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The Effects of Barriers to Technology Adoption on Japanese Prewar and Postwar Economic Growth

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Abstract

Following the start of modern economic growth around the mid-1880s, Japan's economy continued to substantially lag behind leading economies before World War II, but achieved rapid catch-up after the war. To explain the patterns, we build a dynamic model and examine the role of barriers to technology adoption. We find such barriers hampered catch-up in the prewar period and explain about 40 percent of the postwar miracle. Taking a historical perspective, we argue that factors that acted as barriers include low capacity to absorb technology, economic and political frictions with the outside world, and a lack of competition.

Keywords: Japan; Barriers to technology adoption; Investment specific technology; Catch-up; Postwar miracle

JEL classification: N15, N75, O11, O41

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1 Introduction

Japan's modern economic growth began around the mid-1880s following the Meiji Restoration of 1868.[1] Yet, despite modernization, Japan's per capita output in the pre-World-War-II period remained at only around 40 percent of that of the United Kingdom, one of the leading economies at that time, as shown in Figure 1(a). It was only in the 1950s – more than half a century after modernization began – that Japan's per capita output started catching up with the UK. As observed by Hayashi and Prescott (2008), this raises the question why catch-up did not take place during the prewar period. What factors prevented catch-up from materializing? And why did Japan suddenly experience a growth miracle in the postwar period?

To address these questions, we revisit the role of barriers to technology adoption in the spirit of Parente and Prescott (1994, 2000). Specifically, we hypothesize that barriers to technology adoption hampered economic growth during the prewar period and that the reduction of such barriers after the war contributed to the growth miracle, and then examine the hypothesis quantitatively by building a model and qualitatively from a historical perspective.

We formulate our hypothesis regarding technology adoption based on three observations. First, as shown by growth accounting studies such as Hayami and Ogasawara (1999) and model simulation studies such as Otsu (2009) and Esteban-Pretel and Sawada (2014), Japan's growth miracle was driven by rapid technological progress as indicated by strong total factor productivity (TFP) growth. Second, in the literature on Japan's economic history (e.g., Peck and Tamura, 1976) the country during the immediate postwar era is regarded as an outstanding example of purposeful national effort to apply technology to achieve economic growth. Third, data on technology adoption suggest that the number of contracts of technology adoption was much lower in the prewar period than

[1] Ohkawa and Rosovsky (1973: 11).

in the postwar period. Specifically, a survey by the Agency of Industrial Science and Technology (1949: 163), which to our knowledge is the only available official data on technology adoption in the prewar period, suggests that in 1941 there existed only 231 contracts regarding the adoption of technology from abroad. In contrast, calculating the number of contracts for 1960 using official data suggests that the number in that year was 1,413, more than six times as large as the number in 1941.[2] In addition, the number of patents registered in Japan by foreigners – one indicator of technology adoption from foreign countries – remained low during the prewar period and only started increasing sharply during the postwar period, as shown in Figure 1(b).[3]

Among the various types of technology that may potentially have been affected by barriers to technology adoption, this study focuses on investment-specific technology (IST). In the 20th century, during both the prewar and the postwar periods, Japanese technology imports consisted mainly of those related to capital goods such as machinery and equipment that embodied IST.[4] In addition, consistent with the hypothesis on barriers to technology adoption, the relative price of investment – one measure of IST progress[5] – in Japan was much higher than in the UK during the prewar period, but started decreasing and converging to that in the UK in the postwar period, as shown in Figure 1(c). Developments in the ratio of the relative price of investment for Japan to that for the UK – which provides a measure of IST progress in Japan relative to the

[2] See Appendix A for details of our calculation of the number of technology adoption contracts that existed in 1960.

[3] Another study using the number of patents registered in Japan by foreigners as an indicator of the degree of technology adoption from abroad is Otsuka (1987), who examines this issue in the context of the development of the cotton industry in Japan. It is worth noting that Japan's patent laws were modified in 1952, 1959, and 1970, which may have affected the number of patents registered in the postwar period. Yet, in a review of the history of industrial property, Japan Patent Office (1985) does not identify the legal revisions as a main contributor to the increase in the number of patents during the postwar period.

[4] For more details, see Odagiri and Goto (1996) for the prewar period, and Goto (1993) for the postwar period.

[5] As shown by Hulten (1992) and Greenwood et al. (1997) for the US economy, the level of IST can be measured in terms of the relative price of investment.

UK – shown in Figure 1(d) suggest that Japan was much less developed than the UK in terms of IST in the prewar period but caught up with the UK in the postwar period. Moreover, the advances in IST may explain the aforementioned high TFP growth rate in the postwar period. In growth accounting that does not take IST progress into account separately, IST is included in TFP.

We examine the hypothesis on barriers to technology adoption by building a two-sector dynamic model featuring endogenous adoption of IST as well as barriers to IST adoption. The model economy is essentially a closed economy except that it faces the world technology frontier. This modeling reflects the fact that it was technology adoption mainly through licenses that contributed to the high growth in the manufacturing sector in the early post-WWII period (Aoki et al., 2011), but not necessarily an increase in the volume of trades, as the ratio of imports to output was lower in the period than in the prewar period.[6] The model provides a close link between the extent of such barriers and the ratio of the relative price of investment for Japan to that for the UK. This link allows us to quantify the extent of such barriers by using data on the relative price of investment. Simulation results using the model show that the reduction of IST adoption barriers explains about 40 percent of the catch-up attained in the postwar period. If such a decline in barriers had occurred in the beginning of the modern economic growth of the mid-1880s, the gap in per capita output between Japan and the UK in the prewar period would have been narrowed by the same margin. Thus, IST adoption barriers explain about 40 percent of the gap in per capita output in the prewar period.

In addition, the model explains the decrease in the ratio of the relative price of investment observed around the period 1950–1980 shown in Figure 1(d). The model

[6] The average ratio of imports to GNP was 10 percent in the period of 1946-1970 (Japan Statiscal Assosiation, 2007, table13-4 in Appendix on Historical Statistics of Japan) while it was 17 percent in the period of 1890-1940 (Japan Statiscal Assosiation, 2007, table13-3 in Appendix on Historical Statistics of Japan). In the 1950s and 1960s, exports and foreign direct investment to Japan were heavily restricted. Consequently, the only possible way for foreign firms with superior technology to exploit their advantages was to sell the technology to Japanese firms (Goto, 1993:278).

features costly technology adoption so that it takes time to adopt new technology even after a reduction in barriers. The costly technology adoption plays a critical role in replicating the developments in the ratio of the relative price of investment in the postwar period.

In the model, the barriers to technology adoption make it costly and difficult to adopt new technology. However, what form did such barriers to technology adoption take in practice? Taking a historical perspective, we argue that the barriers had to do with low capacity to absorb new technologies, economic and political frictions between Japan and other countries, and a lack of competition in the domestic market.

In the prewar period, capacity to absorb and make use of advanced technology was likely much lower than in the postwar period. In fact, the spread of modern science was slow, and it took decades for heavy industries to begin developing. Also, the number of experts with an engineering major was low, which must have been one obstacle for the development of heavy industries. Another factor acting as a barrier in the prewar period was economic and political frictions between Japan and other countries, culminating in a series of wars and military incidents from 1931 onward, which likely blocked technology adoption from abroad. Moreover, the market environment in the prewar period was considerably less competitive than in the postwar period due, partly, to the presence of the *zaibatsu* (financial conglomerates). The *zaibatsu* controlled a great part of the economy, but their conservative business stance worked to discourage the entry of new firms, investment, and adoption of new technologies. These factors made it costly and difficult to adopt new technology from abroad in the prewar period, but they were mitigated dramatically in the postwar period, and thus can be seen as factors underlying the barriers assumed in the model.

This study contributes to and pertains to the literature on Japan's prewar moderate growth and postwar miracle. In particular, the study is motivated by Hayashi and Prescott's (2008) argument that barriers to labor mobility between agriculture and the manufacturing sector explain about one-fourth of the gap in per capita output between Japan and the United States in the prewar period.[7] Relatedly, Esteban-Pretel and Sawada (2014) argue that while the removal of barriers to labor mobility was one of major contributors to Japan's postwar growth, it is the high growth of non-agricultural TFP that drove the growth miracle.

The idea that Japan's growth miracle can in part be explained by a reduction in barriers to technology adoption is not original to this study. Parente and Prescott (1994, 2000) is a pioneer in model simulation studies. Relatedly, using a two-period overlapping generations model, Ngai (2004) shows that the declines in barriers to introducing IST in the late 19th century and in the postwar period capture Japanese economic growth since 1820 well. The present work differs from these preceding studies in at least three important respects. First, unlike Parente and Prescott (1994, 2000) who focus on TFP, this study focuses on IST and quantifies the barriers to technology adoption from data on the relative price of investment. Second, employing a neoclassical growth framework, this study shows that the increase in technology adoption as a result of the reduction in barriers to technology adoption explains postwar developments in the relative price of investment. It then quantifies the effect of these barriers on Japan's economic growth in the prewar and postwar periods. Third, the study complements the model-based results with historical evidence regarding barriers to technology adoption.

The remainder of the study proceeds as follows. Section 2 presents our dynamic model featuring endogenous technology adoption that we employ for our analysis. Section 3 quantifies barriers to technology adoption, simulates the model, and presents the main result of our analysis. Section 4 then takes a historical perspective and discusses factors that potentially created such barriers. Finally, Section 5 concludes.

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[7] While in this study output is measured in units of consumption for the model and data, Hayashi and Prescott (2008) measure it in units of the non-agricultural good and in terms of GNP for the model and data respectively. Thus, the effects of barriers to technology adoption in this study and those to labor mobility in Hayashi and Prescott (2008) cannot be directly compared.

2 Model

This section presents our two-sector growth model in which adopting technology from the world technology frontier endogenously drives IST progress. The model features barriers to technology adoption that make it costly to adopt new technology. Slow technology adoption due to the barriers leads to a low level of IST, resulting in sluggish per capita output growth.

The model is a variant of Romer's (1990) model of growth through expanding variety of goods, extended to incorporate technology adoption as in Comin and Gertler (2006) and its barriers. The model economy grows through the expansion of the variety of intermediate investment goods and consists of two goods producing sectors, producing a final consumption good and a final investment good respectively, and a household sector. The remainder of this section describes the behavior of economic agents in these sectors.

2.1 Consumption good sector

Under perfect competition, a representative firm produces consumption good $y_{c,t}$ in period t by combining capital $k_{c,t-1}$ and labor $n_{c,t}$ based on the following Cobb-Douglas production function:

$$y_{c,t} = x_t k_{c,t-1}^{\alpha} n_{c,t}^{1-\alpha}, \quad 0 < \alpha < 1,$$

where $x_t = x_0 \gamma^t$ represents exogenous labor-augmenting technological progress or, equivalently, a neutral technology factor, which is common to both the consumption good and investment goods sectors, and grows at a constant rate of γ. The price of the consumption good is taken as the numeraire. Given the real wage w_t and the rental rate of capital r_t, profit maximization by the firm leads to

$$w_t = (1-\alpha)\, x_t \left(k_{c,t-1}/n_{c,t}\right)^{\alpha}, \tag{1}$$

$$r_t = \alpha x_t \left(k_{c,t-1}/n_{c,t}\right)^{\alpha-1}. \tag{2}$$

2.2 Investment goods sector

The investment goods sector produces a final investment good by combining a continuum of intermediate goods. The set of technologies for producing these intermediate goods – those adopted, those not yet adopted, and those as yet unknown – is represented by points on the positive real line. Each point between 0 and $A_{t-1} > 0$ corresponds to a technology that has been adopted and is in practical use at the beginning of period t. Thus, A_{t-1} represents the number of intermediate goods available in period t. Next, each point between A_{t-1} and $Z_{t-1} > A_{t-1}$ corresponds to a technology that is known but still requires development to be turned into a technology for practical use, where Z_{t-1} represents the world technology frontier in the beginning of period t. Finally, each point on the interval greater than Z_{t-1} corresponds to a technology that is not yet known. The technology frontier, Z_{t-1}, is assumed to grow exogenously at a rate of γ_z. The following subsections describe the behavior of economic agents in the investment sector.

2.2.1 Final investment good

Under perfect competition, a representative firm produces final investment good $y_{I,t}$ by combining a continuum of intermediate investment goods $\{y_{I,t}(i)\}$, $i \in [0, A_{t-1}]$ based on the following constant elasticity of substitution production function:

$$y_{I,t} = \left(\int_0^{A_{t-1}} y_{I,t}(i)^{\frac{1}{\theta}} \, di \right)^{\theta}, \quad \theta > 1, \tag{3}$$

where A_{t-1} is the number of adopted technologies, each of which is used for producing an intermediate investment good. Given the price of final investment good $p_{I,t}$ and the price of the i-th intermediate investment good $p_{I,t}(i)$ for all i, the firm maximizes its profit $p_{I,t}y_{I,t} - \int_0^{A_{t-1}} p_{I,t}(i)\, y_{I,t}(i)\, di$ subject to (3). The resulting optimality condition yields the demand curve for the i-th intermediate investment good:

$$y_{I,t}(i) = \left(\frac{p_{I,t}(i)}{p_{I,t}} \right)^{\frac{\theta}{1-\theta}} y_{I,t}. \tag{4}$$

The price of the final investment good is given by

$$p_{I,t} = \left(\int_0^{A_{t-1}} p_{I,t}(i)^{\frac{1}{1-\theta}} \, di \right)^{1-\theta}. \tag{5}$$

2.2.2 Intermediate investment goods

There are a continuum of firms, indexed by $i \in [0, A_{t-1}]$, that produce intermediate investment goods. Each firm i is monopolistically competitive and produces the i-th intermediate investment good $y_{I,t}(i)$ by combining capital $k_{I,t-1}(i)$ and labor $n_{I,t}(i)$ based on the following Cobb-Douglas production function:

$$y_{I,t}(i) = x_t k_{I,t-1}(i)^{\alpha} n_{I,t}(i)^{1-\alpha}. \tag{6}$$

Given the factor prices, the firm minimizes its cost $r_t k_{I,t-1}(i) + w_t n_{I,t}(i)$ subject to production function (6). The optimality conditions imply that the capital-labor ratio is identical for all i, so that the factor prices are given by

$$w_t = mc_{I,t}(1-\alpha) x_t (k_{I,t-1}/n_{I,t})^{\alpha}, \tag{7}$$

$$r_t = mc_{I,t} \alpha x_t (k_{I,t-1}/n_{I,t})^{\alpha-1}, \tag{8}$$

where $mc_{I,t}$ is the marginal cost, $k_{I,t}$ represents capital in the investment goods sector, and $n_{I,t}$ is the labor employed in the investment goods sector. Combining equations (1), (2), (7), and (8) yields $mc_{I,t} = 1$.

Firms maximize their profit $p_{I,t}(i)\, y_{I,t}(i) - mc_{I,t} y_{I,t}(i)$ subject to the demand curve given by equation (4). The optimality condition yields

$$p_{I,t}(i) = \theta mc_{I,t} = \theta. \tag{9}$$

Substituting (9) into (5) yields the price of investment:

$$p_{I,t} = \frac{\theta}{A_{t-1}^{\theta-1}}. \tag{10}$$

Because the price of consumption is taken as the numeraire, $p_{I,t}$ corresponds to the relative price of investment. Equation (10) implies that the relative price of investment decreases as IST advances as a result of the expansion of the number of intermediate investment goods A_{t-1}. In addition, equations (9) and (10) imply that $p_{I,t}(i)/p_{I,t}$ is independent of i, suggesting from equation (4) that the production of the intermediate goods is symmetric. By using this feature and substituting equation (6) into equation (3), the amount of the final investment good, $y_{I,t}$, is given by

$$y_{I,t} = A_{t-1}^{\theta-1} x_t k_{I,t-1}^{\alpha} n_{I,t}^{1-\alpha}. \tag{11}$$

In equation (11) the number of intermediate investment goods A_{t-1} constitutes the level of IST.

Because the intermediate good firms have market power with regard to their product, they earn a positive profit every period given by $\Pi_{I,t}(i) = (\theta - 1) A_{t-1}^{-\theta} y_{I,t} = (\theta - 1) A_{t-1}^{-1} x_t k_{I,t-1}^{\alpha} n_{I,t}^{1-\alpha}$ for all $i \in [0, A_{t-1}]$. Note that the profit is the same for all i. Thus, the value, in units of the consumption good, of a firm that produces an intermediate investment good, denoted by V_t, can be expressed in recursive form as follows:

$$V_t = (\theta - 1) A_{t-1}^{-1} x_t k_{I,t-1}^{\alpha} n_{I,t}^{1-\alpha} + m_{t,t+1} V_{t+1}, \tag{12}$$

where $m_{t,t+1}$ is the discount factor of the representative household.

2.2.3 Technology adoption

There is a continuum of technology-adopting firms, each of which owns a not-yet-adopted technology in the interval $(A_{t-1}, Z_{t-1}]$, where Z_{t-1} is the world technology frontier at the beginning of period t which grows exogenously at a rate of γ_z. Each technology-adopting firm converts technology into usable form for producing an intermediate investment good. Doing so is potentially time-consuming, costly, and affected by barriers to technology adoption. To capture this adoption process, we assume that each firm succeeds in adopting technology with probability λ_t, which is given by

$$\lambda_t = \frac{\lambda_0}{\pi} \left(\frac{A_{t-1}}{A_{t-1}^*} i_{a,t} \right)^{\omega}, \ 0 < \omega < 1, \ \lambda_0 > 0, \tag{13}$$

where $i_{a,t}$ is adoption expenses in terms the consumption good and π is the extent of barriers to technology adoption. Technology adoption is potentially time-consuming because it takes $1/\lambda$ periods on average to adopt technology in steady state. It is costly because it requires an increase in expenses $i_{a,t}$ to raise the probability of technology adoption. This time-consuming and costly process captures the aspect of Japanese technology adoption that were mainly conducted through licenses and the reverse engineering of imported goods in the early post-WWII period. Technology adoption is negatively affected by barriers π because a high value of π lowers the probability of technology adoption. The presence of A_{t-1} in (13) reflects the spillover effect from previously adopted technology on new technology adoption and the presence of $A^*_{t-1} \equiv x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{(\theta-1)\alpha}{1-\alpha}}$ keeps probability λ_t stationary. Because $A_{t-1}/A^*_{t-1} = x_t^{-\frac{1}{1-\alpha}} A_{t-1}^{\frac{1-\alpha\theta}{1-\alpha}}$, the spillover effect is positive as long as $\alpha\theta < 1$, which holds under our parameterization of the model presented in the next section.

Each adopting firm that owns a not-yet-adopted technology chooses the amount of adoption expenses $i_{a,t}$ that maximizes the value of the firm J_t. The technology, if adopted, will be used for producing an intermediate investment good in the next period, so that it will have value V_{t+1}. Thus, the present value of the firm is given by

$$J_t = \max_{\{i_{a,t}\}} \left\{ -i_{a,t} + m_{t,t+1} \left[\lambda_t V_{t+1} + (1-\lambda_t) J_{t+1} \right] \right\}. \tag{14}$$

The optimality condition with respect to $i_{a,t}$ yields

$$1 = \frac{\lambda_0 \omega}{\pi} \left(\frac{A_{t-1}}{A^*_{t-1}} i_{a,t} \right)^{\omega-1} \frac{A_{t-1}}{A^*_{t-1}} m_{t,t+1} \left(V_{t+1} - J_{t+1} \right). \tag{15}$$

Equation (15) implies that adoption expenses $i_{a,t}$ are decreasing in the extent of barriers π and increasing in the difference between the return in the case that technology is adopted, V_{t+1}, and the value of the firm if it fails to adopt technology, J_{t+1}.

In aggregate, new technologies amounting to $\lambda_t \left(Z_{t-1} - A_{t-1} \right)$ are adopted in period t and added to the existing pool of adopted technologies. Thus, the law of motion for the number of adopted technologies, or equivalently, the number of intermediate investment goods, is given by:

$$A_t = A_{t-1} + \lambda_t \left(Z_{t-1} - A_{t-1} \right). \tag{16}$$

2.3 Household sector

There is a representative household that owns capital stock and all firms in the economy. The household supplies one unit of labor inelastically and chooses consumption c_t, investment $y_{I,t}$, and capital stock k_t to maximize utility:

$$\sum_{t=0}^{\infty} \beta^t \log \left(c_t \right),$$

subject to the budget constraint and the law of motion for capital,

$$c_t + p_{I,t} y_{I,t} = w_t + r_t k_{t-1} + T_t,$$

$$k_t = \left(1 - \delta\right) k_{t-1} + y_{I,t},$$

where T_t is the net profit generated by firms and $0 < \delta < 1$ is the capital depreciation rate. The optimality conditions yield the consumption Euler equation:

$$1 = m_{t,t+1} \left[\frac{r_{t+1} + p_{I,t+1} \left(1 - \delta\right)}{p_{I,t}} \right], \tag{17}$$

where the preference discount factor $m_{t,t+1}$ is given by $m_{t,t+1} = \beta c_t / c_{t+1}$. Substituting (11) for $y_{I,t}$ into the law of motion for capital yields

$$k_t = \left(1 - \delta\right) k_{t-1} + A_{t-1}^{\theta-1} x_t k_{I,t-1}^{\alpha} n_{I,t}^{1-\alpha}. \tag{18}$$

2.4 Equilibrium

The model economy is closed by the market clearing conditions for the consumption good, capital stock, and labor, which are given, respectively, by

$$x_t k_{c,t-1}^{\alpha} n_{c,t}^{1-\alpha} = c_t + \left(Z_{t-1} - A_{t-1} \right) i_{a,t}, \tag{19}$$

$$k_t = k_{c,t} + k_{I,t}, \tag{20}$$

$$1 = n_{c,t} + n_{I,t}. \tag{21}$$

Output y_t in units of the consumption good in this economy is defined as $y_t \equiv y_{c,t}+p_{I,t}y_{I,t}$, so that it is given by

$$y_t = x_t k_{c,t-1}^{\alpha} n_{c,t}^{1-\alpha} + p_{I,t} A_{t-1}^{\theta-1} x_t k_{I,t-1}^{\alpha} n_{I,t}^{1-\alpha}. \quad (22)$$

The equilibrium conditions for this economy consist of the following fifteen equations, (1), (2), (7), (8), (10), (12), and (14)-(22), with the same number of endogenous variables, $\{y_t,\ c_t,\ i_{a,t},\ n_{c,t},\ n_{I,t},\ k_t,\ k_{c,t},\ k_{I,t},\ p_{I,t},\ mc_{I,t},\ A_t,\ V_t,\ J_t,\ r_t,\ w_t\}$. Appendix C rearranges the equilibrium conditions into a system of equations, stationarizes the variables, and presents the derivation of the steady state.

3 Quantitative Analyses

Using the benchmark model presented in the previous section, this section quantitatively examines the role of barriers to technology adoption in Japan's low per capita output relative to the UK in the prewar period and the catch-up to the UK in the postwar period. We use the UK as a benchmark economy as in Ngai (2004) because the UK is an advanced country in the entire simulation period of 1890-2000 and data are available in the period. We start by describing our simulation strategy and parameterization of the model and then present our main findings as well as an extension of the model.

3.1 Simulation strategy

Our simulation strategy is to quantify barriers to technology adoption in Japan and the UK from data on the relative price of investment and then examine the effect of a reduction in such barriers in Japan after WWII. To this end, we consider two model economies: one corresponding to Japan and another corresponding to the UK. Each model economy is identical to the benchmark model except for the extent of barriers to technology adoption, π, and the initial level of the neutral technology factor, x_0, where the initial level of a neutral technology factor in the UK is normalized to unity; i.e.,

$x_{0,\mathrm{UK}} = 1$. This setup implies that both Japan and the UK share the same frontier of not-yet-adopted technology, Z_t, which is regarded as the world technology frontier. The assumption that both Japan and the UK face the world technology frontier can be justified by the fact that following the Meiji Restoration the Japanese government was aware of advanced Western technology and promoted its adoption.

For our simulation we apply to the model the key features of the data on per capita output and the relative price of investment for Japan and the UK presented in Figures 1(a) and (d). The data lead to the following four assumptions for our simulation. First, the UK model economy is assumed to be on a balanced growth path in which the growth rate of per capita output is constant for all periods. The extent of barriers to technology adoption is also constant at π_{UK}. This assumption is consistent with the fact that per capita output in the UK over the long run has more or less followed a stable growth path. Second, because per capita output in Japan in the prewar period more or less consistently hovered at about 40 percent of the UK level, it is assumed that the Japanese model economy also followed a balanced growth path in the prewar period, where the extent of barriers to technology adoption was constant at π_{JP}. Third, to capture the sharp drop in per capita output in Japan at the end of the war, unexpected one-time capital destruction is introduced, as in Christiano (1989). Fourth and most importantly, in view of the historical evidence presented in the next section, it is assumed that barriers to technology adoption in Japan declined after the war. Specifically, it is assumed that the extent of such barriers unexpectedly changed from π_{JP} to π'_{JP}, where the value of π'_{JP} is normalized to unity, i.e., $\pi'_{\mathrm{JP}} = 1$.

These four assumptions allow us to identify the values of π_{JP}, π_{UK}, and $x_{0,\mathrm{JP}}$ in the model economies given the data presented in Figures 1(a) and (d) and the other parameter values. Let $p_{I,j}$ and $p'_{I,j}$ for $j \in \{\mathrm{JP}, \mathrm{UK}\}$ denote the relative price of investment in the prewar steady state and in the postwar steady state respectively. Because the relative price reflects the degree of advancement of IST, which is affected by the barriers, the ratio of the relative price for Japan to the UK has the following relationship:

$$\text{Prewar steady state:} \quad \frac{p_{I,\mathrm{JP}}}{p_{I,\mathrm{UK}}} = \left[\frac{a(\pi_{\mathrm{UK}})}{a(\pi_{\mathrm{JP}})}\right]^{\theta-1}, \tag{23}$$

$$\text{Postwar steady state:} \quad \frac{p'_{I,\mathrm{JP}}}{p'_{I,\mathrm{UK}}} = \left[\frac{a(\pi'_{\mathrm{JP}})}{a(\pi'_{\mathrm{UK}})}\right]^{\theta-1}, \tag{24}$$

where function $a(\pi)$ is decreasing in the degree of barriers, π. The derivation of $a(\pi)$ is delegated to Appendix C. Note that $\pi'_{\mathrm{UK}} = \pi_{\mathrm{UK}}$ by assumptions and $\pi'_{\mathrm{JP}} = 1$ from normalization. Then, setting $p'_{I,\mathrm{JP}}/p'_{I,\mathrm{UK}}$ to the average of the values from 1980 to 2000, we obtain the value of $\pi'_{\mathrm{UK}} = \pi_{\mathrm{UK}}$ from equation (24). With the value of π_{UK} in hand, setting the ratio of the relative price, $p_{I,\mathrm{JP}}/p_{I,\mathrm{UK}}$, to the average of the values from 1890 to 1936, the year just before the beginning of the Second Sino-Japanese War, we obtain the value of π_{JP} from equation (23).

Next, consider the value of $x_{0,\mathrm{JP}}$. Transformed output $y_t/(x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{(\theta-1)\alpha}{1-\alpha}})$ becomes constant and independent of π and x_0 in steady state, as shown in Appendix C. Hence, the ratio of output in Japan to that in the UK in the prewar period is given by

$$\frac{y_{\mathrm{JP}}}{y_{\mathrm{UK}}} = \left(\frac{x_{0,\mathrm{JP}}}{x_{0,\mathrm{UK}}}\right)^{\frac{1}{1-\alpha}} \left[\frac{a(\pi_{\mathrm{JP}})}{a(\pi_{\mathrm{UK}})}\right]^{\frac{\alpha(\theta-1)}{1-\alpha}}, \tag{25}$$

where $x_{0,\mathrm{UK}} = 1$ from normalization. With $a(\pi_{\mathrm{UK}})/a(\pi_{\mathrm{JP}})$ in hand, equation (25) gives the value of $x_{0,\mathrm{JP}}$.

We solve the model's non-linear system of equations by using the function iteration method. Details of how the model is solved are provided in Appendix D.

3.2 Parameterization

The unit of time is a year. The subjective discount factor is set at $\beta = 0.97$. The growth rates of exogenous neutral technology γ and technology frontier γ_z are jointly set to match the growth rate of per capita output in the UK economy in the period 1890-2000. In jointly setting these growth rates, the contribution of IST progress to the growth rate of per capita output is assumed to be 0.6 following Greenwood et al. (1997).[8] The capital share and the capital depreciation rate are set at $\alpha = 0.36$ and $\delta = 0.089$ respectively, following Hayashi and Prescott (2002). While the value of $\alpha = 0.36$ is based on Japanese national accounts data, it should be noted that, as highlighted by Parente and Prescott (2000), it would be higher if unmeasured investment were taken into account. Therefore, in addition to $\alpha = 0.36$, following Ngai (2004) we also use a value $\alpha = 0.5$ for our quantitative analysis. The markup is set at $\theta = 1.2$. Based on Comin and Hobijn (2010), who report an average length of time of 8.75 years between the invention and the eventual adoption of a production method in the postwar period for Japan,[9] parameter λ_0 in (13) is set to match the probability of technology adoption of 11.4 percent ($\approx 1/8.75$) in the steady state in which barriers to technology adoption are set to their postwar value of π'_{JP}. Finally, the elasticity of technology adoption with respect to the amount of expenses for adopting technology ω is set at 0.65, so that the model matches the development in the ratio of the relative price of investment for Japan to that for the UK after the war. Table 1 provides a list of the parameter values.

3.3 Main findings

We simulate the parameterized models for Japan and the UK by following the strategy presented in Section 3.1 and compare the simulated data with actual data for per capita output and the ratio of the relative price of investment. Regarding per capita output, the simulated and actual data can be compared without any adjustments because output

[8] The reason that we use the value obtained by Greenwood et al. (1997) for the US is that we suspect that our dataset may underestimate the rate of IST progress. The data for the postwar period in our dataset are taken from the Penn World Table (PWT). However, in the PWT the average rate of decrease in the relative price of investment – one measure of IST progress – for the US is lower than that obtained in previous studies such as Greenwood et al. (1997), who use the quality-adjusted price of investment. This means that our dataset may underestimate the rate of IST progress.

[9] Comin and Hobijn (2010) also report data for the UK and the length of time is 9 years, close to that of Japan.

is measured in units of consumption.[10]

Figure 2(a) plots developments in per capita output, while Figure 2(b) shows developments in the ratio of the relative price of investment. Both series are generated using $\alpha = 0.36$ in the simulation. In the simulation, both the Japanese economy (thick solid line) and the UK economy (thick dashed line) are on a balanced growth path in the prewar period by assumption, and per capita output in Japan remains about 40 percent of that in the UK during the period. The devastation of WWII is taken into account by incorporating unexpected capital destruction into the simulation to match the decline in per capita output between 1944 and 1945 observed in the data, which is taken from the database of the Maddison Project.[11] At the same time, barriers to technology adoption decline from $\pi_{\mathrm{JP}} = 7.66$ to $\pi'_{\mathrm{JP}} = 1$. In Figure 2(a), per capita output recovers quickly and rises beyond the counterfactual path assuming that the barriers remain unchanged (thick dotted line). Meanwhile, the simulated ratio of the relative price of investment for Japan to that for the UK, denoted by "baseline" in Figure 2(b), starts to decline and well captures the actual development of the corresponding data after the war, reflecting the increase in IST resulting from the increase in technology adoption. Technology adoption increases because the reduction in barriers raises the returns on investment for technology adoption and hence results in an increase in such investment.

In 2000, the simulated per capita output in Japan reaches 63 percent of that in the UK. Hence, the reduction in barriers to technology adoption explains about 40 percent ($\approx 1 - (1 - 0.63) / (1 - 0.40)$) of the catch-up achieved after the war. If such a reduction had occurred in Japan at the beginning of the modern growth that started around the

[10] See Greenwood and Krusell (2007) for the use of a consumption-based output measure in a model and growth accounting with IST. If output is measured in units of GDP instead, it is necessary to convert values in terms of purchasing power parity using the Geary-Khamis formula to address differences in the relative price of investment and to make it possible to compare actual and simulated output.

[11] The database indicates that output fell by 47 percent between 1944 and 1945. Introducing unexpected capital destruction helps the model explain the development of per capita output in the early postwar period, but it does not affect our main result on the effect of the reduction in barriers on the growth miracle.

mid-1880s, the prewar gap in per capita output between Japan and the UK would have been narrower by the same margin. Therefore, the high degree of barriers to technology adoption explains about 40 percent of the prewar gap.

The increase in the simulated IST progress can partly explain the actual increase in TFP in the postwar period. If TFP is calculated from the simulated series in this baseline simulation under the assumption of no IST progress, the increase in IST will appear as an increase in TFP. Indeed, as shown in Figure 3, TFP calculated under this assumption for the model (thick line) rises above the trend assuming no removal of barriers (dotted line). The increase in TFP partly explains the rapid increase in actual TFP in the non-primary sector (thin line) – i.e., all industries other than agriculture, fishery, and forestry – calculated under the same assumption.[12] In addition, the model captures the slowdown in TFP after the mid-1970s as the catch-up in IST comes to an end.

We also simulate the model with the capital share set to $\alpha = 0.5$ in order to take into account that there may be unmeasured investment, as argued by Parente and Prescott (2000) and others. Figure 4 plots the simulation results otherwise using the same parameter values as in the previous simulation. The increase in the capital share from 0.36 to 0.5 results in two major differences. First, per capita output in Japan at the end of the observation period in 2000 is higher than in the previous case, reaching 83 percent of the UK level. Consequently, the reduction in barriers now explains about 70 percent ($\approx 1 - (1 - 0.84) / (1 - 0.4)$) of the catch-up achieved after the war, which is much greater than the about 40 percent in the previous case, where $\alpha = 0.36$. To

[12] In Figure 3, actual TFP, denoted by "Data," is calculated for the non-primary sector. We focus on the non-primary sector because it is mainly the non-primary sector that features IST progress. Nevertheless, the observed trend in TFP for the non-primary sector is similar to that obtained by Hayashi and Prescott (2008) for all industries: TFP shows steady increases in the prewar period and rapid growth in the postwar period. Details of how we calculate TFP can be found in Appendix A.

understand this effect, it helps to combine equations (24) and (25), which yields

$$\frac{y'_{\mathrm{JP}}}{y_{\mathrm{UK}}} = \left(\frac{x_{0,\mathrm{JP}}}{x_{0,\mathrm{UK}}}\right)^{\frac{1}{1-\alpha}} \left(\frac{p_{I,\mathrm{UK}}}{p'_{I,\mathrm{JP}}}\right)^{\frac{\alpha}{1-\alpha}}, \tag{26}$$

where $y'_{\mathrm{JP}}/y_{\mathrm{UK}}$ is per capita output in Japan relative to the UK in the postwar steady state. Equation (26) implies that the effect of the relative-price term, $p_{I,\mathrm{UK}}/p'_{I,\mathrm{JP}}$, on $y'_{\mathrm{JP}}/y_{\mathrm{UK}}$ becomes greater as the capital share α increases. An increase in the capital share raises the contribution of capital to output and thereby magnifies the effect on output of the increase in capital stock induced by a drop in the relative price. Second, the convergence rates of per capita output and the relative price of investment become somewhat slower than in the previous case. A higher capital share lowers the marginal product of capital, given the amount of capital, and reduces the speed of capital accumulation.

3.4 Timing of the removal of barriers

The simulations conducted thus far assumed that the barriers to technology adoption declined in 1945 at the end of WWII. This, however, might be slightly early in light of the historical evidence suggesting that major changes in policy and institutions occurred a few years after the end of the war, as discussed in the next section. To address this issue of timing, we repeat the same simulation but with a reduction in barriers in 1950 instead of 1945 for the model with $\alpha = 0.36$. Figure 5 plots the developments in simulated per capita output in Japan for this simulation (thick dotted line). Output recovers sharply just after the war and the recovery slows down somewhat around 1950 when the barriers declined; however, this slowdown is not consistent with the data. What causes this slowdown in the recovery when using 1950 is the income effect of the reduction in the barriers. Such a reduction will increase the level of IST and income in future, which leads households now to consume more and invest less, slowing capital accumulation. This effect is less pronounced in the former simulation, in which the barriers decline in

1945, because the marginal product of capital is quite high due to the destruction of capital in 1945.

One way to address this slowdown in output growth in the simulation is to introduce the subsistence level of consumption, as in Christiano (1989). With the subsistence level of consumption, $\bar{c}$, the periodic utility function is given by $\log\left(c_t - \bar{c}A^*_{t-1}\right)$. Figure 5 plots the simulated per capita output in Japan for the modified model (thick solid line) in which $\bar{c}$ is set to 45 percent of steady state consumption.[13] With this subsistence level of consumption, the speed of capital accumulation becomes slower just after the war and the marginal product of capital remains higher around 1950 than when no subsistence level of consumption is assumed. As a result, there appears no slowdown in output growth around 1950, which is more or less consistent with the data.

4 What were barriers to technology adoption?

The previous section showed within the framework of the two-sector growth model that the existence of barriers to technology adoption explained about 40 percent of the gap in per capita output between Japan and the UK in the prewar period and that the reduction in such barriers explained about 40 percent of the catch-up attained in the postwar growth miracle as well as developments in the relative price of investment. In the model, as represented by equation (13), the barriers lowered the probability of technology adoption for any given amount of technology-adoption expenses. However, what, concretely, were such barriers to technology adoption? What blocked potential technology adoption in the prewar period and what promoted actual technology adoption in the postwar period?

In this section we address these questions from a historical perspective. We point

[13] In 1944, many consumption goods were rationed in Japan due to the war and per capita consumption was about 50 percent of the level in 1937-1938, the period just before WWII began. This observation suggests that the subsistence level of consumption is lower than but possibly not far less than fifty percent.

out three factors that potentially played a role as barriers that made it difficult and costly to adopt technology in the prewar period relative to the postwar period: (i) low capacity to absorb technology; (ii) economic and political frictions between Japan and other countries; (iii) a lack of competition in the market.

It is worth noting that foreign trade and payments including those related to technology adoption were heavily regulated in the early postwar period while such regulations were absent in almost all of the prewar period. It is still controversial whether the regulations promoted or hampered technology adoption. Our argument is that taken the regulations as given the aforementioned three factors greatly declined in importance in the postwar period and thus the barriers were reduced in the period.

The following subsections discuss each of these factors in detail. Appendix B presents a brief historical overview of technology adoption in Japan from 1868 to 1950 to provide additional background to our argument.

4.1 Low absorptive capacity

We define the capacity to absorb new technology as the level of skills and knowledge necessary to learn, manage, and put new technology to practical use in a given period of time. Low absorptive capacity prevents the adoption of advanced technology and limits the kind of technology that can be adopted. Hence, low absorptive capacity corresponds to a high value of π in the model, i.e., high barriers to technology adoption.

We argue that absorptive capacity was low in the pre-WWII period but increased sharply during and after the war. The literature on Japan's economic history suggests that the slow spread of modern science in the pre-WWII period made it difficult for Japan to develop industries that required advanced technology, so that industrialization initially concentrated primarily on light industry.[14] In addition, the technology adopted was not necessarily advanced; instead, most of the technology actually adopted lay be-

[14] See, e.g., Minami (2002: 83).

tween conventional and advanced technology,[15] indicating that technology adoption was restrained by low capacity.

Further evidence of this low absorptive capacity is that until WWII, as shown in Figure 6, the number of new university graduates with an engineering degree did not exceed 5,000 – equivalent to 70 per million population – per year. However, the number of engineering graduates increased sharply during the war, reaching 12,125 (160 per million population) in 1945, i.e., more than twice the number in the pre-WWII period. As a result, the total number of university graduates with an engineering degree – that is, not the flow but the stock of engineering graduates – doubled from 41,080 (601 per million population) in 1934 to 89,500 (1,146 per million population) in 1947.[16] These increases were driven by wartime demand for manufacturing products that called for an increase in the number of engineers, which led the government to expand the size of engineering departments and to newly establish universities with engineering departments.[17] The increase in absorptive capacity during the war did not stimulate technology adoption, however, because the government allocated such capacity exclusively to war-related production.

The expansion of institutions of higher education with engineering departments during the war contributed to the increase in absorptive capacity in the postwar period. Under the new education system that started in 1949, universities with engineering departments were re-established as successors to the higher education institutions set up or expanded during the war.[18] The increase in absorptive capacity triggered by the war effort led to a more efficient use of technology and innovations driven by investment in R&D and education in the postwar period.[19]

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[15] See Makino (1996: 197).

[16] The data regarding the number of engineering graduates and the total population are taken from Sawai (2012b: 113) and Japan Statistical Association (2007: table 2-1), respectively.

[17] See Sawai (2012a: 172-173).

[18] Sawai (2012a: 173).

[19] See, e.g., Goto (1993: 292).

4.2 Economic and political frictions

The second factor acting as a barrier to technology adoption was economic and political frictions between Japan and other countries. Although the government laid the foundations for the introduction of foreign capital and technology as early as 1899, the import of foreign technology was hampered by a series of foreign conflicts such as World War I (1914–1918), the Manchurian Incident (1931), the Second Sino-Japanese War (1937–1945), and World War II (1939–1945). One indicator of the impact of these events on technology in Japan is the share of patents in Japan registered by foreigners, which fell sharply in 1914–1918 as a result of WWI and followed a decreasing trend after 1931, reflecting the deterioration in relations between Japan and the US and the UK.[20] The share dropped particularly sharply – from 18% in 1941 to 8.1% in 1942 – following Japan's declaration of war against the US in December 1941.

In Japan's high growth period after the war, the world political situation was much more stable than in the first half of the 20th century, although there remained geopolitical tensions due to the Cold War. Under these circumstances, world trade in technology as well as goods and services increased rapidly as the world economy grew. Japan benefited from this increase in global economic exchange by importing technology[21] as well as goods and services, which was made possible, in part, by Japan's accession to the International Monetary Fund (IMF) and General Agreement on Tariffs and Trade (GATT). The international currency system provided by the IMF allowed its members to enjoy stable exchange rates until the late 1960s. In addition, GATT contributed to the removal of severe trade barriers such as tariffs. These favorable political and economic developments greatly contributed to Japan's active technology importation in the high growth period after the war.[22]

[20] See Japan Statistical Association (2007: table 17-10).

[21] Comin and Hobijn (2011) show econometrically that economic aid and technical assistance provided by the US in the postwar period contributed to a reduction in technology-adoption costs in Japan.

[22] Goto (1993: 301).

4.3 Lack of competition

In the benchmark model technology-adopting firms are assumed to be competitive and to be able to make choices in a frictionless manner. If, however, the firms are owned by holding companies that distort firms' decision-making due to a lack of competition, this could potentially reduce firms' expenditure $i_{a,t}$ and slow down technology adoption. Thus, a lack of competition plays a similar role to barriers to technology adoption.

Our main argument is that during the prewar period, a lack of competition, of which the presence of the *zaibatsu* is one manifestation, was one of the factors acting as a barrier to technology adoption. Another related factor is the conservatism of the *zaibatsu*. Although the *zaibatsu*, which controlled large parts of the Japanese economy,[23] did adopt new technology, mainly through their subsidiaries,[24] they tended to be very conservative in terms of entering new fields and investing in their subsidiaries.[25] Morikawa (1978), for example, points out that in the process of heavy and chemical industrialization in the 1910s and 1920s some of the major *zaibatsu* companies were extremely conservative and, as a result, occasionally underperformed emerging companies with less capital. Morikawa argues that underlying the conservative stance of *zaibatsu* companies was (i) slow decision making and low dynamism due to the large size of *zaibatsu* companies; (ii) the influence of the *zaibatsu* family, whose priority was to preserve the family's fortunes; and (iii) difficulties in reconciling differences of opinion among subsidiaries that ran diverse operations.[26] Related to (ii), it is worth noting that the holding company at the top of a *zaibatsu* was typically owned by family members that, as owners and partners, were subject to unlimited liability. For this reason, the holding company strictly monitored the investment behavior of its subsidiaries and tended to be conservative in

[23] Hadley (1970: 6)

[24] Ohkawa and Rosovsky (1973: 258).

[25] Miyajima (2004: 178–189).

[26] See Morikawa (1978: 187–193). A more detailed discussion of the conservatism of the *zaibatsu* is provided in Morikawa (1980: 168–202).

terms of subsidiaries' investment decisions and entry into new business areas.[27] As a consequence, the presence of the *zaibatsu* and their conservatism resulted in a lack of competition in the prewar period.

Following WWII, the *zaibatsu* were dissolved and some of their major constituent companies were split up as part of the policy of the Supreme Commander for the Allied Powers under the allied occupation.[28] These changes stimulated competition among firms and contributed to the subsequent high growth.[29] For example, in the steel industry, Japan Iron & Steel was divided into two firms, Yawata Iron & Steel and Fuji Iron & Steel, and this split increased competition and stimulated investment in the industry.[30] In the paper manufacturing industry, Oji Paper was split into three firms, resulting in greater competition and investment in the industry. In this manner, the dissolution of the *zaibatsu* and deconcentration destroyed the old industrial regime and sparked greater competition – including in the area of investment – during the process of economic recovery.[31]

Despite the dissolution of the *zaibatsu*, former *zaibatsu* companies formed new business groups – the *keiretsu* – in the period of rapid economic growth. The *keiretsu*,

[27] See Miyajima (2004: 178–189).

[28] The dissolution of the *zaibatsu* began in 1946. Eighty-three companies were designated as "*zaibatsu* mother companies," and 21 of these were split up. In addition, in 1947, the Law for the Elimination of Excessive Concentration of Economic Power was enacted and 11 companies with a large presence in most industries were split up.

[29] See Minami (2002: 101–102) and Hadley (1970: 438). However, the view that the dissolution of the *zaibatsu* helped to create a more competitive market environment in the postwar period is not without detractors. Miwa (1993: 129–152), for example, argues that the government's policy played no substantial role in strengthening competition.

[30] Japan Iron & Steel was established in 1934 through a merger of the state owned Yawata Iron Factory and a number of private companies. More than half of Japan Iron & Steel's shares were owned by the government and the firm did not act as a competitor to private companies. Japan Iron & Steel was split after the war, however, and the resulting two companies became direct competitors to other companies. To compete with these companies, Kawasaki Steel expanded its operations and became a comprehensive iron and steel manufacturer. This entry into all areas of iron and steel production triggered the entry of three other companies, resulting in severe competition among six major iron and steel manufacturers in total. See Yonekura (1992: 100–103) for details.

[31] See Kosai (1989: 306-307).

however, differed from the *zaibatsu* in the following three respects.[32] First, unlike the *zaibatsu*, the *keiretsu* did not have a centralized corporate structure, in which all subsidiaries in a business group were controlled by a holding company at the top *zaibatsu*. Second, due to this decentralized structure, firms in the same *keiretsu* sometimes competed with each other. Third, the *keiretsu* tended to do business with other business groups more often than did the *zaibatsu*. Moreover, due to competition among the *keiretsu*, markets were oligopolistic but competitive, which led to greater investment and technology adoption by firms in the *keiretsu*.[33]

The intensification of competition in the market during the postwar period contributed to the increase in technology adoption.[34] A survey conducted by the Ministry of International Trade and Industry in 1961 on technology adoption under the Foreign Investment Law, for example, found that the main reasons why firms adopted foreign technology were to enhance their domestic and international competitiveness, to save on the costs of research, and to start up new businesses.[35]

5 Conclusion

In this study we built a dynamic model with endogenous technology adoption and quantitatively analyzed the role of barriers to technology adoption to explain why Japan experienced a growth miracle in the postwar period, but not in the prewar period. To do so, we employed data on the relative price of investment in the model and quantified the extent of such barriers, which pointed at a sharp reduction in barriers from the prewar period to the postwar period. The simulation suggested that the reduction in barriers just after WWII explains about 40 percent of the catch-up achieved in the postwar period. In addition, it indicated that the existence of such barriers explains about 40

[32] See Minami (2002: 102–103) for the first two points and Hadley (1970: Ch.11) for the last.

[33] See Ito (1985: 227–264) for more details.

[34] Goto (1993: 289).

[35] Ministry of International Trade and Industry (1962: 91).

percent of the gap in per capita output between Japan and the UK in the prewar period. Moreover, the model successfully replicated developments in the ratio of the relative price of investment for Japan to that for the UK. Complementing the simulation results, we considered potential factors acting as barriers to technology adoption from a historical perspective, arguing that low absorptive capacity due to skill shortages, economic and political frictions between Japan and other countries, and an insufficiently competitive market environment probably played an important role.

We would like to conclude by highlighting some caveats regarding our main results. First, the quantitative results depend on the data on the relative price of investment, which may contain measurement errors. Such errors are likely to be greater the further we go back into the past before 1950, the earliest year for a cross-country benchmark in which a purchasing-power parity price level is reported for consumption and investment. Second, although this study focused on IST and highlighted the three factors that likely acted as barriers to the adoption of such technology, these factors may also have affected the adoption of other types of technology such as neutral technology. If such effects were taken into account, the overall effect of the three factors on Japanese prewar and postwar growth would potentially be even greater. Third, our findings suggest that barriers to technology adoption explain about 40 percent of the gap between Japan and the UK in the prewar period and that a reduction in such barriers explains about 40 percent of the catch-up achieved in the postwar period. This means that the remaining 60 percent or so is attributable to other factors such as the presence of home production that amplifies the effect of barriers to IST (Parente et al., 2000), barriers to labor mobility (Hayashi and Prescott, 2008), and barriers to the adoption of technologies other than IST.

Appendix

A Data

Relative price of investment: The relative price of investment is defined as the ratio of the price of investment to the price of consumption. For both Japan and the UK in the postwar period from 1950 to 2000, the data are taken from the Penn World Table 7.1 (PWT 7.1).

For the data for the prewar period from 1890 to 1940, we construct linked series of the prices of consumption and investment by using the inflation rates of these prices. For Japan, the data source of the price of investment is the index of investment good prices excluding the prices of residential buildings reported in Ohkawa et al. (1967), table 7. As for the consumption price data, the deflator for personal consumption expenditure in Ohkawa et al. (1974), table 30, is used. To connect the postwar series with the prewar series, we use the linkage scales in Ohkawa et al. (1967: 72) and Ohkawa et al. (1979: 389) for investment and consumption prices respectively.

For the UK for the prewar period, we follow Collins and Williamson (2001). The data for the price of investment are taken from Feinstein and Pollard (1988: 470–471) for the period 1890–1920 and Feinstein (1972), table 61, for the period 1920–1950. The data for the price of consumption are taken from Feinstein (1972), table 61.

Per capita output in units of consumption: The data for the postwar period from 1950 to 2000 are taken from PWT 7.1. We calculate per capita output in units of consumption by multiplying PPP-converted per capita GDP with the GDP price level and dividing this by the price level of consumption.

For the period of 1890 to 1949, we obtain per capita output in units of consumption by extrapolating backward from 1950 using the growth rate of another measure of per capita output in units of consumption. This other measure is the per capita GDP from the Maddison Project[36] multiplied by the GDP deflator and then divided by the price of consumption. The data source of the price of consumption is the same as that used in calculating the relative price of investment for both Japan and the UK. For the GDP deflator, we use the deflator of gross national expenditure in Ohkawa et al. (1974), table 30, for Japan and the price index for gross domestic product at factor cost in Feinstein (1972), table 61, for the UK.

Total factor productivity: We calculate TFP in Japan's non-primary sector, which consists of all industries except agriculture, fishery, and forestry, in Japan using the formula $A = Y/(K^{\alpha}N^{1-\alpha})$, where Y is real output, K is the real capital stock, and N is total hours worked in the non-primary sector. The data for N are taken from Hayashi and Prescott (2008), with N given by the total number of employees multiplied by the average number of hours worked in the non-agricultural sector. For both Y and K, nominal series are divided by the price of consumption. For nominal output, we use data from Cabinet Office (2001) for the period 1955–1998 and Ohkawa et al. (1974), table 9, for the period 1890–1940. For the price of consumption, the same series as that used in the calculation of the relative price of investment is employed. Nominal capital in the period 1890–1940 is constructed by summing up five types of capital stock in the non-primary sector: producers' durable equipment, public works, electric utilities, railroads, and non-residential buildings. The series are constructed from the real capital data presented in Ohkawa et al. (1966), table 5, and deflators in Ohkawa et al. (1967), table 7. Nominal capital stock data for the non-primary sector for the period 1955–1998 are not available, so that we calculate the series as the total nominal capital stock multiplied by the ratio of the nominal gross capital stock in the non-primary sector to the total gross capital stock using data from Cabinet Office (2001).

Number of contracts of technology adoption: For the pre-WWII period, no official

[36] The Maddison Project, http://www.ggdc.net/maddison/maddison-project/home.htm, 2013 version.

statistics regarding technology adoption are available. However, as mentioned in the main text, a government survey cited in Agency of Industrial Science and Technology (1949: 163) suggests that in 1941 there were 231 contracts regarding technology adoption.

In the post-WWII period the average number of contracts of technology adoption was 230 per year in the 1950s,[37] of which about 100 contracts were approved under the Foreign Investment Law, which dealt with cases in which the contract or payment period exceeded one year.

To compare the number of technology adoption contracts between the prewar and postwar periods, we estimated the number of such contracts in 1960 as follows. According to Ministry of International Trade and Industry (1962: 13), technology adoption contracts made in the period 1950–1961 were categorized in terms of their duration. Using such data as well as annual data on the number of technology adoption contracts under the Foreign Investment Law, we estimate that the number of contracts with a duration of more than one year in 1960 was 1,170.[38] For contracts with a duration of one year or less, we take the average of fiscal 1959 and 1960 and arrive at an estimate of 243 contracts. Summing up the two values yields the estimated number of technology adoption contracts in 1960 of 1,413.

To summarize, the number of technology adoption contracts in 1941 is 231 and the estimated number for 1960 is 1,413.

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[37] We calculated the number of technology adoption contracts in the postwar period using the number of technology-assistance contracts under the Foreign Investment Law and the Foreign Exchange and Foreign Trade Control Act, which strictly regulated technology adoption. The technology-assistance contracts included the permission to use or the provision of patent and trademark rights, the provision of technical knowledge, and technical instructions by foreign engineers.

[38] The data on the number of technology adoption contracts are taken from Science and Technology Agency (1965: 153).

B Overview of Technology Adoption in Japan from 1868 to 1950

In Section 4 we argued that in the pre-WWII period in Japan barriers to technology adoption restrained the introduction of new technology from abroad and thus kept the level of IST low relative to the UK. The literature on the history of Japanese technology adoption, however, is not as clear-cut as our argument. A number of studies highlight that technology adoption played an important role in enhancing economic growth in both the prewar and postwar periods;[39] however, there are few studies providing a comparison of technology adoption between the two periods. Our discussion on technology adoption in Section 4 aims to fill this gap.

In this appendix, we present an overview of technology adoption in Japan from the Meiji Restoration of 1868 to 1950, which provides the background to our argument in Section 4. We focus on the period up to 1950 because our argument is that a reduction in barriers occurred just after the end of WWII.

Following the Meiji Restoration, Japan embarked on a course of rapid modernization, industrialization, and development with the aid of technology from the United States and Europe.[40] In the late 19th century, Japan actively imported knowledge and technology by employing foreign engineers who taught the use of advanced technology, by sending Japanese engineers abroad to acquire skills, and by importing capital goods that incorporated advanced technology.[41]

However, although the government actively encouraged the introduction of foreign technology, it sought to restrain foreign investment in Japan. Underlying this seemingly contradictory stance was the painful experience of the 1870s, when foreigners came to

[39] See, e.g., Goto (1993: 277) for the postwar period and Saito (1979: 627 and 630) for the prewar period. Meanwhile, Peck and Tamura (1976: 527) argue that technology adoption played a role in raising productivity not only during the postwar period but also during the prewar period.

[40] Saito (1979: 652).

[41] See, e.g., Uchida (1990: 265–285).

almost control Takashima Coal Mine and Mitsui Gumi – Japan's largest coal mine and financial institution respectively at the time. Subsequently, the government legislated against foreign investment in the mining industry by enacting the Japan Mining Act in 1873 and prohibited foreigners from holding shares in the banking sector by revising the National Bank Act in 1876.[42]

The year 1899 marked a shift in Japan's policy toward foreign capital, and foreign investment was now permitted. The revision of treaties with Western powers in 1899 meant that Japan gained jurisdiction over foreigners in Japan.[43] Consequently, foreign direct investment in Japan was made possible in principle.[44] In addition, the treaty revision necessitated protection of foreigners' industrial property, so that Japan joined the Union for the Protection of Industrial Property in 1899.[45] Moreover, in response to the growing demand for foreign capital as a result of rapid industrialization following the Sino-Japanese War of 1894-1895, the government revised the Commercial Law in 1899 and allowed foreigners to hold stocks and to exercise management participation right.[46] This legal revision effectively transformed Japan's policy stance toward foreign capital from one of exclusion to one of acceptance.[47] The shift resulted in an increase in technology adoption through contracts for technological assistance with large foreign companies, which included the acquisition of the shares of domestic companies by such foreign companies.[48] For example, in the electrical machinery industry, Nippon Electric was established in 1899 as the first foreign company by Western Electric, which held 54% of the equity, and the two companies entered technical cooperation contracts. In 1905 and 1907, General Electric acquired 51% and 23% of the equity of Tokyo Electric and

[42] Ishii (2015: 34-35).

[43] The treaties were revised and signed between 1894 and 1897 and implemented in 1899.

[44] Ishii (2015: 38).

[45] Suzuki (2000: 223).

[46] Miyazaki (1965: 23).

[47] Shinomiya (1994: 40).

[48] Uchida (1990: 286–291).

Shibaura Manufacturing respectively and entered technical cooperation contracts with the two companies.

Despite the change in policy toward foreign capital, there were efforts to encourage the use of domestic products, which likely restrained the introduction of foreign capital and adoption of foreign technology. Against the backdrop of a chronic current account deficit and the resulting foreign currency shortage, the government encouraged purchases of domestic products. For instance, in 1914, the Ministry of Agriculture and Commerce spearheaded efforts to promote the use of domestic products.[49] Such efforts weakened during World War I but strengthened again after the war as Japan ran a large current account deficit. In 1930, the cabinet decided to encourage the use of domestic products – that is, products produced by companies with a Japanese ownership share of at least 51 percent – to promote recovery from the Great Depression.[50] Importantly, under this policy, domestic products excluded those produced using foreign patents.[51] These efforts helped to stimulate domestic R&D, but must have restrained technology adoption from abroad.

In 1931, the official stance toward foreign capital changed in the wake of the Manchurian Incident, and the government started to regulate and ban foreign investment.[52] Technology imports were suspended in the subsequent period of war and the turbulence in the years immediately after WWII. Consequently, the technology level of Japanese industries became substantially lagged behind the US and other countries during these periods.[53]

In the wake of WWII, given the destruction of domestic capital, the government regarded foreign currency procurement and the import of foreign technology as essential in order to achieve technological development and increase the productivity of firms and

[49] Ministry of International Trade and Industry (1985: 132).

[50] Japan Patent Office (1984: 416).

[51] Japan Patent Office (1984: 416).

[52] Shinomiya (1994: 64).

[53] Agency of Industrial Science and Technology (1980: 16-20)

industries.[54] Promoting the adoption of technology consequently became a key economic policy.[55] In fact, the Ashida Cabinet (March–October 1948) made "an economic recovery underpinned by foreign currency procurement and a recovery of trust from foreign countries" its primary objective, and the series of Yoshida Cabinets that followed (October 1948–February 1954) grappled with the procurement of foreign currency as one of its most important challenges.[56]

In the period just after WWII, the Japanese economy experienced considerable instability due to the damage to supply capacity and the resulting high inflation. In 1949, the Dodge Line – a set of contractionary fiscal and monetary policies – brought an end to high inflation and a fixed exchange rate regime was established, laying the economic foundations for the procurement of foreign currency. In 1949 and 1950, the government introduced relevant legislation in the form of the "Foreign Exchange and Foreign Trade Control Act" and the "Foreign Investment Law" respectively. While the former heavily regulated foreign trade and payments in view of Japan's chronic current account deficit and limited foreign reserves, the latter aimed to promote the import of superior technology from abroad by allocating limited foreign reserves to the import of key technology. Once the government had approved the import of a particular technology and allocated the necessary foreign exchange, no further approval was required.[57] Under the Foreign Investment Law, direct investment in Japan was severely restricted until the late 1960s and early 1970s when the government began to gradually liberalize direct investment.[58] Also, although trade liberalization started in the beginning of 1960s, the share of imports in Japanese goods markets remained low. Under these environment, foreign firms often had to sell technologies rather than products. Hence, technology adoption through

[54] Suzuki (1956: 157).

[55] Ministry of International Trade and Industry (1972: 237).

[56] Asai (2001: 97).

[57] Yoshida (1967: 74); Ministry of International Trade and Industry (1972: 236–239); Ministry of Finance (1976: 105–106).

[58] Goto (1993: 281); Paprzycki and Fukao (2008: 38).

inward direct investment and imports was limited in the high growth period. Technology was imported and adopted actively, however, through technology licensing and the reverse engineering of imported capital goods.[59]

C Equilibrium Conditions and the Steady State

C.1 Equilibrium conditions

The fifteen equilibrium conditions, namely equations (1), (2), (7), (8), (10), (12), and (14)-(22), can be arranged and transformed into eight equations. Equations (1), (2), (7) and (8) imply

$$\frac{k_{c,t-1}}{n_{c,t}} = \frac{k_{I,t-1}}{n_{I,t}} = \frac{\alpha}{1-\alpha}\frac{w_t}{r_t}.$$

The identical capital-labor ratio implies $mc_{I,t} = 1$ from (1) and (7) and also leads to the following identity: $k_{c,t-1}/n_{c,t} = k_{I,t-1}/n_{I,t} = k_{t-1}$. Therefore, the six equations (1), (2), (7), (8), (10), and (12) can be arranged into the following four equations:

$$r_t = x_t \alpha k_{t-1}^{\alpha-1}, \tag{27}$$

$$w_t = x_t (1-\alpha) k_{t-1}^{\alpha}, \tag{28}$$

$$p_{I,t} = \frac{\theta}{A_{t-1}^{\theta-1}}, \tag{29}$$

$$V_t = (\theta - 1) A_{t-1}^{-1} x_t k_{t-1}^{\alpha} n_{I,t} + m_{t,t+1} V_{t+1}. \tag{30}$$

Equations (17) and (18) can be written as

$$1 = m_{t,t+1}\left[\frac{A_{t-1}^{\theta-1}}{\theta} x_{t+1}\alpha k_t^{\alpha-1} + \frac{A_{t-1}^{\theta-1}}{A_t^{\theta-1}}(1-\delta)\right], \tag{31}$$

$$k_t = (1-\delta) k_{t-1} + A_{t-1}^{\theta-1} x_t k_{t-1}^{\alpha} n_{I,t}, \tag{32}$$

Equations (19) and (22) can be written as

$$x_t k_{t-1}^{\alpha}(1 - n_{I,t}) = c_t + (Z_{t-1} - A_{t-1}) i_{a,t}, \tag{33}$$

$$y_t = [1 + (\theta - 1) n_{I,t}] x_t k_{t-1}^{\alpha}. \tag{34}$$

[59] Goto (1993: 282-300).

The system of equations for this model economy now consists of the eight equations (14)-(16) and (30)-(34) with the following eight unknowns: $\{k_t, n_{I,t}, V_t, A_t, J_t, i_{a,t}, y_t, c_t\}$. The return on capital r_t, wage w_t, and the relative price of investment $p_{I,t}$ are given by (27), (28), and (29) respectively.

C.2 Transformed equilibrium conditions

We stationarize variables in the system of equations (14)-(16) and (30)-(34) as follows:

$$\begin{aligned}
\hat{k}_{t-1} &\equiv \frac{k_{t-1}}{x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{\theta-1}{1-\alpha}}}, \hat{y}_t \equiv \frac{y_t}{x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{(\theta-1)\alpha}{1-\alpha}}}, \hat{c}_t \equiv \frac{c_t}{x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{(\theta-1)\alpha}{1-\alpha}}}, a_t \equiv \frac{A_t}{Z_t}, \\
\hat{V}_t &\equiv \frac{V_t A_{t-1}}{x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{(\theta-1)\alpha}{1-\alpha}}}, \hat{J}_t \equiv \frac{J_t A_{t-1}}{x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{(\theta-1)\alpha}{1-\alpha}}}, \hat{\imath}_{a,t} \equiv \frac{i_{a,t} A_{t-1}}{x_t^{\frac{1}{1-\alpha}} A_{t-1}^{\frac{(\theta-1)\alpha}{1-\alpha}}}, \gamma_{A,t} \equiv \frac{A_t}{A_{t-1}}
\end{aligned}$$

The transformed system of equations for this economy consists of nine equations:

$$a_t \gamma_{z,t} = a_{t-1} + \lambda_t (1 - a_{t-1}), \tag{35}$$

$$\hat{J}_t = -\hat{\imath}_{a,t} + m_{t,t+1} \gamma_{t+1}^{\frac{1}{1-\alpha}} \gamma_{A,t}^{\frac{\alpha(\theta-1)}{1-\alpha}-1} \left[\lambda_t \hat{V}_{t+1} + (1-\lambda_t) \hat{J}_{t+1} \right], \tag{36}$$

$$1 = \frac{\lambda_0 \omega}{\pi} \hat{\imath}_{a,t}^{\omega-1} m_{t,t+1} \gamma_{t+1}^{\frac{1}{1-\alpha}} \gamma_{A,t}^{\frac{\alpha(\theta-1)}{1-\alpha}-1} \left(\hat{V}_{t+1} - \hat{J}_{t+1} \right), \tag{37}$$

$$\hat{V}_t = (\theta-1) \hat{k}_{t-1}^{\alpha} n_{I,t} + m_{t,t+1} \gamma_{t+1}^{\frac{1}{1-\alpha}} \gamma_{A,t}^{\frac{\alpha(\theta-1)}{1-\alpha}-1} \hat{V}_{t+1}, \tag{38}$$

$$\hat{k}_t \gamma_{t+1}^{\frac{1}{1-\alpha}} \gamma_{A,t}^{\frac{\theta-1}{1-\alpha}} = (1-\delta) \hat{k}_{t-1} + \hat{k}_{t-1}^{\alpha} n_{I,t}, \tag{39}$$

$$1 = m_{t,t+1} \gamma_{t+1}^{\frac{1}{1-\alpha}} \left[\frac{\alpha}{\theta} \left(\hat{k}_t \gamma_{A,t}^{\frac{\theta-1}{1-\alpha}} \right)^{\alpha-1} + \gamma_{A,t}^{-(\theta-1)} (1-\delta) \right], \tag{40}$$

$$\hat{k}_{t-1}^{\alpha} (1 - n_{I,t}) = \hat{c}_t + \left(\frac{1}{a_{t-1}} - 1 \right) \hat{\imath}_{a,t}, \tag{41}$$

$$\hat{y}_t = [1 + (\theta-1) n_{I,t}] \hat{k}_{t-1}^{\alpha}, \tag{42}$$

$$\gamma_{A,t} = \frac{a_t}{a_{t-1}} \gamma_{z,t}, \tag{43}$$

where

$$m_{t,t+1} = \beta \frac{\hat{c}_t}{\hat{c}_{t+1}} \left(\gamma_{t+1}^{\frac{1}{1-\alpha}} \gamma_{A,t}^{\frac{\theta-1}{1-\alpha}} \right)^{-1},$$

$$\lambda_t = \frac{\lambda_0}{\pi} \hat{\imath}_{a,t}^{\omega},$$

with nine unknowns $\left\{\hat{k}_t, n_{I,t}, \hat{V}_t, a_t, \hat{J}_t, \hat{\imath}_{a,t}, \hat{y}_t, \hat{c}_t, \gamma_{A,t}\right\}$. The growth rates γ_t and $\gamma_{z,t}$ are exogenously given.

C.3 Steady state

Equation (43) implies that the growth rate of A_t becomes equal to the growth rate of Z_t:

$$\gamma_A = \gamma_z.$$

Equation (40) implies that capital is given by

$$\hat{k} = \gamma_z^{-\frac{\theta-1}{1-\alpha}} \left\{ \frac{\alpha}{\theta} \left[\frac{\gamma_z^{\frac{\sigma(\theta-1)}{1-\alpha}} \gamma^{\frac{\sigma-1}{1-\alpha}}}{\beta} - \gamma_z^{-(\theta-1)} (1-\delta) \right]^{-1} \right\}^{\frac{1}{1-\alpha}}.$$

From equation (39), labor in the investment goods sector is given by

$$n_I = \left(\gamma^{\frac{1}{1-\alpha}} \gamma_z^{\frac{\theta-1}{1-\alpha}} - 1 + \delta \right) \hat{k}^{1-\alpha}.$$

From equation (42), output is given by

$$\hat{y} = \left[1 + (\theta - 1) n_I\right] \hat{k}^{\alpha}.$$

Note that output $\hat{y}$ is independent of π and x_0. From equation (38), the value of an intermediate good firm in the investment goods sector is given by

$$\hat{V} = \frac{(\theta-1)\hat{k}^{\alpha} n_I}{1 - \beta \gamma^{\frac{1-\sigma}{1-\alpha}} \gamma_z^{-\frac{(\sigma-\alpha)(\theta-1)}{1-\alpha} - 1}}.$$

Keeping in mind that $\lambda = \frac{\lambda_0}{\pi} \hat{\imath}_a^{\omega}$, equation (36) can be written as

$$\hat{J} = \hat{J}(\hat{\imath}_a) = \frac{-\hat{\imath}_a + \beta \gamma^{\frac{1-\sigma}{1-\alpha}} \gamma_z^{-\frac{(\sigma-\alpha)(\theta-1)}{1-\alpha} - 1} \frac{\lambda_0}{\pi} \hat{\imath}_a^{\omega} \hat{V}}{1 - \beta \gamma^{\frac{1-\sigma}{1-\alpha}} \gamma_z^{-\frac{(\sigma-\alpha)(\theta-1)}{1-\alpha} - 1} \left(1 - \frac{\lambda_0}{\pi} \hat{\imath}_a^{\omega}\right)}.$$

Substituting this equation into (37) yields

$$\hat{\imath}_a^{1-\omega} = \frac{\lambda_0 \omega}{\pi} \beta \gamma^{\frac{1-\sigma}{1-\alpha}} \gamma_z^{-\frac{(\sigma-\alpha)(\theta-1)}{1-\alpha} - 1} \left(\hat{V} - \hat{J}(\hat{\imath}_a) \right).$$

The amount of expenses for the adoption of technology, $\hat{\imath}_a$, is determined by solving this fixed point problem. Now, λ is written as a function of the extent of barriers to technology adoption: $\lambda = \frac{\lambda_0}{\pi}\hat{\imath}_a^{\omega} \equiv \lambda(\pi)$. From equation (35), the ratio of A_t to Z_t is given by

$$a = a(\pi) = \frac{1}{\left(\frac{\gamma_z}{1-\delta_A} - 1\right)\lambda(\pi)^{-1} + 1}.$$

Finally, consumption is given by (41), which can be rewritten as follows:

$$\hat{c} = \hat{k}^{\alpha}(1 - n_I) - \left(\frac{1}{a} - 1\right)\hat{\imath}_a.$$

D Solution Method

To solve the model, we adapt Richter, Throckmorton, and Walker's (2011) function-iteration method in the following manner.

1. We discretize states as $\hat{k}_{t-1} \in \hat{\mathbf{k}} \equiv \left\{\hat{k}^1, ..., \hat{k}^n\right\}$ and $a_{t-1} \in \mathbf{a} \equiv \{a^1, ..., a^m\}$, setting $n = m = 30$.

2. We guess the rules for $\hat{\imath}_{a,t} = \hat{\imath}_a(\hat{k}_{t-1}, a_{t-1})$, $\hat{c}_t = \hat{c}(\hat{k}_{t-1}, a_{t-1})$, $\hat{V}_t = \hat{V}(\hat{k}_{t-1}, a_{t-1})$, and $\hat{J}_t = \hat{J}(\hat{k}_{t-1}, a_{t-1})$ for $(\hat{k}_{t-1}, a_{t-1}) \in \hat{\mathbf{k}} \times \mathbf{a}$, setting the initial rules to those derived from the linearized version of the model.

3. For each state $(\hat{k}_{t-1}, a_{t-1}) \in \hat{\mathbf{k}} \times \mathbf{a}$, the probability of technology adoption is given by $\lambda_t = (\lambda_0/\pi)\, i_{a,t}^{\omega}$. The distance to the frontier a_t is given by (35) by:

$$a_t = \frac{a_{t-1} + \lambda_t(1 - a_{t-1})}{\gamma_z}.$$

   The growth rate of A_t is obtained by rewriting (43) as follows:

$$\gamma_{A,t} = \frac{a_t}{a_{t-1}}\gamma_z.$$

   The fraction of labor used in the investment goods sector, $n_{I,t}$, is derived from (41), which can be rewritten as follows:

$$n_{I,t} = 1 - \hat{k}_{t-1}^{-\alpha}\left[\hat{c}_t + \left(\frac{1}{a_{t-1}} - 1\right)\hat{\imath}_{a,t}\right].$$

From (39), capital stock is given by:

$$\hat{k}_t = \frac{(1-\delta)\,\hat{k}_{t-1} + \hat{k}_{t-1}^{\alpha} n_{I,t}}{\gamma_{A,t}^{\frac{\theta-1}{1-\alpha}}}.$$

With a_t and $\hat{k}_t$ in hand, we calculate $\hat{c}_{t+1} = \hat{c}(\hat{k}_t, a_t)$, $\hat{V}_{t+1} = \hat{V}(\hat{k}_t, a_t)$, and $\hat{J}_{t+1} = \hat{J}(\hat{k}_t, a_t)$ using the guessed rules for $\hat{c}_t$, $\hat{V}_t$, and $\hat{J}_t$ respectively. We set $\hat{\imath}_{a,t}$, $\hat{c}_t$, $\hat{V}_t$, and $\hat{J}_t$ so as to satisfy (36), (37), (38), and (40):

$$\hat{J}_t = -\hat{\imath}_{a,t} + \frac{\beta \hat{c}_t}{\hat{c}_{t+1}} \gamma_c^{1-\sigma} \gamma_{A,t}^{\frac{(\alpha-\sigma)(\theta-1)}{1-\alpha}-1} \left[\lambda_t \hat{V}_{t+1} + (1-\lambda_t)\,\hat{J}_{t+1} \right],$$

$$1 = \frac{\lambda_0 \omega}{\pi} \hat{\imath}_{a,t}^{\omega-1} \frac{\beta \hat{c}_t}{\hat{c}_{t+1}} \gamma_c^{1-\sigma} \gamma_{A,t}^{\frac{(\alpha-\sigma)(\theta-1)}{1-\alpha}-1} \left(\hat{V}_{t+1} - \hat{J}_{t+1} \right),$$

$$\hat{V}_t = (\theta-1)\,\hat{k}_{t-1}^{\alpha} n_{I,t} + \frac{\beta \hat{c}_t}{\hat{c}_{t+1}} \gamma_c^{1-\sigma} \gamma_{A,t}^{\frac{(\alpha-\sigma)(\theta-1)}{1-\alpha}-1} \hat{V}_{t+1}$$

$$1 = \frac{\beta \hat{c}_t}{\hat{c}_{t+1}} \left(\gamma_c \gamma_{A,t}^{\frac{\theta-1}{1-\alpha}} \right)^{-\sigma} \gamma_c \left[\frac{\alpha}{\theta} \left(\hat{k}_t \gamma_{A,t}^{\frac{\theta-1}{1-\alpha}} \right)^{\alpha-1} + \gamma_{A,t}^{-(\theta-1)} (1-\delta) \right].$$

4. With the new rules for $\hat{\imath}_{a,t}$, $\hat{c}_t$, $\hat{V}_t$, and $\hat{J}_t$ in hand, we stop if the distance between the old rules and the new rules is sufficiently small. Else, we go back to step 3 with the new rules.

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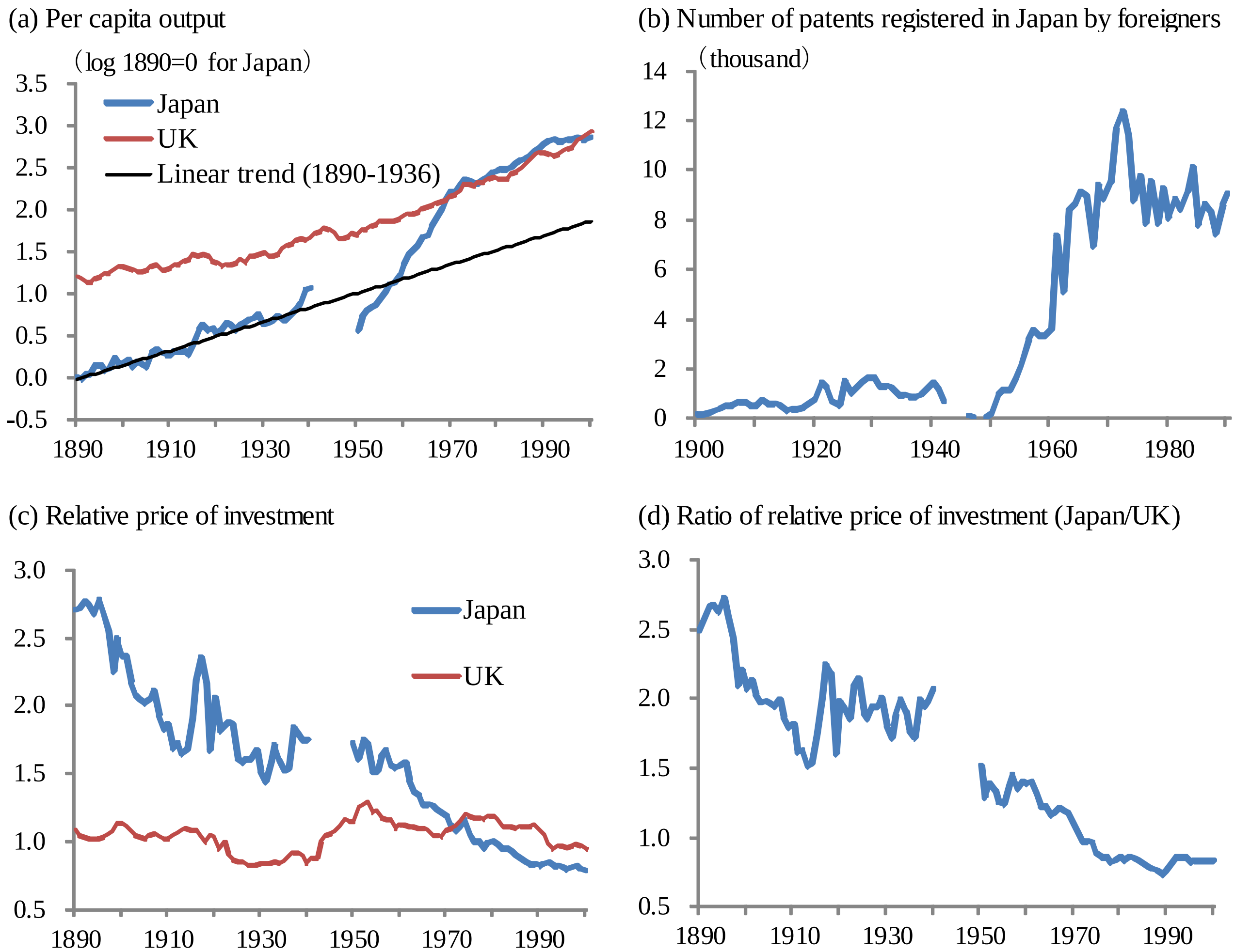
Table 1: Parameterization of the model

Parameter	Description	Value
β	Subjective discount factor	0.97
α	Capital share	0.36 or 0.5
δ	Capital depreciation rate	0.089
θ	Gross markup	1.2
γ	Gross growth rate of neutral technology	1.0061
γ_z	Gross growth rate of the technology frontier	1.0463
λ	Probability of technology adoption in steady state, Japan, postwar	0.114
ω	Elasticity of technology adoption	0.65

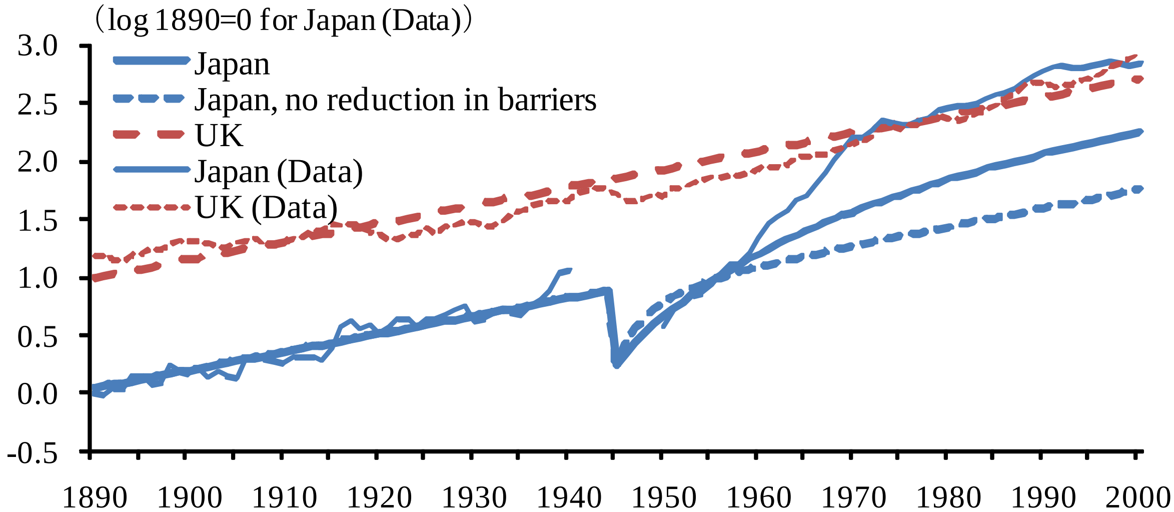
Figure 1: Key indicators



Notes: See Appendix A for the data sources for panels (a), (c), and (d). The data for panel (b) are from Japan Statistical Association (2007), table 17-10.

Figure 2: Simulation in the case of $\alpha = 0.36$

(a) Per capita output



(b) Ratio of the relative price of investment: Japan/UK

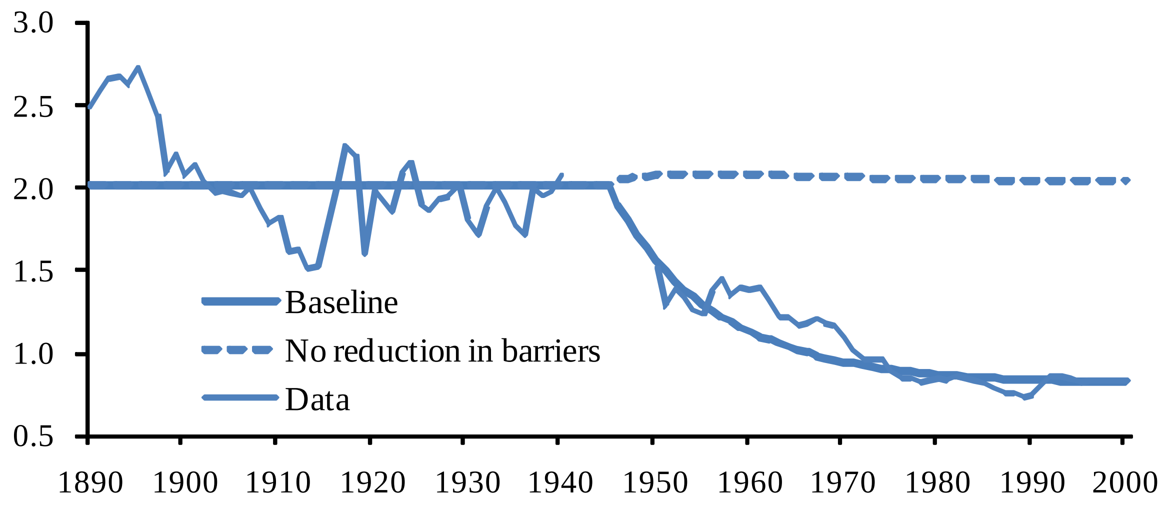
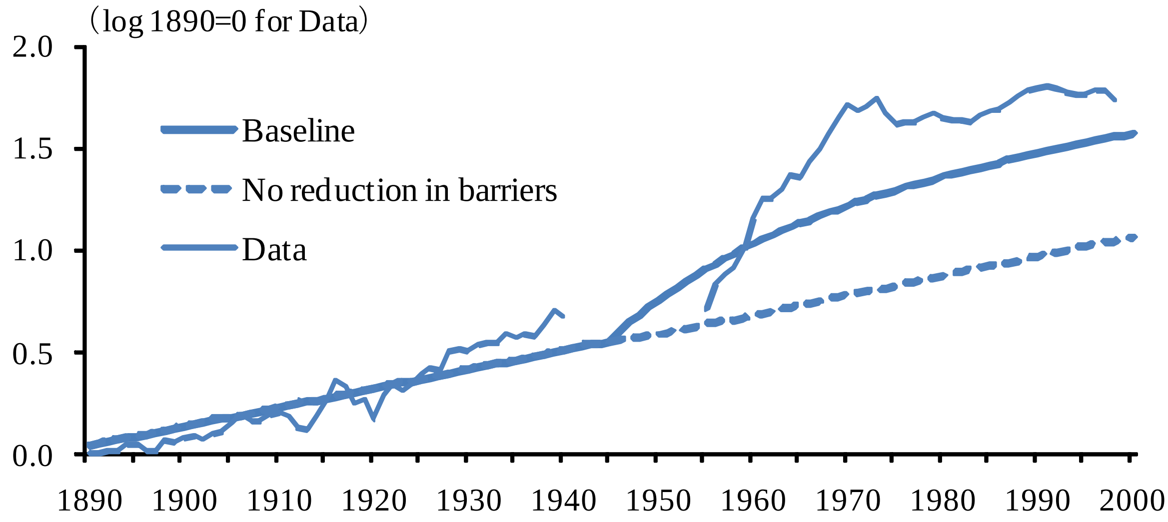


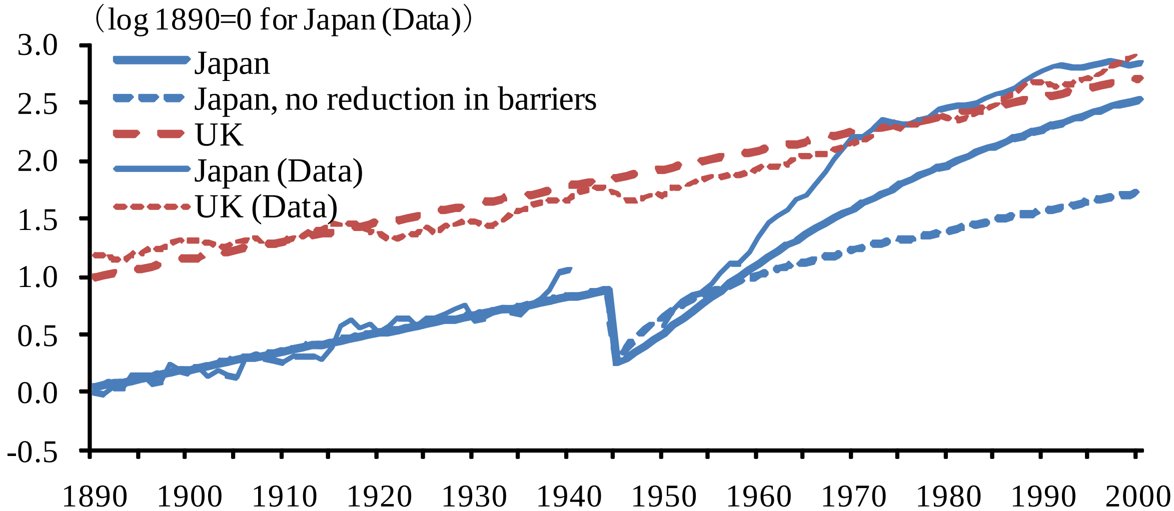
Figure 3: TFP calculated under the assumption of no IST



Notes: The figure shows the TFP of the non-primary sector, calculated under the assumption of no IST. For the calculation and data sources, see Appendix A.

Figure 4: Simulation in the case of $\alpha = 0.5$

(a) Per capita output



(b) Ratio of the relative price of investment: Japan/UK

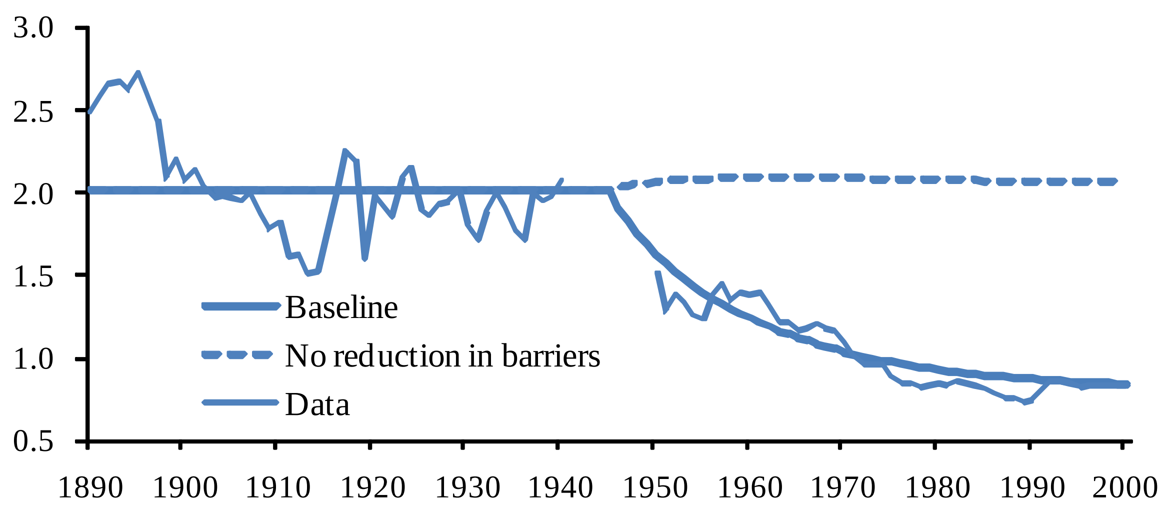


Figure 5: Output in the simulation in the case of a reduction in barriers in 1950

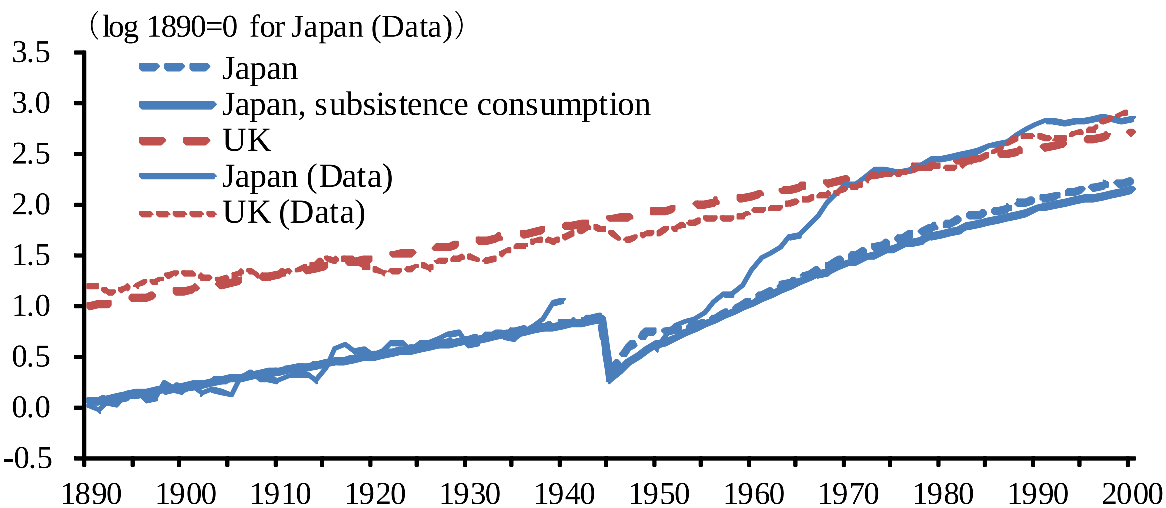
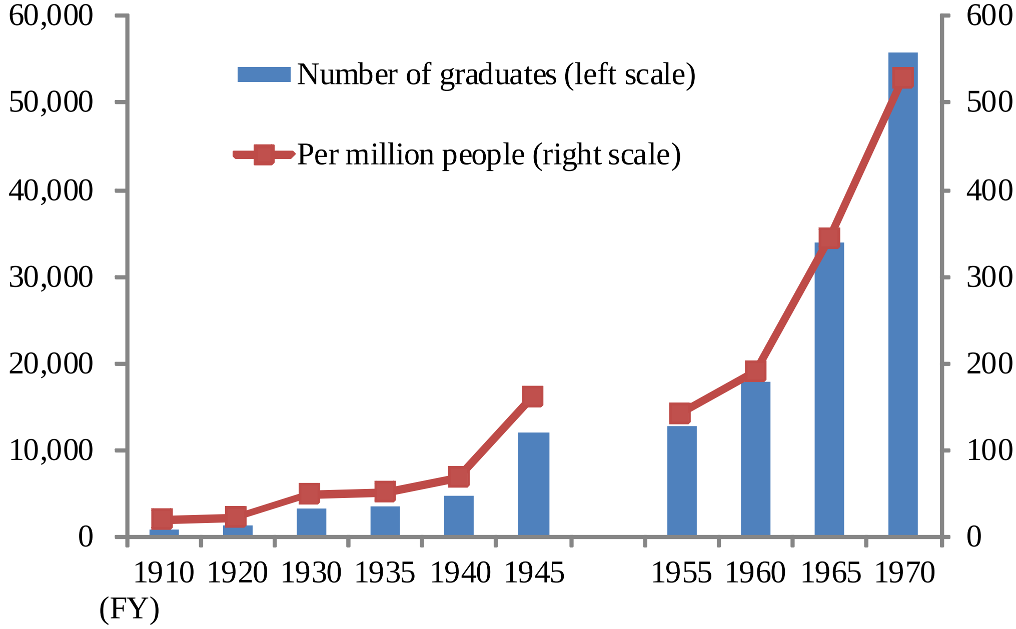


Figure 6: Number of university graduates with an engineering degree



Notes: The figures up to 1945 show the sum of graduates with an engineering degree from a university and those from an engineering high school under the old education system. University and high school students under the old education system roughly correspond to university students under the current education system that started in 1949. The figures from 1955 show the number of university graduates with an engineering degree under the current education system. The data are from Sawai (2012a: 172), figure 10-2, for the number of graduates up to 1945, Japan Statistical Association (2007), table 2-1, for the population, and the School Basic Survey, Ministry of Education, Culture, Sports, Science and Technology for the number of graduates from 1955 onward.