (7) implies that, when the degree of substitution between the inputs is low ($\sigma > 1$), an increase in A_E lowers the share of energy in the total cost, ceteris paribus. In this sense, an increase in A_E represents energy-saving technical change. In the period of rising energy prices (P_E), firms will be inclined to promote energy-saving technical change so that they can increase A_E, and thereby mitigate the impact of energy price increases.

Next, we describe the relationship between energy intensity, as shown in Section II, and the productivity in energy use (A_E), which we are discussing in this section. Since the energy intensity of firms (θ_f) is the ratio of energy consumption volume to value added in the business sector, it can be written as:

$$\theta_f = \frac{E_f}{\left(P_K K + wL - P_E E_f\right)/P_f}, \tag{8}$$

where P_f is the deflator for firms' expenditure. Note that we assume the following: the market is perfectly competitive; as for value added in the business sector, the production function is homogeneous of degree one; the value added is distributed to capital and labor; and energy is the sole intermediate input. Substituting Equations (4)–(6) into Equation (8) yields:

$$\theta_f = \frac{P_f/P_E}{\left(\frac{P_K/A_K}{P_E/A_E}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{w/A_L}{P_E/A_E}\right)^{\frac{\sigma-1}{\sigma}} - 1}. \tag{9}$$

As is the case with the share of energy in the total cost, an increase in A_E leads to improvement of energy intensity in the business sector, when the degree of substitution among inputs is low. Equation (9) shows that energy intensity is also affected by the relative price of each input.

Such a relationship between energy prices and technical change has been examined in the existing studies. Acemoglu *et al.* (2019) indicate the possibility that technical change progresses in tandem with energy price rises, as discussed above. They also point out that decreases in energy prices due to the Shale Revolution in the 2000s prevented a shift to the use of clean energy (energy-saving technical change). Acemoglu *et al.* (2012) develop a two-sector model in which firms in the brown sector discharge pollutants in their production process while firms in the green sector do not. Using the model, they show that firms are inclined to prioritize their R&D in the brown sector, since technologies have already been accumulated in this sector. That said, they also point out that in cases where energy prices rise or the government provides subsidies for the development of clean energy, technical change that utilizes clean energy may occur in the green sector.

B. Estimation of Energy-Saving Technical Change in the Business Sector

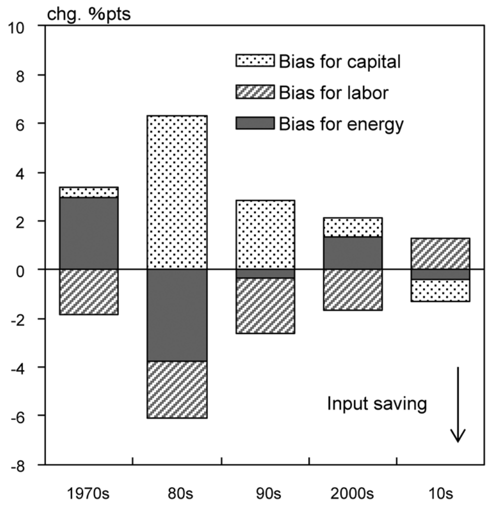
Jin and Jorgenson (2010) measure technical change in the business sector. Specifically, based on the discussion above by Hicks (1932), they measure energy-saving technical change that enables firms to decrease their energy input relative to other inputs such as capital and labor, or in other words, to decrease the energy share (see Appendix for details on the calculation method). Jin and Jorgenson (2010) estimate energy-saving technical change in the United States from 1960 to 2005, and find that such change started to be seen from around 1980. Fukunaga and Osada (2009) measure the energy-saving technical change in Japan, following Jin and Jorgenson (2010). Fukunaga and Osada (2009) consider technical change as increasing total factor productivity (TFP), rather than merely substituting among the inputs. In this paper, based on the analysis by Fukunaga and Osada (2009)—which covers the period from 1970 to 2008—we estimate energy-saving technical change until more recent years.

The estimation results show that energy-saving technical change progressed considerably in the 1980s (Phase I), following a significant rise in energy prices during the Oil Shocks (Chart 5). Such change remained sluggish from the 1990s to the 2000s (Phase II) but seems to have progressed slightly again in the 2010s (Phase III).[7] However, even since Phase II, energy prices occasionally rose to a significant extent, such as in the 2000s before the global financial crisis. The model above suggests that energy-saving technical change should have progressed in such phases. Then, why has the significant progress seen in Phase I not been observed since Phase II (Chart 5)? Firms may have become reluctant to improve energy efficiency; however, considering the fact that the development of energy-efficient final products such as eco-friendly automobiles and home appliances has been promoted, their positive attitude toward energy saving seems to have continued.[8]

This section only captures the energy-saving technical change in the production process at factories. Production has already become increasingly automated, leaving less room for energy-saving technical change in the production process. It is likely that, as a result, such energy saving technology did not progress compared with the past, even when energy prices rose.[9] Therefore, firms may have been focusing more on improving the energy efficiency of final products—or, in other words, developing

7. As Ogawa *et al.* (2009) discuss, energy-saving technical change measured in this paper refers to technical change that makes changes in the shares of inputs (see also Appendix). The impact that such technical change has on energy intensity depends on the degree of substitution among inputs. As discussed in Section III, when the degree of such substitution is low, energy-saving technical change seems to lower the share of energy in the total cost, and in turn lower energy intensity.
8. In assessing the state of technical change by firms, it is necessary to bear in mind that there may be some time lag before firms endogenously make shifts in biases of technical change by their choice (Ogawa *et al.* [2009]). Although we employ static models in this paper, taking account of this point, it would be beneficial to extend the models to dynamic ones.
9. Nomura (2018) points to the possibility that, in Phase II, available energy-saving technology decreased, and thus marginal costs to improve energy efficiency increased gradually.

Chart 5 Developments in Energy-Saving Technical Change in Japan: Overall



Note: See the main text and APPENDIX for details on the estimation method.

energy-saving products.

The following section examines the energy efficiency of the household sector, which is likely to play a crucial role in increasing Japan's energy efficiency going forward.

IV. Energy Efficiency in the Household Sector

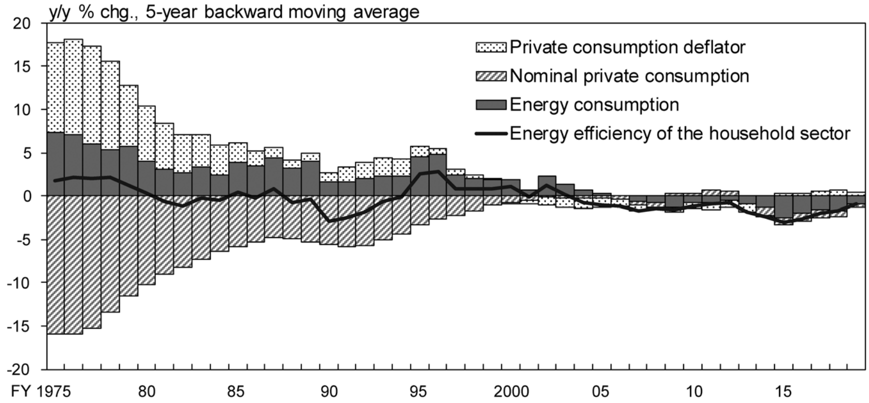
A. Model

First, the energy efficiency of the household sector has improved significantly in recent years (Chart 3). When we decompose this into changes in energy consumption, nominal private consumption, and private consumption deflator, it is shown that the recent improvement in energy efficiency is mainly attributable to a decline in energy consumption (Chart 6).[10] Based on this fact, we construct a model in which households use energy (as input) for their consumption activities.

In general, there are two channels through which energy consumption and the share of energy in household expenditure could decrease. The first channel is through a decline in consumption or the consumption share of goods that use energy (hereafter referred to as energy-using goods). For example, if people reduce their use of automobiles and electrical appliances due to increased environmental awareness, energy consumption will decrease. In addition, if the share of energy-using goods in total consumption decreases with a structural change toward a service economy, the share of energy in household expenditure will decline, even without a change in environmental

10. Chart 6 shows that an increase in nominal consumption contributed to an improvement in energy intensity, while a rise in prices (increase in private consumption deflator) contributed to a deterioration in such intensity, in the household sector from 1975 through around 2000.

Chart 6 Energy Efficiency of the Household Sector



Note: Figures for the energy consumption are the sum of that in the "residential sector" and that of "passenger vehicles for household use" in the *General Energy Statistics*.
Sources: Agency for Natural Resources and Energy; Cabinet Office, Government of Japan.

awareness.[11] The second channel is the one through which households purchase and use energy-efficient goods. This includes an improvement in the fuel efficiency of automobiles and an increase in the energy efficiency of electrical appliances. This channel can be achieved through an increase in the energy efficiency of goods supplied by firms, in response to consumers' growing environmental awareness and positive attitude toward saving energy.[12] As discussed in the previous section, firms' efforts in this channel are not necessarily captured as the energy-saving technical change in the business sector.

In relation to the first channel, a structural change toward a service economy appears to have progressed, but the pace has been moderate recently.[13] In addition, although an increase in environmental awareness has been seen, it is unlikely that people have refrained from using energy-using goods. Therefore, this section focuses on the second channel, which is through an improvement in the efficiency of energy-using goods. The following examines the efficiency of energy-using goods consumed by households using a simple static model and measures such efficiency.

Specifically, we consider a model with three types of goods: "energy"; "energy-

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11. A shift toward a service economy with a maturation of the economy can be explained mainly by the following two hypotheses. The first hypothesis focuses on the income elasticity for goods and services. In a case where the income elasticity for services is higher than that for goods, the share of services in total expenditure would increase as the economy grows. The second hypothesis concentrates on the difference in the rates of increase in productivity between the goods and services sectors. When the rate of increase for the goods sector is higher than that for the services sector, and the elasticity of substitution between goods and services is small enough on the consumer side, the share of services in total expenditure would increase as the economy grows. For research on such changes in economic structures, see Herrendorf, Rogerson, and Valentinyi (2014).
12. While the previous sections mainly discuss energy intensity, which indicates energy consumption per real GDP, this section uses goods models, and energy efficiency refers to fuel efficiency and the efficiency of consumption of each type of good. We discuss the relationship between energy intensity and energy efficiency in Section IV-B.
13. For example, the increase in the share of services in domestic final consumption expenditure of households was very moderate from the 2000s (58.8 percent on average) to the 2010s (59.1 percent on average).

using goods"; and "non-energy-using goods." A representative household derives utility from the consumption of "energy-using goods" and "non-energy-using goods." Energy-using goods refer to goods that cannot be used by themselves and can only be used when accompanied by energy input (e.g., automobiles, which require gasoline, etc., and electrical appliances, which require electricity). On the other hand, non-energy-using goods refer to goods that do not require energy input by consumers (e.g., desks and chairs). Note that services are assumed to be included in non-energy-using goods, given that consumers need not put energy into them.

Based on the above approach, we assume the utility derived from energy and energy-using goods as the following CES function.

$$C = C(E_h, M) = \left[(B_E E_h)^{1-\sigma} + (B_M M)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}, \tag{10}$$

where C is the utility derived from energy and energy-using goods, E_h is energy consumption (of households), M is the input of energy-using goods, B_E and B_M denote efficiency with energy and energy-using goods, respectively. σ (> 0) denotes the degree of substitution between energy and energy-using goods.

In the limit where σ approaches infinity (zero elasticity of substitution), energy and energy-using goods are perfect complements, resulting in a Leontief-type utility function. Since the elasticity of substitution is assumed to be small for households, it is useful to discuss households using this Leontief-type function. For example, consider an automobile as the energy-using goods and gasoline as energy, then to obtain utility from them, both are needed, not one or the other, and therefore they are in perfect complements.[14] In other words, we assume that the utility (C) that households derive from consumption of energy-using goods is given by the following Leontief utility function:

$$C = \min\{B_E E_h, M\}. \tag{11}$$

Although we assume $B_M = 1$ in Equation (11), the generality of the argument is not lost. The greater value of B_E indicates the higher energy efficiency of the household sector, in the sense that a smaller amount of energy consumption is needed to achieve the same level of utility.

The assumption of Equation (11) seems realistic since firms decide the fuel economy of automobiles and energy efficiency of electrical appliances during the process of product development and design; therefore, there is virtually no room for households to change them (i.e., change the input ratio between E_h and M with C held constant). While we assume that households take B_E as given, this assumption is also realistic from the perspective that B_E indicates the quality of products.[15]

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14. In microeconomic theory, when the existence of only one or the increase in the number of either, such as "automobiles" and "gasoline" or "car bodies" and "tires" of automobiles, makes no sense, i.e., when both are of use value only when both are present, they are described as perfect complements. In these cases, the inputs are always in the same proportion, and their utility functions are shown in the Leontief-type function.
15. In reality, there may be some cases where B_E changes as a result of changes in consumer behavior attributed to such factors as an increase in environmental awareness and changes in energy prices. For instance, when

Next, we assume that the utility derived from consumption of energy-using and non-energy-using goods is expressed as follows:

$$U = U(C, G), \tag{12}$$

where G is the consumption of non-energy-using goods. U is a concave function that satisfies standard assumptions of a utility function.

Finally, we define budget constraints of the representative households.[16] Let I be the nominal total expenditure in this period. The budget constraint of the household is given by:

$$P_E E_h + P_M M + P_G G = I. \tag{13}$$

The expenditure related to energy-using goods consists of the purchasing cost of energy-using goods ($P_M \times M$) and that of energy ($P_E \times E_h$), where P_M and P_E are nominal prices of energy-using goods and energy, respectively. The expenditure on non-energy-using goods is expressed as $P_G \times G$, with P_G denoting the nominal prices of non-energy-using goods.

The household chooses E_h, M, and G to maximize the utility function of Equation (12) under the constraints given by Equations (11) and (13), taking prices (P_E, P_M, and P_G) and energy efficiency B_E as given. It is useful to solve this utility maximization problem in two steps. The first step is the problem of expenditure on energy and energy-using goods. Since we assume the Leontief utility function for energy and energy-using goods, the optimum consumption satisfies the following:

$$C = B_E E_h = M. \tag{14}$$

Using Equation (14), the expenditure related to energy-using goods, which we denote as X, can be written as:

$$X = P_E E_h + P_M M = \left(\frac{P_E}{B_E} + P_M \right) M. \tag{15}$$

Using $C = M$ from Equation (14), Equation (15) can be rewritten as follows:

$$X = P_E E_h + P_M M = \left(\frac{P_E}{B_E} + P_M \right) C \equiv QC. \tag{16}$$

Q can be interpreted as the expenditure per 1 unit of consumption of energy-using goods (the sum of the expenditure on energy and purchase costs of goods).

many consumers choose to purchase fuel-efficient automobiles over other affordable automobiles, B_E of the overall economy will improve. We assume only one type of energy-using goods in this paper, and thus such a mechanism is excluded from the measurement.

16. Although we use a static model in this paper, we can also interpret that expenditure I in this period is optimally decided based on a dynamic utility maximization problem. This does not affect the following analyses regarding energy efficiency.

The second step is the problem of expenditure on energy-using goods and non-energy-using goods. Using Equation (16), budget constraints of households (Equation (13)) can be rewritten as follows:

$$QC + P_G G = I. \tag{17}$$

The household chooses C and G to maximize Equation (12) under the budget constraint (17). As is evident from Equations (16) and (17), an improvement in energy efficiency (i.e., an increase in B_E) lowers Q, and has a downward effect on the relative prices of energy-using goods to non-energy-using goods.

B. Energy Efficiency and the Share of Energy in Household Expenditure

Based on the above framework, we analyze factors that affect the share of energy in household expenditure. To begin with, we derive the relationship between B_E and the share of energy in household expenditure (S_E) for ease of economic interpretation.

Equation (14) can be rewritten as:

$$B_E = \frac{M}{E_h}\left(\Leftrightarrow E_h = \frac{M}{B_E}\right). \tag{18}$$

The definition of S_E is given by the following equation:

$$S_E = \frac{P_E E_h}{P_E E_h + P_M M + P_G G}, \tag{19}$$

where the denominator is the nominal total consumption expenditure. Substituting Equation (18) into Equation (19) yields:

$$S_E = \frac{P_E \frac{M}{B_E}}{P_E \frac{M}{B_E} + P_M M + P_G G}. \tag{20}$$

Equation (20) can be further rewritten as:

$$S_E = \frac{\frac{P_E}{P_M}}{\frac{P_E}{P_M} + \frac{P_M M + P_G G}{P_M M} B_E}. \tag{21}$$

Now, let S_M be the share of energy-using goods in "household expenditure excluding energy." S_M can be expressed as follows:

$$S_M = \frac{P_M M}{P_M M + P_G G}. \tag{22}$$

S_M excludes the expenditure on energy by definition, and thus it indicates households' preference between energy-using goods and non-energy-using goods. By substituting

Equation (22) into Equation (21), we obtain:

$$S_E = \frac{\frac{P_E}{P_M} S_M}{\frac{P_E}{P_M} S_M + B_E}. \tag{23}$$

Note that variables on the expenditure share (S_E and S_M) take the value between 0 and 1.

The above discussion suggests that three factors affect the share of energy in household expenditure (S_E).[17] First, when the share of energy-using goods in household expenditure excluding energy (S_M) rises, energy consumption also increases, which in turn leads to a rise in S_E. This phenomenon seems to have been observed in Japan from the 1960s to the 1990s when the use of automobiles and electrical appliances became widespread. Second, when the energy efficiency of goods improves (i.e., increase in B_E), S_E declines. This relationship appears to have been seen recently in the process of widespread energy-saving products replacing existing products. Third, when prices of energy rise relative to those of energy-using goods (i.e., an increase in P_E/P_M), S_E increases.

Next, we summarize the relationship between energy intensity, as shown in Section II, and energy efficiency of goods (B_E), which we are discussing in this section. Since the energy intensity of households (θ_h) is the ratio of the energy consumption to real final consumption expenditure, it can be written as:

$$\theta_h = \frac{E_h}{\left(P_E E_h + P_M M + P_G G\right)/P_C}, \tag{24}$$

where P_C is the household consumption deflator.[18,19] Substituting Equation (18) into Equation (23) yields:

$$\theta_h = \frac{P_C}{P_E} \cdot S_E. \tag{25}$$

Thus, the energy intensity of households is affected by the relative prices of energy (P_E/P_C) as well as the aforementioned share of energy in household expenditure (S_E). Using the relationship described in Equation (23), Equation (25) can be further rewritten as:

$$\theta_h = \frac{\frac{P_C}{P_M} S_M}{\frac{P_E}{P_M} S_M + B_E}. \tag{26}$$

17. Note that we assume a ceteris paribus condition for this discussion.
18. Regarding the calculation of energy intensity and energy efficiency, energy consumption (E_h) refers to energy consumed when using goods purchased not only in this period but also in or before the previous period, while the denominator of energy intensity (final consumption expenditure) and the numerator of energy efficiency (input of energy-using goods) are those for this period.
19. In fact, final consumption expenditure of households includes, for example, direct purchases overseas by domestic residents, but such purchases are abstracted from the calculation in this paper.

As Equation (26) shows, the energy intensity of households is affected by the energy efficiency of goods (B_E). In addition, it can fluctuate due to developments in the share of energy-using goods (S_M), the relative prices of energy to energy-using goods (P_E/P_M), and the relative prices of overall prices (the household consumption deflator) to energy-using goods (P_C/P_M). For example, an increase in the energy efficiency of goods (i.e., an increase in B_E) leads to an improvement in energy intensity (i.e., a decrease in θ_h). Moreover, with each of the relative prices remaining the same, active purchases of energy-using goods by households increase the share of energy-using goods (S_M), which causes a deterioration in energy intensity. That said, if households purchase energy-saving goods, this may bring about an improvement in B_E; as a result, deterioration in energy intensity would be mitigated, or such intensity would improve.

Finally, we discuss the energy efficiency of goods (B_E). For ease of discussion, we multiply both the numerator and denominator of Equation (18) by $P_M \cdot P_E$ to obtain:

$$B_E = \frac{P_M M}{P_E E_h} \cdot \frac{P_E}{P_M}. \tag{27}$$

This result implies that the energy efficiency of households B_E can be calculated using the ratio of the nominal expenditure on energy-using goods and that on energy ($P_M M/P_E E_h$), and the relative prices of energy to energy-using goods (P_E/P_M). This formula is based on the assumption that the utility function is of Leontief-type. We assume that there is only one type of energy-using goods, and thus B_E is an exogenous variable to households. That said, in reality, there are multiple types of energy-using goods with different energy efficiencies; therefore, if the relative consumption of such goods changes, the energy efficiency of goods (B_E) at the aggregate level will change accordingly.

For example, when households increasingly purchase energy-saving products, with the relative prices of energy to energy-using goods remaining the same, the expenditure on energy-using goods relative to that on energy ($P_M M/P_E E_h$) increases, which leads to an improvement in the energy efficiency of goods. In contrast, when households increasingly purchase products with low energy efficiency, the expenditure on energy rises, and this causes a decrease in $P_M M/P_E E_h$ compared with the aforementioned case; as a result, the energy efficiency of goods decreases. Moreover, if households shift to an energy-saving behavior, given a rise in the relative prices of energy, the energy efficiency of goods would improve.[20] It is appropriate to interpret changes in B_E, measured in the following section, including such household behavioral changes.

C. Estimation of the Energy Efficiency of the Household Sector

1. Estimation method

Based on the above discussions, we measure the expenditure shares of the household sector (S_E and S_M), relative prices (P_E/P_M), and energy efficiency (B_E), using data from Japan. Specifically, we mainly use the relationships described in Equations (19), (22), and (27) for this purpose. Regarding the relative prices of energy to energy-using

20. If only the relative prices of energy rise, with household behavior remaining the same, energy efficiency of goods obviously would not change.

goods, for P_E, we refer to energy prices in the consumer price index (CPI), compiled by the Ministry of Internal Affairs and Communications (MIC). For P_M, we first calculate the average unit price, item by item, using sales prices and sales volumes in the *Current Survey of Production* released by the Ministry of Economy, Trade and Industry; then, the weighted average of such unit price is computed using expenditure shares as weights. For calculating $P_M M$, $P_G G$, and $P_E E_h$, we use the *Family Income and Expenditure Survey* compiled by the MIC.[21] Annual figures from 1990 to 2020 of each dataset are used for the estimation.

2. Estimation results

Charts 7–10 show the developments in the major variables and the estimation results. Looking at the developments in each variable, the share of energy in household expenditure (S_E) had followed an uptrend but has recently been more or less flat. The recent trend change is likely to be attributed to the widespread use of eco-friendly automobiles and home appliances and the improvement in the energy efficiency of major durable goods (Charts 11–13). The share of energy-using goods in the household expenditure excluding energy (S_M) seems to have been more or less flat over the estimation period (Chart 8).[22] The relative prices of energy to energy-using goods (P_E/P_M) have seen more or less the same developments as energy prices; specifically, the relative prices have declined after increasing through the middle of 2010 (Chart 9).[23]

Chart 10 indicates the estimation results for energy efficiency (B_E). Energy efficiency had declined through the middle of the 2000s but has been on an improving trend thereafter. The declining phase of such efficiency through the middle of the 2000s generally falls into Phase II, which is explained in Section II. It is also attributable to the following factors. First, with crude oil prices remaining at low levels, it is likely that households' energy-saving behavior came to a halt, and they started to select goods that consume more energy in this phase.[24] Second, it is possible that the composition of energy-using goods changed in terms of the amount of energy they consume. For example, people's lifestyles changed drastically since the high economic growth period, and more people started using such goods as air conditioners that consume more energy relative to other energy-using goods; this may have led to a decrease in energy efficiency at the aggregate level (Chart 14). As previously mentioned, the share of energy in household expenditure (S_E) seems to have increased in this phase.

Energy efficiency appears to have improved since the middle of the 2000s, albeit with fluctuations. This phase falls into Phase III, which is mentioned in Section II,

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21. Although we assume only one type of energy-using goods in Equation (27), we regard an aggregate of the following 13 items as "energy-using goods" in this section: household electrical appliances (refrigerators, washing machines, air conditioners, televisions, microwave ovens, electric rice-cookers, vacuum cleaners, personal computers (desktop), personal computers (notebook), and PC printers) and automobiles (light motor vehicles, small motor vehicles, and motor vehicles). Note that our analysis only covers a limited number of items, although we select the major ones.
22. S_M may decline due to such factors as a shift toward a service economy. However, as mentioned in Section IV, it is highly likely that no clear changes have been confirmed by the data at this point.
23. Since 2020, energy prices had declined following the outbreak of COVID-19, before entering the recovery phase, during which they had risen significantly due in part to the situation in Ukraine.
24. For example, the decline in energy efficiency may have reflected the fact that households started to use larger automobiles. Our models in this paper cannot capture such changes in consumer behavior, and thus future analysis could focus on this point.

Chart 7 Share of Energy in Household Expenditures (S_E)

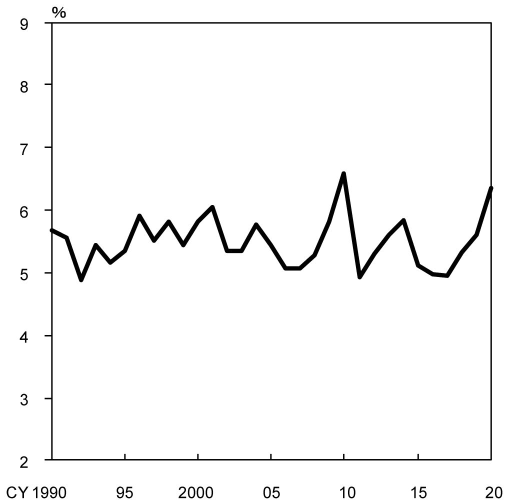
Note: Figures are calculated as energy expenditures divided by consumption expenditures. Energy expenditures are the sum of “fuel, light, and water charges” and “maintenance of vehicles.” Consumption expenditures exclude “pocket money,” “social expenses,” and “remittance” (same applies to the charts below).
Source: Ministry of Internal Affairs and Communications.

and the improvement seems to have reflected the growth in the use of eco-friendly automobiles and home appliances (Charts 8–10).[25] As mentioned above, the share of energy in household expenditure (S_E) became more or less flat in this phase, after following an uptrend. People started to increasingly use energy-efficient products while the relative prices of energy to energy-using goods (P_E/P_M) declined in the second half of the 2010s; this, in particular, is likely to have led to a peaking-out of the share of energy in household expenditure.

Energy efficiency (B_E) of households calculated in this section have seen similar developments with the energy intensity of households shown in Chart 2 since around 1990 until recently; therefore, developments in energy intensity can be explained mainly by those in the energy efficiency of goods. That said, looking at this in detail, energy efficiency has fluctuated to a larger degree compared to energy intensity, and their developments differ from time to time. In addition, energy intensity has improved significantly recently, whereas the degree of improvement in energy efficiency has been relatively limited. This may be attributed to the following factors. First, only a limited number of products, such as eco-friendly automobiles and home appliances, are selected as energy-using goods in this section, which can affect the estimation results regarding energy efficiency. For example, energy-efficient housing-related goods have been increasingly used in recent years, as shown in Chart 13, but this is not covered in

25. It seems to be related to the large scale electricity saving efforts triggered by the Fukushima nuclear power plant accident following the Great East Japan Earthquake and the spread of energy-efficient home appliances (e.g., LED light bulbs).

Chart 8 Share of Energy-Using Goods in Non-Energy Household Expenditures (S_M)



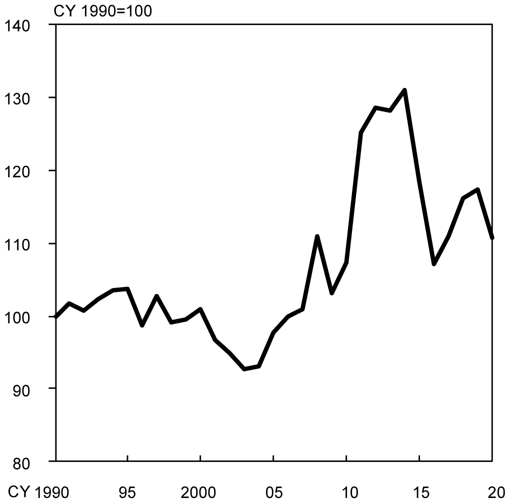
Note: Figures are calculated as expenditures on energy-using goods divided by non-energy consumption expenditures. Expenditures on energy-using goods are the sum of "durable goods assisting housework," "heating and cooling appliances," "purchases of vehicles," and "recreational durable goods." Non-energy consumption expenditures are consumption expenditures minus "fuel, light, and water charges" and "maintenance of vehicles."
Source: Ministry of Internal Affairs and Communications.

the calculation regarding energy efficiency in this section. In addition, the energy intensity can be affected by factors other than energy efficiency, such as various relative prices and the share of energy-using goods, as indicated in Equation (26). The energy intensity has likely improved significantly in recent years, reflecting the changes in effective relative prices, including those due to the government subsidies for purchasing energy-saving products and the resultant growth in the use of such products.

In this regard, the role of the government sector in improving energy efficiency is also examined. The government has introduced multiple measures to support purchases of energy-efficient automobiles and home appliances since the second half of the 2000s.[26] In addition, various ministries and agencies, as well as municipalities, have introduced many support measures toward the widespread use of eco-friendly automobiles in recent years. These measures include subsidies for R&D of eco-friendly automobiles, those for purchases of such automobiles and infrastructure development, as well as tax cuts.[27] The business sector has been working on developing energy-saving

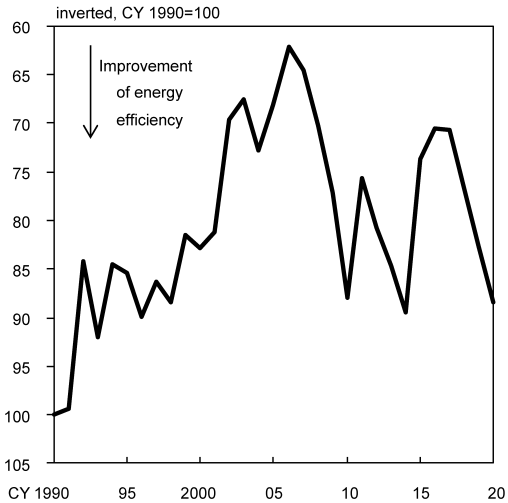
26. The government gave subsidies for or cut taxes on purchases of automobiles with a high environmental performance. It also provided reward points for purchases of such products as televisions and air conditioners that meet certain energy-saving criteria. For details, see Ministry of Economy, Trade and Industry and Ministry of Land, Infrastructure, Transport and Tourism (2012), Ministry of the Environment, Ministry of Economy, Trade and Industry, and Ministry of Land, Infrastructure, Transport and Tourism (2011), and Higashi and Kawata (2017).
27. For example, for firms, the government has implemented measures to support R&D of batteries for electric vehicles and other products, while for individuals, it has taken measures to support purchases of eco-friendly

Chart 9 Relative Price of Energy (P_E/P_M)



Note: Figures are calculated as energy prices divided by prices of energy-using goods. The CPI for energy is used as the energy price. See the main text for the price of energy-using goods.
Sources: Ministry of Internal Affairs and Communications; Ministry of Economy, Trade and Industry.

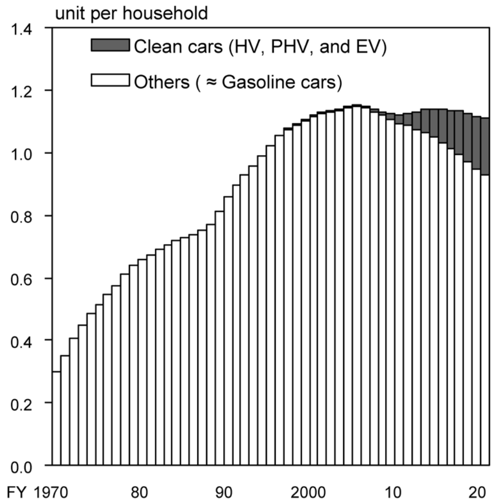
Chart 10 Energy Efficiency in the Household Sector (B_E)



Note: Figures are the estimated values.

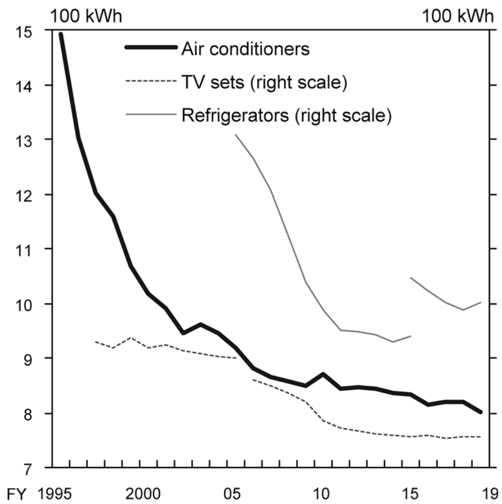
automobiles.

Chart 11 Prevalence of Clean Automobiles



Sources: Automobile Inspection and Registration Information Association; Ministry of Internal Affairs and Communications.

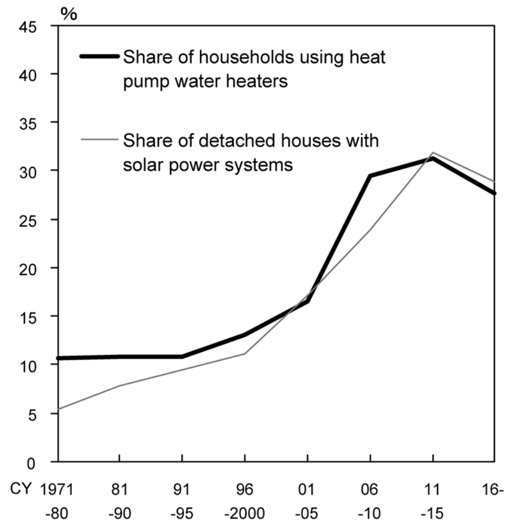
Chart 12 Energy Consumption of Household Electrical Appliances



Note: Figures for TV sets and refrigerators contain discontinuities due to the changes in the Japanese Industrial Standards or surveyed products.

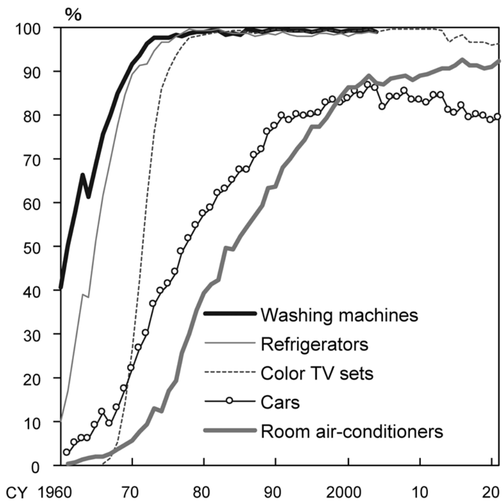
Source: Agency for Natural Resources and Energy (2021).

Chart 13 Prevalence of Eco-Friendly Housing (by Year of Construction)



Source: Ministry of the Environment.

Chart 14 Ownership Rate of Durables



Note: The survey for washing machines and refrigerators has ended as of CY 2004.
Source: Cabinet Office, Government of Japan.

final products, while the household sector has been purchasing these products, using the support of the government sector; this seems to have led to the recent improvement in the energy efficiency of households (Yoshida *et al*. [2010], Ita, Nakano, and Washizu [2012], and Higashi and Kawata [2017]).

On this point, Acemoglu *et al*. (2012) claim that R&D in the green sector, in which energy-efficient goods are produced, and the use of such goods generate a positive externality; however, this positive externality may not have enough effect in a market where people have free choice in what to purchase. For example, new energy-efficient goods tend to be more expensive than existing goods, especially soon after their launch. Thus, even if they have a positive externality, such differences in prices may prevent them from being widely used. It is likely that support from the government sector for the household and business sectors will be able to bring in such a positive externality. In particular, support measures for purchases of new energy-efficient goods can be effective as a policy option.

V. Concluding Remarks

This paper has overviewed the developments in energy efficiency in Japan. We confirm that energy efficiency improved significantly from the 1970s to the 1980s, but the pace of improvement decelerated from the 1990s to the first half of the 2000s; thereafter, such efficiency has improved moderately again in recent years. The background to such changes in energy efficiency is analyzed by sector (the business and household sectors) using simple models. The role of the government sector is also examined. The main results of our analysis are as follows.

First, energy-saving technical change progressed in the business sector (manufacturing sector) from the 1970s to the 1980s, and this seems to have led to the improvement in energy efficiency at the aggregate level. Next, the driving force of the recent improvement in energy efficiency has changed from the business sector to the household sector. This is not because the technical change in the business sector has stopped progressing. It rather reflects the fact that, while there remains little room for energy-saving technical change in the production process, households have purchased and used energy-efficient final products that firms have continued to make efforts to develop. Although the prices of new energy-efficient products tend to be higher than existing goods, adjusting such price differences through support from the government sector is expected to promote the spread of new energy-efficient products. The government has taken support measures for purchases of energy-efficient automobiles and other products recently. This seems to have encouraged the spread of new products and in turn, has contributed to an improvement in energy efficiency at the aggregate level.

Recently there has been a growing interest in climate change globally, and accelerating the efforts toward decarbonization is required in Japan. Based on the discussion in this paper, the business sector, the household sector, and the government sector are expected to further their efforts toward improving energy efficiency to achieve carbon neutrality.

Lastly, future research agendas are touched upon. This paper examines the models regarding the energy efficiency of the business and household sectors, respectively. These sectors may obviously behave in a mutually dependent manner. Future research could further develop our models while taking account of this point, examining the developments in a unified manner. In doing so, the models can be extended to dynamic models. In addition, the empirical analysis in this paper (Section IV-B) uses the data up through 2020. Energy prices rose significantly due partly to the situation in Ukraine during the recovery phase from COVID-19, and future research may also analyze the behavior of each sector during such a phase.

APPENDIX. MEASURING ENERGY-SAVING TECHNICAL CHANGE

In this appendix, we explain how to measure energy-saving technical change. Jin and Jorgenson (2010) and Fukunaga and Osada (2009) measure biases of technical change by estimating the following translog-type price function and the distribution rate function derived from it instead of using the production function described in Section III-A.[28]

First, the translog-type price function is expressed in the following equation.

$$lnP_{Yt} = \alpha_0 + \sum_i \alpha_i \ln P_{it} + \alpha_t \cdot t + \frac{1}{2}\sum_{i,k}\beta_{ik} \ln P_{it} \ln P_{kt} + \sum_i \beta_{it} \ln P_{it} \cdot t + \frac{1}{2}\beta_{tt} \cdot t^2, \quad \text{(A1)}$$

where P_Y is the product price, P_i is input price, i and k indicate input factors, t indicates time and technology level. The translog-type function is an approximate expression for any general function that is second-order differentiable, and if $\beta_{ik} = 0, \beta_{it} = 0, \beta_{tt} = 0$, the above equation is a price function corresponding to a Cobb-Douglas type function.

Next, assuming perfect competition and constant returns to scale the input share of factor i is equal to the partial differentiation of Equation (A1) by $\ln P_{it}$, for the following.

$$v_t^i \equiv \frac{P_t^i X_t^i}{P_{Yt} Y_t} = \alpha_i + \sum_k \beta_{ik} \ln P_{kt} + \beta_{it} \cdot t, \quad \text{(A2)}$$

where β_{ik} is the share elasticity, which represents the percentage change in the input share of factor i when the price of factor of production k changes by one percent. The last term in equation (A2), $\beta_{it} \cdot t$, represents the change in the input share through time, independent of the change in the factor of production price, and can be said to indicate the bias of technological change for input factor i.

The bias of technical change is measured by estimating the translog-type price function in Equation (A1) and the factor input share function in Equation (A2). Many previous studies have considered t as a fixed time trend and estimated fixed parameters such as β_{ik}, β_{it} and β_{tt}, while Fukunaga and Osada (2009) follow Jin and Jorgenson (2010) and construct a state space model with the variable parameters f_{it} and f_t as latent variables, and then estimate them by Kalman filter:

$$f_{it} \equiv \beta_{it} \cdot t, \qquad f_t \equiv \alpha_t \cdot t + \frac{1}{2}\beta_{tt} \cdot t^2. \quad \text{(A3)}$$

In Equation (A3), f_{it} represents the bias of the level of technology toward the input factor i (the effect on the input share v_t^i). It indicates input-using technical change when $\Delta f_{it} > 0$, and input-saving technical change when $\Delta f_{it} < 0$.

28. Fukunaga and Osada (2009) point out that the price function is more convenient when making estimates such as those in this paper, because there are measurement technical difficulties in handling data in a production function (e.g., in the case that the input of input factors is zero). Nomura (2004), on the other hand, measures biases of technological changes by estimating the production function.

By using these equations, Equations (A1) and (A2) can be rewritten as follows, respectively.

$$\ln P_{Yt} = \alpha_0 + \sum_i \alpha_i \ln P_{it} + \frac{1}{2}\sum_{i,k}\beta_{ik} \ln P_{it} \ln P_{kt} + \sum_i \ln P_{it} \cdot f_{it} + f_t, \tag{A1$'$}$$

$$v_t^i = \alpha_i + \sum_k \beta_{ik} \ln P_{kt} + f_{it}. \tag{A2$'$}$$

In the estimation, the number of parameters to be estimated is reduced to some extent by applying constraints such as first-order homogeneity, monotonicity, symmetry, and local concavity of the model. In addition, to account for the possibility of endogeneity of explanatory variables, we estimate using instrumental variables.

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