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Energy Transition without Dirty Capital Stranding [*]

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Abstract: Avoiding dirty asset stranding matters for protecting wealth and employment in the economies that are rich in pollution-intensive fossil energy and resource assets. This paper analyzes, empirically and theoretically, the mechanism for energy transition without dirty capital stranding. We show that a shock that tightens pollution regulations will lead to downward adjustments of capital stocks, investment, capital values, and outputs. However, when the transition includes dynamically accumulating clean capital to induce green structural change, the transition path will move to an equilibrium where both dirty and clean capital can coexist and grow simultaneously. Clean capital, by eliminating the polluting effect of dirty capital, protects the economic values of dirty capital and thus mitigates the extent of dirty capital stranding. When the preference has a unitary elasticity of substitution between consumption and environmental goods and there is no adjustment cost in clean capital accumulation, the energy transition can occur along a balanced growth path with sustained growth of consumption, production, and capital stocks in the long run.

Keywords: Energy Transition; Green Growth; Pollution Regulations; Capital Accumulation; Stranded Assets.

JEL Codes: Q54; Q43; Q32; O13; O44; C61

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1 Introduction

There is a critical question regarding the energy transition: does accumulating renewable-based clean energy such as solar and wind necessarily lead to the stranding of fossil-based dirty energy such as coal, oil, and natural gas? The existing literature on the stranded asset shows that environmental regulations induce demand shifts towards renewables and fully replace the polluting fossil energy. As a result of the replacement effect, a substantial share of fossil-based dirty assets such as coal resource reserves and coal-fired power plants would be at risk of becoming stranded assets (e.g., Allen et al., 2009; McGlade and Ekins, 2015; van der Ploeg, 2018). As a departure from the existing view, this paper shows that clean capital investment as induced by stringent environmental regulations might not necessarily lead to the stranding of dirty capital, and the future energy landscape is compatible with the coexistence between fossil-based dirty and renewable-based clean energy.

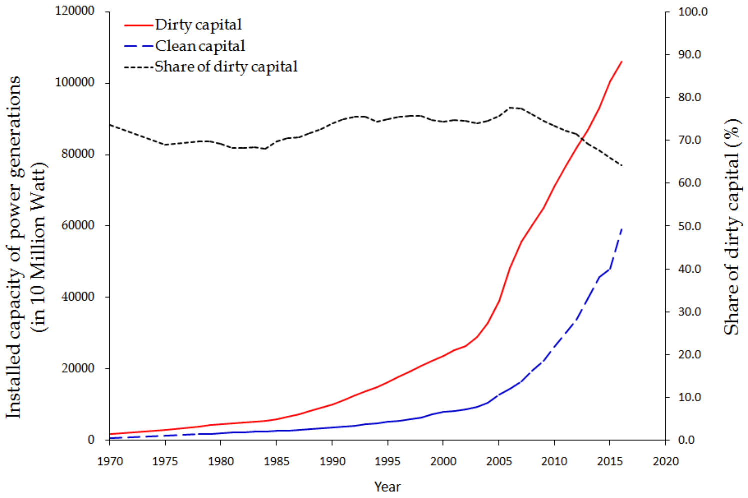

Figure 1: China's installed capacity of power generation using fossil energy such as coal, oil, and natural gas (dirty capital) and using renewable energy such as solar, wind, hydropower, and nuclear (clean capital). *Source: Statistics of China Electric Power Industry 2017* (China Electric Power Press, 2017b)

Our claims are supported by the stylized fact given in Figure 1. When China's investments in clean energy assets kick-off and accelerate during 1970-2016, the installed capacity of generations based on fossil dirty energy augments at the same pace rather than falls precipitously in the face of renewable-based clean energy assets. Even when environmental regulations are tightened to curb pollution around 2005, the installed capacity of fossil energy capital is still in a rising trend, though the share of dirty capital shows a sign of decline. There is no clear evidence that fossil-based dirty capital would necessarily become stranded and fully replaced by renewables during the energy transition.

Given the above-mentioned stylized fact, we are motivated to explore a mechanism through which energy transition can accommodate the simultaneous accumulation of both dirty and clean capital. By doing this, we wish to find a way to avoid the potential stranding of dirty capital during the energy transition. The conventional pattern of the energy transition, by developing clean energy to replace dirty one, entails a process of creative destruction that destroys the economic values of fossil resources. Fossil fuel-based assets (e.g., coal resource reserves, and coal-fired power plants) would thus be at risk of becoming stranded assets. As massive stranding of fossil resources and carbon-intensive capital assets translates into huge losses of wealth and jobs. Resource-rich economies such as OPEC, China, Australia, and Russia might have strong incentives to rescue the potential stranded dirty assets and pursue energy transition without the stranding of dirty assets. In other words, when policymakers choose the conventional way of transition that uses clean energy to replace dirty one, it is the case where energy transition is at risk of asset stranding and wealth losses. In contrast, if policymakers pay attention to avoiding capital stranding, the mechanism presented in this paper might be a potential way to achieve energy transition without asset stranding.

A future energy landscape with the coexistence of both fossil dirty and renewable clean capital may arise from concerns with the security of energy supplies, diversification, intermittency of renewables, and path dependence in the energy market (van der Ploeg and Withagen, 2012b; Fouquet, 2016). Furthermore, when we extend the scope of clean capital to include facilities such as climate geoengineering and carbon capture and storage (CSS), the clean capital is expected to decarbonize dirty capital, and the latter will no longer be constrained by environmental regulations and thereby keep on growing with clean capital.(e.g., Moreno-Cruz, 2013, 2015; Moreno-Cruz and Smulders, 2017; Moreno-Cruz et al., 2017; Heutel et al., 2016, 2018).[1] By doing so, stranding of the fossil-based dirty capital can be avoided, and the economic values of dirty capital could be protected, which matters for preserving wealth and protecting employment in resource-rich economies.

In this context, we are motivated to rationalize the above-mentioned stylized fact: energy transition can accommodate an outcome where both fossil-based dirty and renewable-based clean energy capital coexist - a claim that is consistent with the long-run energy trends and projections (e.g., BP, 2019; IEA, 2019). In this paper, we analyze, both theoretically and empirically, the interaction between dirty and clean capital under environmental constraints. As the focus of our investigations is on the effect of clean capital on avoiding the stranding of dirty capital, the Uzawa-Lucas growth model is arguably a methodologically appealing framework that facilitates an analysis of the interaction between dirty and clean capital under environmental constraints. The classical Uzawa-Lucas growth model focuses on the interaction between

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[1] In a more radical case, the development of negative emission technologies, such as bioenergy with CCS, could contribute to the removal of carbon pollutants from the atmosphere, thus making more room for the continual deployment of dirty assets (e.g., National Research Council, 2015a,b; Bui et al., 2018).

human and physical capital for endogenous economic growth. We adapt the Uzawa-Lucas growth model into the green growth context and thus develop a green growth model. Based on this modified model, we specifically investigate how dirty and clean capital can interact and affect the energy transition.

We show that a shock that tightens pollution regulations will lead to downward adjustments of capital stocks, investment, capital values, and outputs. However, when the transition includes dynamically accumulating clean capital to induce green structural change, the transition path will move to an equilibrium where both dirty and clean capital can coexist and grow simultaneously. Both dirty and clean capital can interact and benefit each other. On the one hand, clean capital offsets pollution damages, protects dirty capital values, and avoids stranding of dirty capital. On the other hand, the dirty capital, without stranding, facilitates the production of outputs that provide economic resources for clean capital investment. Hence, interactions between dirty and clean capital generate complementarity that prompts the simultaneous accumulation of both capital stocks.

In the above-mentioned case, green structural change via stepping-up of clean capital accumulation could generate a path of transition along which both dirty and clean capital can coexist and grow simultaneously. While this pattern of transition can generate a stronger growth momentum as compared to the case without green structural change (i.e., the transition is only driven by dirty capital accumulation), the transition path still cannot sustain growth and will end up with a steady-state equilibrium in the long run. The reasons are that correcting for the effect of convex pollution damages needs to allocate an increasing amount of resources towards clean capital, thus crowding out the resources available for consumption and investment. Meanwhile, the adjustment costs that exist in the clean capital investment shrink the resources available for investment. Accordingly, the pattern of transition cannot attain endogenous growth.

We thus consider another model variant in which the transition can achieve endogenous growth without converging to a steady state. We show that the endogenous growth can be attainable with sustained growth of consumption and capital stocks when the following two conditions are met: 1) the preference has a unitary elasticity of substitution between consumption and environmental goods, and 2) investment goods allocated towards clean capital are fully installed without adjustment costs. The implications of these two conditions for endogenous growth are as follows. The first condition implies that pollution damages need to be concave with bounded marginal damages. Otherwise, an overwhelming amount of economic resources needs to be allocated towards pollution abatement, thus crowding out the amount of resources allocated towards investment and consumption. This condition suggests that it's crucial to break the link between pollution and environmental damages by taking mitigation and adaptation measures. The second condition implies that it's also important to improve the efficiency of creating clean capital assets. The more efficient the conversion of investment goods into clean capital stocks, the more likely the transition can harness green structural change through clean capital accumulation to achieve endogenous growth. Alternatively, if investing in clean capital is subject to substantial adjustment costs (i.e., the efficiency of clean capital accumulation is low), then economic resources allocated towards clean capital for green structural change are shrinking over time, thus losing the momentum to sustain endogenous growth of consumption and capital investment during the transition process.

Related Literature. Our work is closely related to the literature of growth and the environment which finds its origin in Grossman and Krueger (1995). The existing studies explore the mechanism for green growth transitions through the following three channels. First, a strand of literature focuses on pollution abatement and control. A fraction of production outputs is allocated towards spending on pollution abatements that eliminates the negative effects of pollution emissions arising from production or consumption. (e.g., Andreoui and Levinson, 2001; Hartman and Kwon, 2005; Bartz and Kelly, 2008; Brock and Taylor, 2010).

Second, a growing body of literature uses the theory of endogenous technical change to address growth and the environment (e.g., van Zon and Yetkiner, 2003; di Maria and Valente, 2008; Rubio et al., 2009; Peretto, 2009; Bretschger and Smulders, 2012; Jin and Zhang, 2016; Bretschger et al., 2017). In particular, Smulders and de Nooij (2003) and Acemoglu et al. (2012) present directed technical change models that endogenize the rate and direction of pollution-augmenting technological change. The focus of this strand of works is on allocating resources towards innovation to create new varieties or improve the qualities of intermediate inputs that enhance productivity/efficiency of natural resources/pollution emissions.

Third, our work also connects with the works emphasizing substitutions between dirty and clean energy and regime switches from carbon-based exhaustible energy to carbon-free renewable backstops (e.g., Tsur and Zemel, 2005; Chakravorty et al., 2006, 2008; Smulders et al., 2012; van der Ploeg and Withagen, 2012a, 2014). As this strand of the literature concludes transition from fossil-based dirty to renewable-based clean energy regimes, it reflects the natural progression of economic development and structural change from dirty industrial to clean service economies (e.g., Kongsamut et al., 2001; Ngai and Pissarides, 2007). As a departure from the existing literature, this paper focuses on the channel of clean capital accumulation for green growth transitions. We consider dirty and clean inputs as accumulative capital stocks, and both dirty and clean capital can interact and generate intertemporal trade-offs. In this regard, our model builds on the Lucas-Uzawa two-sector endogenous growth with physical and human capital (e.g., Uzawa, 1965; Lucas, 1988; Mulligan and Sala-i-Martin, 1992; Hartman and Kwon, 2005; Ruiz-Tamarit, 2008).

Layout. The rest of this paper is structured as follows. Section 2 provides empirical evidences. Section 3 presents the model. Section 4 gives the results of the analysis and numerical simulations. Section 5

Table I: Descriptive Statistics of Clean and Dirty Capital in China and EU

Region	Capital	Mean	Std.Dev.	Min.	Max.
China	clean capital	121.37	145.78	6.24	590.67
	dirty capital	306.77	310.38	17.53	1060.94
E.U.	clean capital	393.72	90.31	290.28	555.88
	dirty capital	452.66	31.71	401.34	497.39

Note: Capital is measured by installed capacity of electricity generation in gigawatts.

concludes.

2 Empirical Evidences

To show that clean capital investment as induced by environmental regulations does not necessarily lead to the stranding of dirty capital, this section provides empirical tests of both the short- and long-run correlation between clean and dirty capital.

Data Sources. As the major sources of atmospheric pollutants are fossil energy combustion for electricity generation, we use the data from the power generation sector for our empirical investigations. Specifically, we measure the stock of dirty capital by the installed capacity of power generation using fossil energy such as coal, oil, and natural gas, while the stock of clean capital by the installed capacity of power generation using low-carbon energy such as solar, wind, hydropower, and nuclear, etc. Furthermore, we test these relationships in two different types of economies: China as a developing country, and the European Union (EU) as a developed economy. China's installed capacity of power generation is obtained from *Statistics of China Electric Power Industry 2017* (China Electric Power Press, 2017b) and *China Electric Power Yearbook 2017* (China Electric Power Press, 2017a).[2] The data for EU is provided by *Eurostat Regional Yearbook 2019* (European Commission, 2019).[3] Table I summarizes the descriptive statistics of clean and dirty capital (measured by install capacity of electricity generation) in China and the EU.

Unit-root Test. As the first step of our empirical analysis, we employ the Augmented Dicky-Fuller (ADF) unit-root test to show the stationary of each variable and to determine the selection of models.

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[2] The installed generation capacity data for China is obtained from *Statistics of China Electric Power Industry 2017* (China Electric Power Press, 2017b). It covers data on fossil-fired power plants and hydroelectric power plants from 1970 to 2016. We then extend the data by including the installed capacity of nuclear and renewable energies such as wind, solar, and biomass power plants, which are obtained from *China Electric Power Yearbook 2017* (China Electric Power Press, 2017a).

[3] *Eurostat Regional Yearbook 2019* includes the total installed capacity of all 28 EU member states, differentiated by technologies including combustible fuels, hydro, geothermal, wind, solar, tide, wave, ocean, and nuclear, for 2000-2017. The dirty capital is measured by the capacity of combustible fuels, and the clean capital is a sum of all the renewable capacity and nuclear (European Commission, 2019).

The test results are reported for two cases: one with an intercept, and the other with both intercept and trend. Table II shows that the unit root problem exists at both level and first-difference among all variables. As the empirical time-series models require stationary assumptions, we cannot use the level variables for our analysis. The problem is eliminated by further differencing. Specifically, the first difference of capital stock is an approximation of the growth rate of capital, and the first difference in the growth rate corresponds to changes in the growth rate. Therefore, the level variables are $I(2)$, and the growth rate variables are $I(1)$. In the following, our empirical tests are based on the growth rate variables.

Table II: Augmented Dickey-Fuller Unit-root Tests

	Variables	Intercept only	Intercept & trend	Optimal lag
Panel I: level				
China	LnClean	3.860	-0.100	1
	LnDirty	-0.674	-3.079	3
EU	LnClean	-0.270	-3.096	2
	LnClean	-2.310	-0.999	3
Panel II: first-difference (first difference of a log variable $\approx$ the growth rate of a variable)				
China	ΔLnClean (or grClean)	-1.254	-3.382*	3
	ΔLnDirty (or grDirty)	-2.765*	-2.631	2
EU	ΔLnClean (or grClean)	-1.387	-1.140	1
	ΔLnDirty (or grDirty)	-0.735	-2.038	1
Panel III: first-difference of the growth rate				
China	ΔgrClean	-4.576***	-4.483***	4
	ΔgrDirty	-5.040***	-5.061***	0
EU	ΔgrClean	-4.339***	-4.313***	0
	ΔgrDirty	-5.470***	-5.491***	0

Note: “Ln” indicates the natural log operator, “gr” the growth rate, and Δ the first difference operator. Significant levels are denoted as * of 10%, ** of 5%, *** of 1%. Optimal lag orders are determined based on Akaike information criteria (AIC).

Long-run Relationship Test. We test the long-run relationship between dirty and clean capital by using the method of autoregressive distributed lag (ARDL) models as proposed by Pesaran and Shin (1999).[4] This provides an approach to model the relationship between variables in a single-equation time-series setup, and it is also capable of dealing with nonstationary variables via a re-parameterization in an error-correction (EC) form (Engle and Granger, 1987; Hassler and Wolters, 2006). The existence of

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[4] In the time series literature, the traditional approach to examine correlations is bivariate cointegration test (Engle and Granger, 1987) or multivariate cointegration analysis (Johansen, 1988, 1991). However, there are some drawbacks: the order of integration of the variables needs to be determined. It uses OLS in the first step to estimate the static levels model, which can create bias in finite samples due to the omitted short-run dynamics Banerjee et al. (1986). Such bias further transmits to poor estimates in the second step.

a long-run relationship can thus be tested based on the EC representation. A bounds testing procedure is available to draw inference without knowing whether the order of integration of the variables (Pesaran et al., 2001). Specifically, the two ARDL-EC models are formulated as follows:

$$\Delta grClean_t = \alpha_0 + \alpha_1 t + \lambda_1 grClean_{t-1} + \lambda_2 grDirty_{t-1} + \sum_{i=1}^{p} \beta_i \Delta grClean_{t-1} + \sum_{i=1}^{q} \gamma_i \Delta grDirty_{t-1} + e_t,$$

$$\Delta grDirty_t = \alpha'_0 + \alpha'_1 t + \lambda'_1 grClean_{t-1} + \lambda'_2 grDirty_{t-1} + \sum_{i=1}^{p'} \beta'_i \Delta grClean_{t-1} + \sum_{i=1}^{q'} \gamma'_i \Delta grDirty_{t-1} + e'_t,$$

where “Δ” is the first difference operator, “gr” the growth rate of a given variable, and the error term, e_t, is assumed to follow *i.i.d.*. λ_j $j=1,2$ is the long-run coefficient, and there is no long-run or cointegration relationship between clean and dirty capital if $\lambda_j = 0$. β_i and γ_i are the short-run coefficients. p and q are the number of lags in the short-run equations. The superscript symbol “′” represents all respective estimated parameters for model with alternative dependent variable. The optimal lag structure of our model is selected by Akaike information criteria (AIC), as it performs better with small samples (Lütkepohl, 2005). From empirical results of the ARDL-EC model given in Table III, we do not find long-run correlations between dirty and clean capital growth. However, Table III documents the result supporting the existence of a short-run correlation between dirty and clean capital growth: the growth of clean capital positively affects the growth of dirty capital in the short run.

Graphical Assessment by Chi-plot. We offer a graphical assessment of our sample for robustness tests. Fisher and Switzer (1985) and Fisher and Switzer (2001) propose a graphical method to assess the correlation with Chi-plot. It enables to investigate the complex relationship between variables and local characteristics by scatter plot of respective statistics. Following Fisher and Switzer (1985), we draw the Chi-plot, where the values of χ_i (that measures the correlation between two variables) and the values of λ_i (that measures the distance of observation to the sample center) need to be calculated. Both parameters fall within a range between -1 and 1, and two variables are strictly monotonically increasing with each other when χ_i equals 1. Figure 2 provides the scatter plots of the growth rate of two types of capital in China and the EU and the respective Chi-plot. Panel (a) of Figure 2 shows that China's values are close to zero within the 95% confidence interval, represented by two flat dished lines. We, therefore, conclude that both dirty and clean capital grow independently, which is consistent with the previous results. Similarly, panel (b) of Figure 2 gives a similar result for the EU: most of the data points are within the two flat dished lines. This implies that the growth of two types of capital in the EU also has an independent relationship.

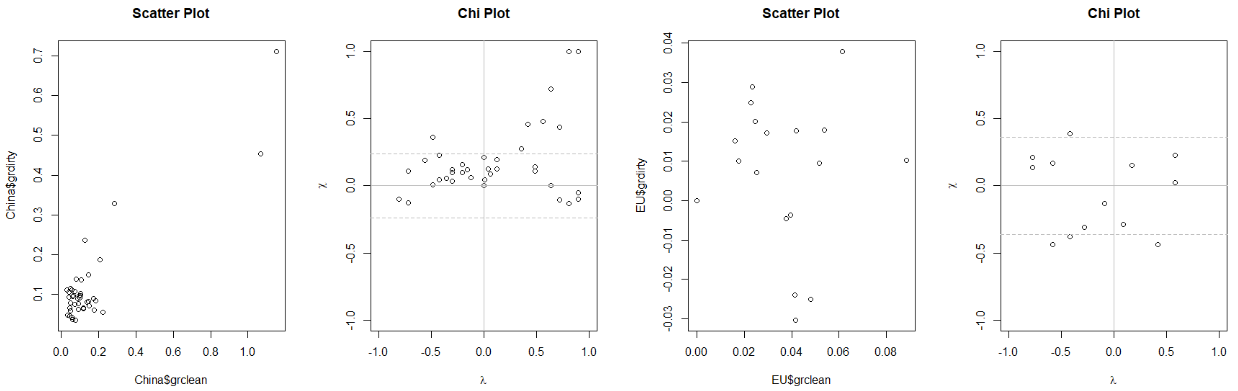
Table III: Empirical Test of the ARDL-EC Model

	China		E.U.	
Dependent variable	ΔgrClean	ΔgrDirty	ΔgrClean	ΔgrDirty
Long run				
L1.grClean	-0.206	-0.104	-0.978	-1.199
	(0.193)	(0.256)	(0.449)	(0.572)
L1.grDirty	1.796	-0.459***	-0.521	-0.739
	(2.183)	(0.128)	(0.381)	(0.356)
Short run				
LD.grClean	-0.662**	0.429***	1.179	1.456**
	(0.254)	(0.121)	(0.723)	(0.393)
L2D.grClean	-0.574**		0.750	0.398
	(0.257)		(0.514)	(0.380)
L3D.grClean			1.118	1.016*
			(0.525)	(0.467)
D1.grClean		0.040		-0.421
		(0.099)		(0.379)
LD.grDirty		0.368**	0.612	0.239
		(0.152)	(0.499)	(0.585)
L2D.grDirty			-0.813	-0.604
			(0.532)	(0.367)
L3D.grDirty			-0.593	
			(0.392)	
D1.grDirty	0.369		-0.535	
	(0.247)		(0.438)	
constant	-0.009	0.033	0.041	
	(0.033)		(0.018)	
Optimal lag for p	3	2	4	3
Optimal lag for q	0	2	4	4
ARDL Bounds test	1.913[a]	7.937[a]	2.369[a]	4.608[a]
	No cointeg.	Cointeg.	No cointeg.	No cointeg.
R-squared	0.38	0.526	0.835	0.860
Log likelihood	57.51	77.04	48.69	48.69
Breusch-Pagan test	2.16	2.27	2.12	0.10
for heteroskedasticity	(0.142)[b]	(0.132)[b]	(0.145)[b]	(0.145)[b]

Note: [a] F-statistic; [b] p-value, standard error in parenthesis. Symbol "L" indicates lag. "D" denotes first difference. Significant levels are denoted as * of 10%, ** of 5%, *** of 1%. Optimal lag orders p and q are determined based on Akaike information criteria (AIC).

3 The Model

As discussed in previous sections, stranded assets are assets that have suffered from premature write-downs, devaluations, or conversion to liabilities. A variety of risk factors represent a discontinuity able to profoundly alter asset values and cause stranded assets (Caldecott and McDaniels, 2014; Caldecott et al.,



(a) China

(b) European Union

Figure 2: Scatter plot of the growth rate of two types of capital and the Chi-plot for (a) China and (b) EU.

2014). When the pattern of the energy transition is at the cost of asset stranding, countries that are rich in fossil resources and capital would suffer from substantial losses in revenues, employment, and wealth linked to fossil fuels. Our theoretical expositions are thus motivated to explore the potential mechanism through which energy transition can occur without asset stranding. For that purpose, we develop a two-sector green growth model to analyze the interaction between dirty and clean capital. In the end, we will show that the general equilibrium effect of pollution regulations, efficiency improvement, and structural change leads to an outcome where both dirty and clean capital can coexist and grow simultaneously. Dirty capital can continue to grow alongside clean capital (i.e., complementarity between dirty and clean capital).

The framework for theoretical expositions is the two-sector green growth model in the spirit of the endogenous growth theory *a la* Uzawa (1965) and Lucas (1988). Our green growth model considers a dynamic problem that maximizes intertemporal utility

$$\max_{[C(t),I_C(t)]_0^\infty} \int_0^\infty e^{-\rho t}[U(C(t))-V(P(t))]dt, \tag{1}$$

subject to the law of motion for dirty capital K_D and clean capital K_C as:

$$\dot{K}_D(t)=F(K_D(t),K_C(t))-C(t)-I_C(t)-\delta K_D(t), \qquad \dot{K}_C(t)=\Phi(I_C(t))-\delta K_C(t), \tag{2}$$

given the initial conditions: $K_D(0)=K_D^0$ and $K_C(0)=K_C^0$. The preference of the representative household is additively separable over consumption C and pollution P. The utility from consumption is concave and satisfied the Inada condition, i.e., $U'(C)>0$, $U''(C)<0$, and $\lim_{C\to 0}U'=\infty$. Disutility from pollution is convex with the condition $V'(P)>0$, $V''(P)>0$, and $\lim_{P\to 0}V'(P)=0$.

Note that, the main feature of our model is that clean (abatement) capital is specified as an accumulative stock while Smulders and Gradus (1996) considers abatement as a flow variable. The long-run balanced growth path might not change qualitatively when extending the abatement flow into stock. But it might be more appealing to conceptualize clean (abatement) capital as a stock variable because equipments/facilities for pollution control and abatement are indeed one kind of accumulative capital that requires investment to augment over time (e.g., investments scale up the deployment of renewable energy facilities over time, and this accumulative process is the same as the capital used to produce consumption goods).[5]

Both dirty and clean capital are imperfect substitute in final goods production according to the technology $Y=F(K_D,K_C)$ with $F_{K_D}>0$, $F_{K_C}>0$. The production function is homogenous of degree one and satisfies the following assumption: the marginal product of dirty capital rises with clean capital, i.e., $F_{K_DK_C}\equiv \partial F_{K_D}/\partial K_C>0$. This assumption is commonly used in standard specifications of production technologies such as the Cobb-Douglas or Constant Elasticity of Substitution (CES) function, i.e., $F(K_D,K_C)=K_D^{\alpha}K_C^{1-\alpha}$ or $F(K_D,K_C)=[\beta K_D^{\frac{\sigma-1}{\sigma}}+(1-\beta)K_C^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$, where K_D and K_C are imperfect substitutes and the marginal product of K_D increases with K_C. Note that, as in the green growth literature (e.g., Tahvonen and Salo, 2001; Tsur and Zemel, 2005; Acemoglu et al., 2012; Long, 2014; van der Meijden, 2014), our paper just imposes the assumption that K_D and K_C are imperfect substitutes with a certain degree of substitution on the production side, rather than directly assuming that K_D and K_C are complementary.[6]

In our model, simultaneous accumulation (complementarity) of K_D and K_C is an endogenous outcome of interactions among pollution regulations, efficiency improvement, and structural change. Specifically, we consider that pollution emissions are proportional to dirty capital, i.e., $P=mK_D$, where the emission intensity m is inversely related to the output Y as given by $m=\psi Y^{-1}$, and ψ is a coefficient. This specification is in line with efficiency improvement caused by the learning-by-doing effect: production

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[5] We also argue that different specifications of abatement could generate different effects on consumption and welfare. When abatement is specified as a flow, the optimal amount of economic resources allocated towards abatement will be sufficiently large at each instantaneous time point, such that convex pollution damages can be effectively corrected. As a result, final goods allocated towards consumption will be crowded out, thus reducing the level of consumption and utility gains. In contrast, when abatement is specified as a stock that can be accumulated by an investment over time, the amount of final goods allocated towards investment in clean (abatement) capital could be much smaller as compared to the case of abatement flows. As a result, the amount of final goods allocated towards consumption would be larger, yielding a higher level of welfare gains.

[6] Note that, the assumption that the marginal product of K_D increases with K_C, i.e., $\frac{\partial F_{K_D}}{\partial K_C}>0$, does not necessarily translate into the condition of complementarity between K_D and K_C, i.e., $\frac{\partial K_D}{\partial K_C}>0$, where an increase in the demand for clean capital will cause a larger quantity of dirty capital to be demanded if K_C is a gross complement to K_D. Given that the production function is homogenous of degree one, we have $F(K_D,K_C)=K_DF_{K_D}+K_CF_{K_C}$. Rearranging and differentiating with respect to K_C yields

$$\frac{\partial F_{K_D}}{\partial K_C}=\frac{1}{K_D}F_{K_C}-\left(\frac{K_C}{K_D}F_{K_CK_C}+\frac{1}{K_D}F_{K_C}\right)=-\frac{K_C}{K_D}F_{K_CK_C}>0,$$

where the positive sign follows from the assumption of concavity $F_{K_CK_C}<0$. Therefore, we argue that the assumption $\frac{\partial F_{K_D}}{\partial K_C}>0$ does not necessarily lead to the condition of complementarity $\frac{\partial K_D}{\partial K_C}>0$. The mechanism that generates simultaneous accumulation (complementarity) of both K_D and K_C is not the assumption that the marginal product of K_D increases with K_C, i.e., $\frac{\partial F_{K_D}}{\partial K_C}>0$.

at a larger scale tends to generate efficiency improvements that drive a decline in the emission intensity (e.g., Arrow, 1962; Gillingham et al., 2008).[7] Then environmental regulations for internalizing pollution damages will induce clean capital investment to restructure the economy that is originally driven by dirty capital accumulation. With the contribution of clean capital to structural change, outputs are produced by both K_D and K_C. Substituting $Y = F(K_D, K_C)$ into the emission function $P = \psi K_D Y^{-1}$ yields

$$P = \frac{\psi K_D}{F(K_D, K_C)} = \frac{\psi K_D}{K_D f(K_C/K_D)} = \frac{\psi}{f(K_C/K_D)}, \tag{3}$$

where the second equality follows from the homogeneity of degree one, i.e., $F(K_D, K_C) = K_D F(1, K_C/K_D) = K_D f(K_C/K_D)$. As equation (3) shows, the emission is homogenous of degree zero with respect to K_C and K_D, meaning that there will be no growth in emissions when both dirty and clean capital is accumulated at the same pace. In other words, the accumulation of clean capital can play a pivotal role to stabilize emission growth and offset pollution damages caused by the use of dirty capital. With the build-up of clean capital to eliminate the polluting effect of dirty capital, the latter will not be affected by the emission constraints. Both dirty and clean capital can thus grow simultaneously (complementarity).[8]

The emission function $P = P(K_D, K_C)$ specified in (3) thus implies that $P_{K_D} > 0$ and $P_{K_C} < 0$. Generally, the scope of clean capital can be extended to include any forms of environment-friendly capital such as human capital (that is much less polluting than physical capital deployed in pollution-intensive manufacturing sectors). In the field of energy economics, empirical studies such as Salim et al. (2017), Yao et al. (2019), and Yao et al. (2021) show that there is a significantly negative relationship between human capital and energy consumption or carbon emissions in the long run. These empirical results suggest that human capital can generate a positive effect to reduce energy use and pollution emissions. From this perspective, we argue that clean capital could also play an important role to reduce the polluting effect associated with dirty capital.

Both dirty and clean capital are accumulative stocks and evolve according to the law of motion $\dot{K_D} = I_D - \delta K_D$ and $\dot{K_C} = \Phi(I_C) - \delta K_C$, where I_D and I_C are the investment in dirty and clean capital, respectively. δ is the rate of capital depreciation. Production outputs of final goods are allocated towards consumption and investment in equilibrium, and the aggregate resource constraint thus reads

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[7] The intensity of carbon emission m is inversely related to the output Y in line with empirical evidence that supports a declining emission intensity.

[8] In the real world, this knife-edge case corresponds to a scenario where energy transition is characterized by substantial efficiency improvement and emission intensity reduction. For example, the energy system is restructured by deploying a massive capacity of generation powered by renewables, high-efficiency facilities, climate geoengineering, carbon capture and storage, and negative-emission clean technologies which have already become technically feasible. The development and deployment of clean technologies could contribute to reducing the emission intensity of dirty capital or even sucking carbon out of the atmosphere, thus making room for the continual deployment of dirty capital (e.g., Moreno-Cruz, 2013, 2015; Moreno-Cruz and Smulders, 2017; Heutel et al., 2016, 2018).

$Y = C + I_C + I_D$.[9] Furthermore, one unit of final goods allocation towards investment in dirty capital accumulates one unit of capital stocks in the dirty sector. However, allocating one unit of final goods towards clean capital investment leads to less than one unit of capital accumulation in the clean sector, because there are costs of conversion between two different types of capital (the clean capital differs from the dirty one). In other words, capital goods are convertible between dirty and clean types, but this is subject to intersectoral conversion costs as measured by the function Φ. The following properties hold: $\Phi'(.) > 0$, $\Phi''(.) < 0$, $\Phi(0) = 0$, and $\Phi'(0) = 1$. That is, the more irreversible the dirty capital, the higher the costs associated with converting dirty into clean capital. The capital conversion costs vanish when there is no allocation towards clean capital investments.

The model specified in equations (1)-(2) captures the potential interaction between dirty and clean capital through the following three channels. First, clean capital as an imperfect substitute can interact with dirty capital on the production side, and an increase in clean capital will raise the marginal product of dirty capital, e.g., $\partial F_{K_D}/\partial K_C > 0$, (this does not necessarily translate into the complementarity as detailed above). Second, clean capital can fully eliminate the polluting effect of dirty capital through the environmental channel, i.e., the emission function is homogenous of degree zero. Third, final goods outputs net of consumption are allocated towards investments, and clean capital competes with dirty capital for investment goods, i.e., $I_C + I_D = F(K_D, K_C) - C$. The equilibrium allocation of investment between dirty and clean capital depends on Tobin's Q (dynamic benefits) of these two capital stocks.

As an endogenous general equilibrium outcome of the above-mentioned interaction between dirty and clean capital, we will show below that there is simultaneous accumulation (complementarity) of both dirty and clean capital. In other words, we are not intended to say there are no reverse causalities between dirty and clean capital. On the one hand, stepping-up of clean capital accumulation offsets emission growth and thus provides more room for further deployment of dirty capital. On the other hand, with further accumulation of dirty capital, more outputs can be produced to provide economic resources that facilitate clean capital accumulation. Both dirty capital and clean capital could thus coexist and grow simultaneously in the energy transition.

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[9] Rewriting the aggregate resource constraint yields $I_D = Y - C - I_D$, and substituting it into the law of motion for dirty capital yields the first expression of (2).

4 Results

4.1 Characterizations of the Optimum

The Pontryagin Maximum Principle of the optimal control is used to solve the problem of maximizing (1) subject to (2). The following proposition is derived to characterize the optimum.

Proposition 1. *For the green growth problem that maximizes (1) subject to (2), the optimal allocations are characterized by the necessary conditions of optimality as follows:*

$$U'(C)=\lambda_D,\quad \Phi'(I_C)=\frac{\lambda_D}{\lambda_C},\quad (\rho+\delta)\lambda_D-\dot{\lambda}_D=\lambda_D F_{K_D}-V'P_{K_D},\quad (\rho+\delta)\lambda_C-\dot{\lambda}_C=\lambda_D F_{K_C}-V'P_{K_C},\quad (4)$$

and transversality conditions: $\lim_{t\to+\infty}e^{-\rho t}\lambda_D K_D=0$ *and* $\lim_{t\to+\infty}e^{-\rho t}\lambda_C K_C=0$*, where* λ_D *and* λ_C *are the shadow values associated with dirty and clean capital, respectively.*

Following the characterizations of the optimum given in (4), we derive the following set of differential equations that describe transitional dynamics of the optimal growth path:

$$\dot{K}_D=F(K_D,K_C)-C(\lambda_D)-I_C(\lambda_C,\lambda_D)-\delta K_D,\qquad \dot{K}_C=\Phi(I_C(\lambda_C,\lambda_D))-\delta K_C,\qquad (5a)$$

$$\dot{\lambda}_D=(\rho+\delta)\lambda_D+V'P_{K_D}-\lambda_D F_{K_D},\qquad \dot{\lambda}_C=(\rho+\delta)\lambda_C+V'P_{K_C}-\lambda_D F_{K_C},\qquad (5b)$$

where consumption $C(\lambda_D)$ and clear capital investment $I_C(\lambda_C,\lambda_D)$ are optimally determined by λ_C and λ_D according to the first two expressions of equation (4). Equations (5a)-(5b) describe the law of motion for capital stocks and their shadow values, respectively.

Given the initial stocks of capital $[K_D(0),K_C(0)]$, there is a stable saddle path that endogenously determines the initial shadow values $[\lambda_D(0),\lambda_C(0)]$. Then starting from the initial condition, the economy evolves along the stable saddle path and converges to the long-run equilibrium. Furthermore, the first-best optimal allocations can be implemented in a decentralized market equilibrium by pricing emissions at a level that is equal to marginal pollution damages divided by marginal utility of consumption, i.e., $\tau=V'(P)/U'(C)$ (Appendix A provides the details).

4.2 Simultaneous Investment in Dirty and Clean Capital

This subsection shows that the optimal path of energy transition can be characterized by simultaneous investment in both dirty and clean capital. First, for the existence of investment in dirty capital, the Inada condition implies that dirty capital always has dynamic benefits as measured by a positive shadow value, i.e., $U'(C) = \lambda_D$. Meanwhile, the Hamilton-Jacobi-Bellman equation characterizing the optimal path of the shadow value is given by $(\rho+\delta)\lambda_D - \dot{\lambda}_D = U'F_{K_D} - V'P_{K_D}$, where the right-hand side denotes instantaneous benefits of holding dirty capital that should be positive along the optimal path at each instantaneous time point. We thus have $\lambda_D(t) > \lambda_D(t')$ for $t < t'$, i.e., investment in dirty capital creates a larger shadow value (dynamic benefits) at an earlier date over the time horizon. As a result, it is optimal to allocate a positive amount of investment to augment dirty capital stock over time, i.e., $K_D(t) < K_D(t')$ for $t < t'$.

Second, for the existence of investment in clean capital, the second condition of optimality in equation (4), i.e., $\Phi'(I_C) = \frac{\lambda_D}{\lambda_C}$, characterizes the optimal amount of investment in clean capital. This can be generalized as a complementarity slackness condition: $\lambda_C \Phi'(I_C) \leq \lambda_D$, $I_C \geq 0$, $(\lambda_C \Phi'(I_C) - \lambda_D) I_C = 0$. That is, if marginal dynamic benefits (as measured by the shadow values) associated with clean capital investments are strictly less than those of dirty ones, i.e., $\Phi'(I_C)\lambda_C < \lambda_D$, it is efficient to allocate all final goods net of consumption towards dirty capital investment and there is thus no investment in clean capital, i.e., $I_C = 0$. But this case will not happen because stopping clean capital investment is inefficient for the energy transition (see Appendix B for details). In other words, as long as it is inefficient not to accumulate clean capital, it is the case that clean capital investment is needed on top of the existing investment in dirty capital. The efficient growth path satisfies equalization of marginal dynamic benefits between dirty and clean capital (e.g., the non-arbitrage condition). As a result, the optimal path of the energy transition is characterized by the simultaneous accumulation of both dirty and clean capital.

Proposition 2. *For the problem maximizing (1) subject to (2), it is efficient to allocate a positive amount of investment towards both dirty and clean capital, i.e.,* $I_C(t) > 0$, $\forall t \in [0, \infty)$. *The optimal path of the energy transition is thus driven by the simultaneous accumulation of capital in both dirty and clean sectors.*

Proof. See Appendix B. ☐

The intuitions of Proposition 2 are as follows. The equilibrium amount of investment in clean capital depends on the ratio of shadow values between dirty and clean capital, i.e.,[10]

$$I_C(t) = \Phi'^{-1}\left(\frac{\lambda_D(t)}{\lambda_C(t)}\right) = \Phi'^{-1}\left(\frac{\int_t^\infty e^{-(\rho+\delta)(s-t)}(U'F_{K_D} - V'P_{K_D})ds}{\int_t^\infty e^{-(\rho+\delta)(t-s)}(U'F_{K_C} - V'P_{K_C})ds}\right), \tag{6}$$

where Φ'^{-1} is the inverse function (denoted by "$^{-1}$") of the derivative (denoted by "$'$") of the cost function of clean capital conversion Φ. When the investment goods are allocated towards dirty capital accumulation, marginal benefits through the production channel, $U'F_{K_D}$, decrease with K_D. Marginal costs in terms of

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[10] Integrating the last two expressions of (4) yields the analytical expression of the shadow value of both dirty and clean capital.

pollution damages, $V'P_{K_D}$, increase with K_D. In contrast, for clean capital investments, marginal benefits through the production channel, $U'F_{K_C}$, decrease with K_C. Marginal costs through the environmental channel, $V'P_{K_C}$, also decrease with K_C. Therefore, intertemporal benefits gained by clean capital investments could be larger than dirty ones. It is thus efficient to allocate investment goods towards clean capital.

4.3 Transitional Dynamics

Table IV: Specifications of functional forms

Function	Specification
utility	$U(C)=C^{1-\eta}/(1-\eta)$
pollution damage	$V(P)=0.5\kappa P^2$
production technology	$F(K_D,K_C)=A[\alpha K_D^{\frac{\sigma-1}{\sigma}}+(1-\alpha)K_C^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$
pollution emissions	$P(K_D,K_C)=\psi K_D Y^{-1}=\psi A^{-1}[\alpha+(1-\alpha)(K_C/K_D)^{\frac{\sigma-1}{\sigma}}]^{-\frac{\sigma}{\sigma-1}}$
clean capital investment	$\Phi(I_C)=I_C-0.5\phi I_C^2$

Table V: Parameters for simulations

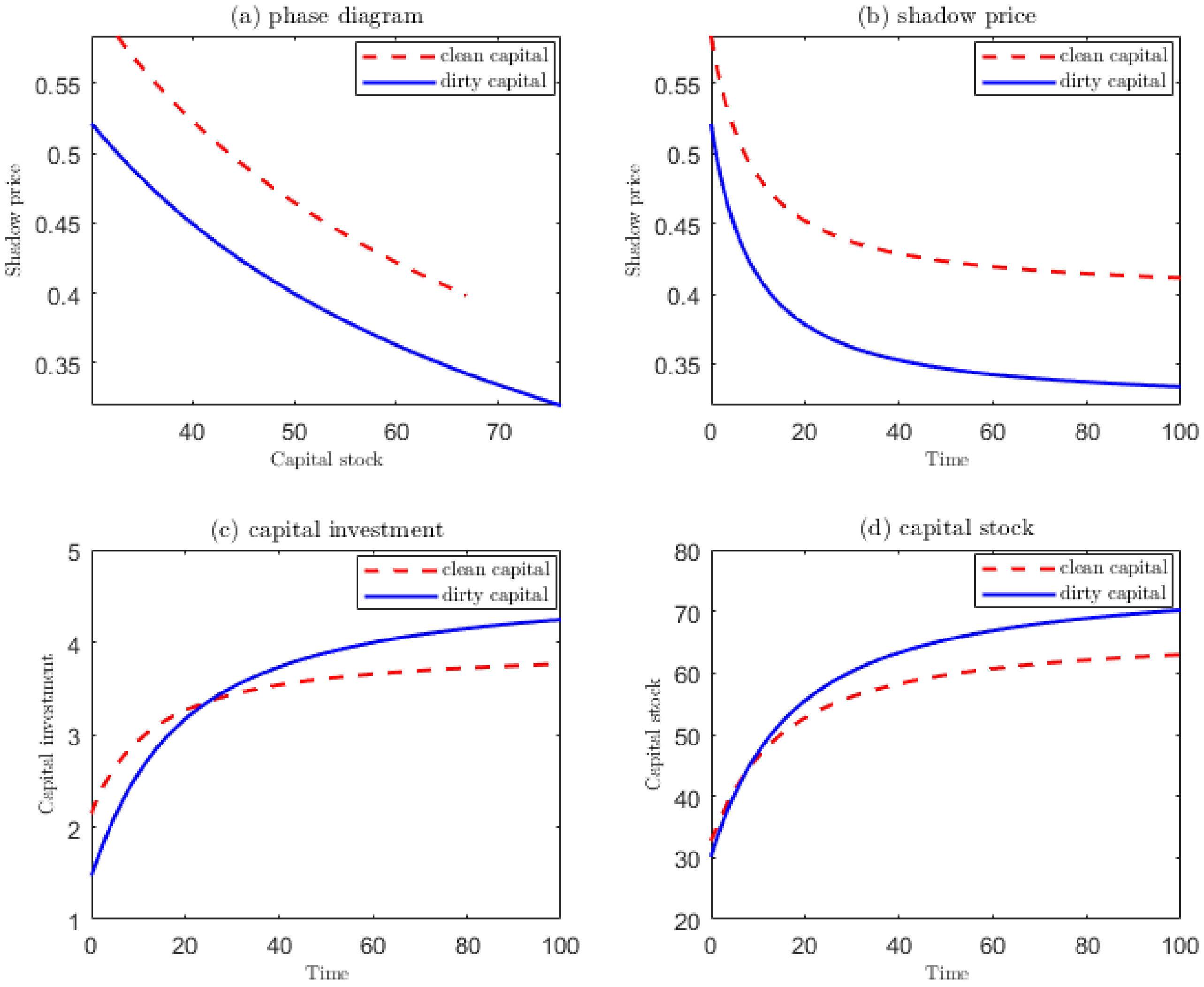
Description	Parameter	Value
coefficient of relative risk aversion	η	0.5
coefficient of marginal pollution damage	κ	0.4
share parameter	α	0.5
elasticity of substitution	σ	1.5
coefficient of efficiency improvement	ψ	0.32
capital productivity	A	0.25
coefficient of capital conversion costs	ϕ	0.5
rate of time preference	ρ	0.06
rate of capital depreciation	δ	0.05

We numerically solve the model to simulate the trajectory of transitional dynamics. The specific functional forms and parameters for model simulations are given in Table IV-V. The utility function is CRRA, and the coefficient of relative risk aversion is set at $\eta=0.5$ within the consensus range 0.4-1 (e.g., Mehra and Prescott, 1985; Epstein and Zin, 1991; Acemoglu et al., 2012). The rate of time preference is given by $\rho = 0.06$ which is within the standard range. The pollution damages are convex as specified as a quadratic function, where the coefficient of marginal pollution damages is set at $\kappa = 0.4$. The production function is specified as CES technology, where the parameter of capital productivity is set at $A = 0.25$, and the input share parameter is $\alpha = 0.5$. According to the empirical estimates of Papageorgiou et al. (2017), the elasticity of substitution between clean and dirty energy inputs is significantly greater than unity - around 2 for the electricity-generating sector and close to 3 for nonenergy industries. Hence, the benchmark value of the elasticity of substitution is set at $\sigma = 1.5$. We also consider a lower degree of substitution at $\sigma = 0.5$ and a higher degree of substitution at $\sigma = 2.5$, which allows us to investigate the robust trend of energy transition under different degrees of substitution. The learning-by-doing effect drives a decline in emission intensity and gives an emission function with homogenous of degree zero. The coefficient governing the emission intensity decline is given by $\psi = 0.32$. Converting final goods into capital goods in clean sectors is subject to capital conversion costs, and the coefficient of conversion costs is set at $\phi = 0.5$. Given these function specifications, transitional dynamics are characterized by the law of motion for capital stocks $[K_D, K_C]$ and their corresponding shadow values $[\lambda_D, \lambda_C]$ as follows:

$$\begin{aligned}
\dot{K}_D &= K_D A[\alpha + (1-\alpha)k^{-\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} - \lambda_D^{-\frac{1}{\eta}} - \phi^{-1}(1-\lambda_D/\lambda_C) - \delta K_D,\\
\dot{K}_C &= \phi^{-1}(1-\lambda_D/\lambda_C) - (2\phi)^{-1}(1-\lambda_D/\lambda_C)^2 - \delta K_C,\\
\dot{\lambda}_D &= (\rho+\delta)\lambda_D - \alpha A \lambda_D \Delta(k) + (\psi/A)^2 \kappa (1-\alpha) K_D^{-1} \Theta(k),\\
\dot{\lambda}_C &= (\rho+\delta)\lambda_C - (1-\alpha) A k^{\frac{1}{\sigma}} \lambda_D \Delta(k) - (\psi/A)^2 \kappa (1-\alpha) K_C^{-1} \Theta(k).
\end{aligned}$$

where $k \equiv \frac{K_D}{K_C}$, $\Delta(k) \equiv [\alpha + (1-\alpha)k^{-\frac{\sigma-1}{\sigma}}]^{\frac{1}{\sigma-1}}$, $\Theta(k) \equiv [\alpha + (1-\alpha)k^{-\frac{\sigma-1}{\sigma}}]^{-(\frac{2\sigma}{\sigma-1}+1)} k^{-\frac{\sigma-1}{\sigma}}$. Solving the system of differential equations yields four eigenvalues with two positive and two negative, suggesting that the transitional dynamics are saddle-path stable.

Figure 3(a) plots the phase diagram of transitional dynamics driven by simultaneous investment in both dirty and clean capital. Both dirty and clean capital evolve along their corresponding stable saddle paths and converge towards their steady-state equilibria. Figure 3(b) shows the time paths of shadow values, where the dashed red line representing the shadow value of clean capital lies above the solid blue one denoting the shadow value of dirty capital over the phase of transitional dynamics. This result suggests that investing in clean capital can create larger dynamic benefits as compared to dirty ones along the efficient path of transition. Since clean capital can protect economic values of dirty capital by mitigating the social cost of pollution damages incurred by dirty capital, it is efficient to accumulate clean capital besides the existing dirty capital. This is demonstrated in Figure 3(c), where the amount of investment in both dirty and clean capital increases over time. As a result, the stock of dirty capital



(a) phase diagram

(b) shadow price

(c) capital investment

(d) capital stock

Figure 3: Simulation paths of transition driven by simultaneous investment in both dirty and clean capital. Panel (a) plots the phase diagram of transitional dynamics. Panel (b) plots the time path of shadow prices. Panel (c) plots the time path of capital investment. Panel (d) plots the time path of capital stocks.

is augmented alongside clean capital accumulation, rather than falls precipitously in the face of the potential substitution by clean capital, as shown in Figure 3(d). This result rationalizes our argument that energy transition might accommodate a case where both dirty and clean capital can coexist and grow simultaneously. Energy transition might not necessarily lead to stranding of the existing dirty capital.

Figure 4 shows how both environmental regulation stringency and green structural change via clean capital accumulation affect the path of transition. Specifically, in a benchmark case excluding green structural change, there is no investment to dynamically accumulate clean capital, and the pattern of

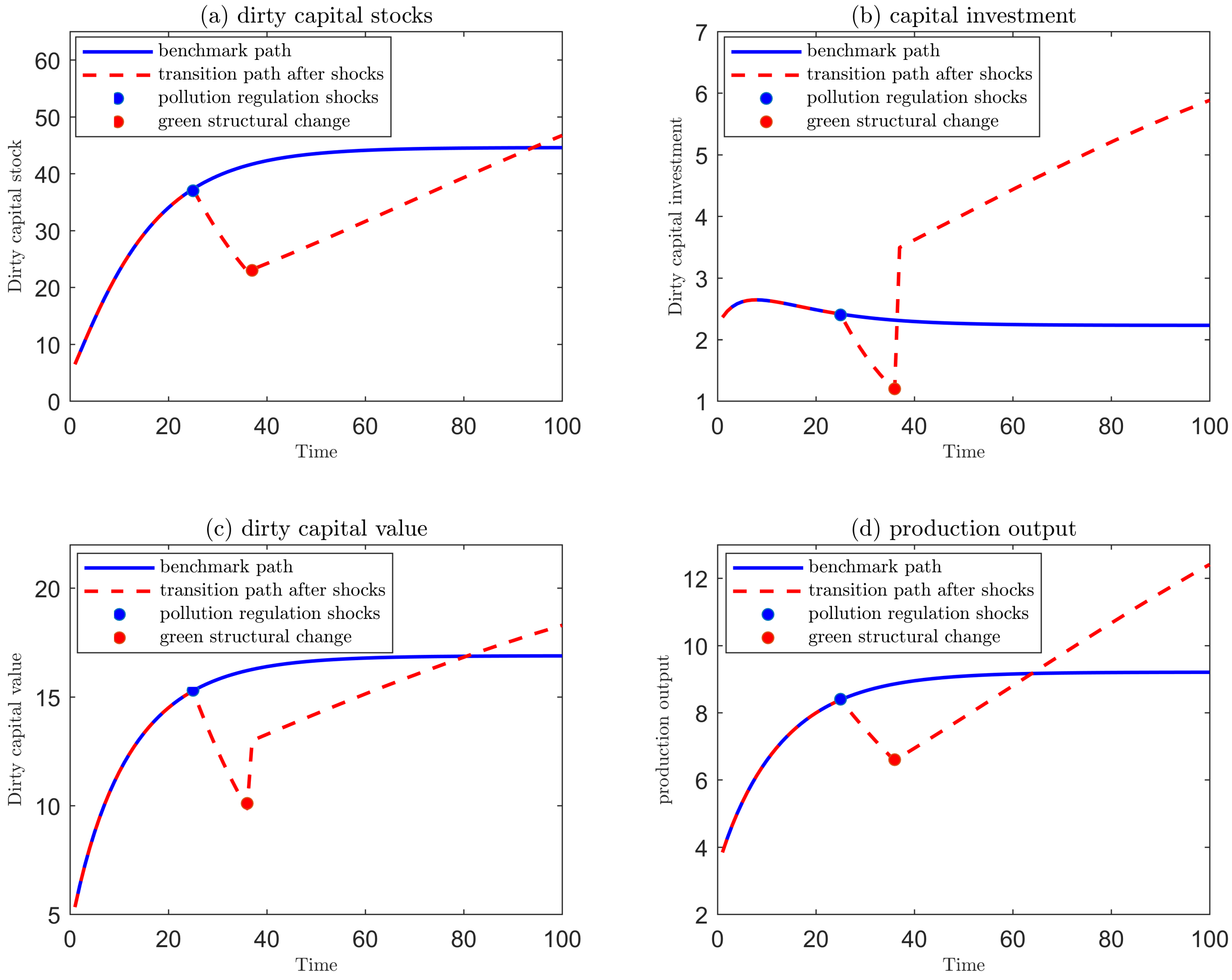


Figure 4: Comparison between the benchmark transition and transition after the shocks. (a) dirty capital stocks; (b) dirty capital investments; (c) dirty capital values; (d) production outputs. The solid blue line corresponds to the benchmark path of transition without both pollution regulation shocks and green structural change (excludes dynamic accumulation of clean capital). The dashed red line shows the path of transition after the shock to environmental stringency and green structural change. Green structural change refers to the stepping-up of clean capital accumulation. The marker of the blue circle denotes the time at which the shock to pollution regulation stringency leads to downward adjustments of capital. The marker of red circle denotes the time at which transition includes green structural change via stepping-up of clean capital accumulation.

transition will only be driven by the accumulation of dirty capital. As Figure 4 shows, without a shock to environmental stringency to internalize pollution damages (i.e., the coefficient of marginal pollution damages is set to null $\kappa = 0$), capital stocks, investment, capital values, and production outputs evolve along the solid blue line in this benchmark case and converge to the steady state in the long run.

In contrast, when there is a shock that tightens environmental regulations (implemented as an increase in the coefficient of marginal pollution damages from $\kappa = 0$ to $\kappa = 0.4$), the path of transition as shown by the red dashed line will differ substantially. Specifically, at the time of a shock to environmental stringency (marked by the blue circle), the tightening of pollution regulations leads to a phase where capital stocks, investment, capital values, and outputs all have seen large downward adjustments. However, when the transition includes dynamically accumulating clean capital for green structural change at the time marked by the red circle, this change will move the transition upwards to an equilibrium path with continual growth. Along this transition path, dirty capital stocks, investments, capital values, and production outputs will all end up with higher levels as compared to those in the benchmark case.

Accordingly, with the stepping-up of clean capital accumulation for green structural change, the transition can potentially accommodate the continual growth of dirty capital, not necessarily leading to dirty capital stranding. Both dirty and clean capital can coexist and grow simultaneously during the transition. On the one hand, clean capital, by eliminating the polluting effect of dirty capital, protects the economic values of dirty capital and thus rescue stranded dirty assets. On the other hand, dirty capital, without stranding, enables production at a larger scale, which in turn provides more economic resources to facilitate clean capital investment.

We also simulate the path of the energy transition with various degrees of substitution between dirty and clean capital. As Figure 5, the trend of simultaneous accumulation (complementarity) of both dirty and clean capital are still robust with various degrees of substitution between dirty and clean capital. In the case of a higher degree of substitutability (the elasticity of substitution $\sigma = 2.5$), clean capital as induced by the tightening of pollution regulations will substitute out dirty capital. But the production input of dirty capital is still necessary for final good production. This is because marginal benefits of consumption should be equal to the shadow value of dirty capital, and the Inada condition requires that the dirty capital needs to create a positive shadow value. Dirty capital investments are always needed to deliver benefits through the production channel to offset pollution damages, such that the positive shadow value can be generated by dirty capital investment. As a result, along the efficient path of the energy transition, dirty capital will continue to augment alongside clean capital when the latter is induced to augment in the presence of stringent climate regulations. Meanwhile, in the case of a lower degree of substitutability (the elasticity of substitution $\sigma = 0.5$), dirty capital investment drives output growth, but

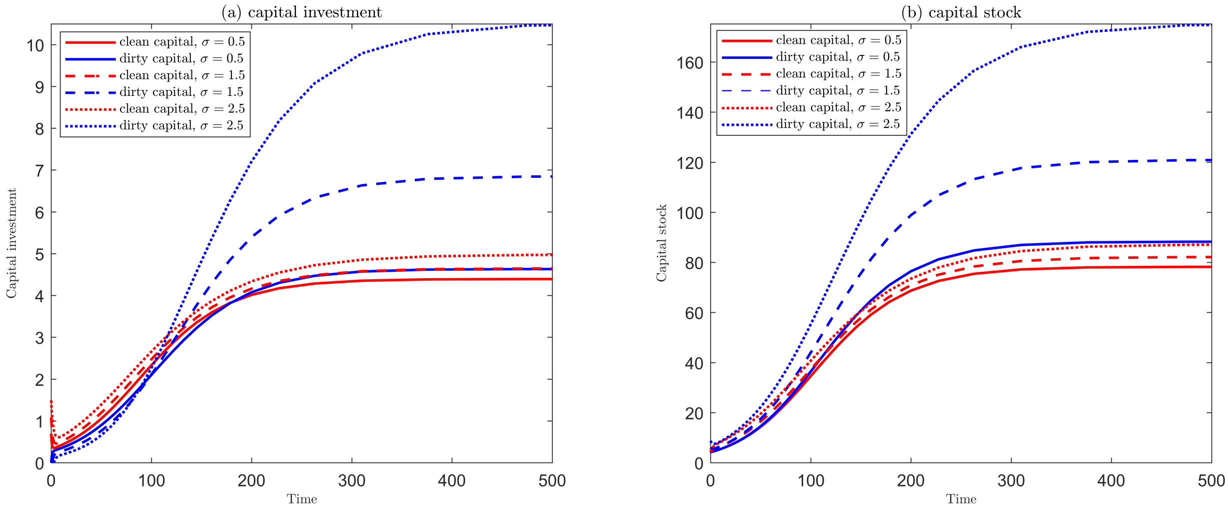


Figure 5: The optimal path of energy transition under different degree of substitution: (a) capital investment; (b) capital stock. The red and blue lines denote clean and dirty capital, respectively. The solid, dashed, dotted lines correspond to the lower degree of substitution $\sigma = 0.5$, the benchmark degree of substitution $\sigma = 1.5$, and the higher degree of substitution $\sigma = 2.5$, respectively.

this will also lead to emissions and pollution damages. It is efficient to launch clean capital investment to eliminate the polluting effect of dirty capital and correct for convex pollution damages. As a result, both dirty and clean capital is needed in the efficient path of the energy transition.

4.4 Balanced Growth Mechanism

The previous section shows that the interaction among pollution regulations, efficiency improvement, and structural change could generate an effect that leads to simultaneous accumulation (complementarity) of both dirty and clean capital. But this trend of transition is not sustained and will end up with a steady-state in the long run. In this section, we proceed by considering a mechanism of balanced growth through which consumption and capital accumulation can be sustained in the long run.

For simplicity, the balanced growth path (BGP) is considered as a path along which consumption C, dirty capital K_D, and clean capital K_C grow at the same rate. The ratio between consumption, dirty capital and clean capital thus remains constant, i.e.,

$$\frac{\dot{C}}{C} = \frac{\dot{K}_D}{K_D} = \frac{\dot{K}_C}{K_C} = g, \quad \frac{C}{K_D} = c, \quad \frac{K_D}{K_C} = k, \tag{7}$$

where g is the rate of balanced growth, c the consumption-dirty capital ratio, and k the dirty-clean capital ratio. Given that the production technology is homogenous of degree (HoD) one and the emission function is HoD zero, the corresponding intensive-form expressions are given by

$$f(k)=F(K_D/K_C,1)=F(k,1)=A[\alpha k^{\frac{\sigma-1}{\sigma}}+(1-\alpha)]^{\frac{\sigma}{\sigma-1}} \tag{8a}$$

$$p(k)=P(K_D/K_C,1)=P(k,1)=\psi A^{-1}[\alpha+(1-\alpha)k^{-\frac{\sigma-1}{\sigma}}]^{-\frac{\sigma}{\sigma-1}}. \tag{8b}$$

The derivatives of $f(k)$ and $p(k)$ with respect to the input argument are determined by

$$f'(k)=F_{K_D}(K_D,K_C)=A\alpha[\alpha+(1-\alpha)k^{-\frac{\sigma-1}{\sigma}}]^{\frac{1}{\sigma-1}} \tag{9a}$$

$$p'(k)=K_C P_{K_D}(K_D,K_C)=\psi A^{-1}(1-\alpha)[\alpha+(1-\alpha)k^{-\frac{\sigma-1}{\sigma}}]^{-(\frac{\sigma}{\sigma-1}+1)}k^{-(\frac{\sigma-1}{\sigma}+1)}. \tag{9b}$$

Then the optimal path of transition characterized by (4) can yield balanced growth through the following mechanism.

Proposition 3. *When the preference has a unitary elasticity of substitution between consumption and pollution, i.e.,*

$$\frac{\partial\log(U'(C)/V'(P))}{\partial\log(C/P)}=-1 \quad \Leftrightarrow \quad \frac{U'(C)}{V'(P)}=\frac{P}{C}, \tag{10}$$

and investment goods allocated towards clean capital can be fully installed as clean capital stocks without conversion costs, i.e.,

$$\dot{K}_C=\Phi(I_C)=I_C-\delta K_C, \tag{11}$$

the balanced growth path as characterized by $[g,c,k]$ is determined by the following set of equations:

$$f'(k)-ck\frac{p'(k)}{p(k)}-\rho-\delta-g=0, \tag{12a}$$

$$f(k)-ck-(g+\delta)(1+k)=0, \tag{12b}$$

$$f(k)-(1+k)f'(k)+ck(1+k)\frac{p'(k)}{p(k)}=0. \tag{12c}$$

where ρ is the rate of time preference, and δ the rate of capital depreciation. The triple $[g,c,k]$ is defined by (7). $f(k)$, $g(k)$, $f'(k)$ and $g'(k)$ are given by (8)-(9).

Proof. See Appendix C. □

For the characterizations of the BGP, (12a)-(12c) provide the intensive-form expression of the Euler consumption rule, the law of motion for capital stocks, and the non-arbitrage condition between dirty and clean capital investment, respectively. For the conditions that ensure the BGP, equation (10) implies that pollution damages need to be concave with bounded marginal damages. Otherwise, an increasing amount of final goods needs to be allocated towards clean capital investment, thus crowding out resources available for investment and consumption. Meanwhile, equation (11) suggests that investment goods allocated towards clean capital should be fully converted into capital stocks in the clean sector without conversion costs. If converting investment goods into clean capital is subject to conversion costs, then the resources available for investment will shrink over time, thus losing the momentum of sustained growth.

Using the functional specification and parameter values given in Table IV-V, we solve (12a)-(12c) for the dirty-clean capital ratio k^* and yiled

$$\frac{1-(1+k)\frac{p'(k)}{p(k)}}{-(1+k)\frac{p'(k)}{p(k)}}=\frac{f(k)-(1+k)(f'(k)-\rho)}{f(k)-(1+k)f'(k)} \quad \Rightarrow \quad k=0.106.$$

Given $k=0.106$, the consumption-dirty capital ratio c and the rate of balanced growth g^* are determined, respectively, by

$$c=\frac{f(k)-(1+k)f'(k)}{-k(1+k)\frac{p'(k)}{p(k)}}=0.626, \qquad g=f'(k)-\left(\frac{f(k)-(1+k)f'(k)}{-(1+k)\frac{p'(k)}{p(k)}}\right)\frac{p'(k)}{p(k)}-\rho-\delta=0.071.$$

When the conditions (10)-(11) are met, there is a BGP alone which consumption, dirty capital, and clean capital grow at a rate of 7.1%. Meanwhile, the BGP is characterized by a ratio between consumption, dirty and clean capital: $c:=C/K_D=0.626$ and $k:=K_D/K_C=0.106$.

5 Conclusion

Tightening of environmental regulations induces demand shifts towards carbon-free renewables that replace carbon-intensive fossil fuels. Carbon-intensive capital linked with fossil fuels would thus be at risk of becoming stranded assets and suffer from premature write-down and devaluations. This paper contributes to a mechanism through which fossil fuel-rich countries can rescue the stranded assets and protect wealth and employment linked to fossil fuel resources.

Our empirical analysis tests the relationship between dirty and clean capital based on the data of the power generation sector in China from 1970 to 2016 and in EU member countries from 2000 to 2017. The empirical results show that the growth of clean capital can positively affect the growth of dirty capital in the short run, and both types of capital can grow independently in the long run. To rationalize the empirical evidence, we investigate a potential mechanism through which both dirty and clean capital can coexist and grow simultaneously. More specifically, stepping-up of clean capital accumulation induced by stringent environmental regulations offsets the polluting effect of dirty capital, and thus provides more room for further deployment of dirty capital. With the further accumulation of dirty capital, more outputs can be produced to provide economic resources for clean capital accumulation. As a result, the energy transition can potentially accommodate the simultaneous accumulation of both dirty and clean capital, not necessarily leading to the stranding of dirty capital. Furthermore, when the preference has a unitary elasticity of substitution between consumption and pollution and there is no adjustment cost in clean capital accumulation, the pattern of energy transition can fall into a balanced growth path along which consumption, dirty capital, and clean capital can grow sustainedly in the long run.

There are still important caveats. First, in our two-sector growth model, specifications of the law of motion for capital focus on the channel of intrasectoral capital investment. One important direction of extension is to incorporate intersectoral capital reallocation into the dynamic process of capital accumulation. This extension can give new insights into the potential effect of capital malleability on asset stranding (e.g., Baldwin et al., 2020; Hambel et al., 2020). For example, if capital is malleable with smaller intersectoral reallocation costs, capital deployed in the dirty sector (coal-fired power plants) could be reallocated and deployed in the clean sector (PV facility or windmills), thus avoiding the stranding of dirty capital in the energy transition. Second, in the context of climate mitigation, pollution damages are closely related to temperature increases caused by cumulative emissions (e.g., Dietz and Venmans, 2019; van den Bijgaart et al., 2016; van der Ploeg et al., 2020). It is thus important to extend the analytical framework by explicitly considering the connection between cumulative emissions, temperature rise, and the damaging effects of warming on the economy. We leave detailed expositions of these areas for future research.

Appendix A Implementing the Optimum in a Market Equilibrium

In the market equilibrium, the problem of the representative household is to maximize $\int_0^\infty \exp(-\rho t)U(C)dt$ subject to $\dot{K}_D = \pi + r_D K_D - C - I_C$, and $\dot{K}_C = \Phi(I_C) + r_C K_C$. The representative household owns dirty and clean capital stock K_D and K_C and receives remunerations by renting capital at the rate of return given by r_D and r_C, respectively. The household also has an ownership of a representative firm using dirty and clean capital to produce final goods and receives profits π. Solving the household problem yields characterizations: $U'(C) = \lambda_D$ for consumption, $\lambda_D = \Phi'(I_C)\lambda_C$ for clean capital investment, $\rho\lambda_D - \dot{\lambda}_D = r_D\lambda_D$ for dirty capital stock, and $\rho\lambda_C - \dot{\lambda}_C = r_C\lambda_C$ for clean capital stock.

Meanwhile, a representative firm uses clean and dirty capital to produce final goods and faces a profit maximization problem: $\pi(t) = F(K_D, K_C) - r_D K_D - \frac{r_C}{\Phi'(I_C)}K_C - \tau P(K_D, K_C)$, where instantaneous profits π are obtained by subtracting the costs of renting dirty and clean capital owned by the household. The rate of return is r_D for dirty capital, and the rate of return of clean capital r_C in unit of clean capital is converted to final goods units by dividing $\Phi'(I_C)$. The firm problem is characterized by $F_{K_D}=r_D+\tau P_{K_D}$ and $F_{K_C}=\frac{r_c}{\Phi'(I_C)}+\tau P_{K_C}$ for dirty and clean capital, respectively. Combining characterizations of both household and firm problems, the equilibrium is characterized by: $U'(C)=\lambda_D$, $\lambda_D=\Phi'(I_C)\lambda_C$, $\rho\lambda_D-\dot{\lambda}_D=(F_{K_D}-\tau P_{K_D})\lambda_D=\lambda_D F_{K_D}-\tau\lambda_D P_{K_D}$, and $\rho\lambda_C-\dot{\lambda}_C=(F_{K_C}-\tau P_{K_C})\Phi'(I_C)\lambda_C=\lambda_D F_{K_C}-\tau\lambda_D P_{K_C}$. It is easy to verify that by setting $\tau=\frac{V'(P)}{U'(C)}$, the equilibrium allocations are characterized by $U'(C)=\lambda_D$, $\lambda_D=\Phi'(I_C)\lambda_C$, $\rho\lambda_D-\dot{\lambda}_D=(F_{K_D}-\tau P_{K_D})\lambda_D=\lambda_D F_{K_D}-V'(P)P_{K_D}$, and $\rho\lambda_C-\dot{\lambda}_C=(F_{K_C}-\tau P_{K_C})\Phi'(I_C)\lambda_C=\lambda_D F_{K_C}-V'(P)P_{K_C}$, which is the same as the social optimum allocations.

Appendix B Proof of Proposition 2

We will prove that there always exists a time point at which clean capital investment should be launched in the optimal growth path. This is equivalent to verifying that it is impossible not to launch clean capital investment over the entire time frame. This argument can be proved by contradiction. Suppose there is no investment in clear capital over the entire time frame, i.e., $\lambda_D(t)-\Phi'(I_C(t))\lambda_C(t)>0$, with $I_C(t)=0$, $\forall t\in[0,\infty)$. This is equivalent to

$$\int_t^{\infty} e^{-\rho(s-t)}\left[U'(s)(F_{K_D}(s)-F_{K_C}(s))-V'(s)(P_{K_D}(s)-P_{K_C}(s))\right]ds>0, \tag{B.1}$$

where $\Phi'(I_C(t))=\Phi'(0)=1$ with $I_C(t)=0$ for $\forall t\in[0,\infty)$. To find the contradiction, we consider the long-run steady state, say at the time point t^*, and (B.1) thus boils down to

$$\rho^{-1}\left[U'(t^*)(F_{K_D}(t^*)-F_{K_C}(t^*))-V'(t^*)(P_{K_D}(t^*)-P_{K_C}(t^*))\right]>0. \tag{B.2}$$

Here U' is bounded due to the concavity of utility. $F_{K_D}(t^*)-F_{K_C}(t^*)<F_{K_D}(0)-F_{K_C}(0)$ holds because $F_{K_D}-F_{K_C}$ decreases in K_D and K_D increases over time. Meanwhile, pollution damages are convex, and the marginal pollution damages V' are thus sufficiently large. $P_{K_D}>P_{K_C}$ due to $P_{K_D}>0$ and $P_{K_C}<0$. Therefore, the sign of (B.2) is negative which contradicts with the positive sign.

Appendix C Proof of Proposition 3

We impose the condition of homogeneity as follows: $F(\psi K_D,\psi K_C)=\psi F(K_D,K_C)$, and $P(\psi K_D,\psi K_C)=P(K_D,K_C)$ $\forall\psi\in\mathbb{R}_+$, where the production function is homogenous of degree (HoD) one, and the emission function is HoD zero. The intensive-form functions of production technology and pollution emissions are given by

$$f(k):=F(K_D/K_C,1)=F(k,1),\quad p(k):=P(K_D/K_C,1)=P(k,1),$$

where $k:=K_D/K_C$ is the input argument, and the derivatives are given by:

$$f'(k)=F_{K_D}(K_D/K_C,1)=F_{K_D}(K_D,K_C),\quad p'(k)=P_{K_D}(K_D/K_C,1)=\left(\frac{1}{K_C}\right)^{-1}P_{K_D}(K_D,K_C).$$

The intensive-form representation of the Euler equation is given by

$$\frac{\dot{C}}{C}=F_{K_D}(K_D,K_C)-\rho-\delta-\frac{V'(P)P_{K_D}(K_D,K_C)}{U'(C)}=F_{K_D}(K_D,K_C)-\rho-\delta-\frac{CP_{K_D}(K_D,K_C)}{P(K_D,K_C)},$$

where $F_{K_D}(K_D,K_C)=f'(k)$. Given that $P(K_D,K_C)$ is HoD zero and $P_{K_D}(K_D,K_C)$ is HoD -1, we have

$$C\frac{P_{K_D}(K_D,K_C)}{P(K_D,K_C)}=\frac{C}{K_C}\frac{\left(\frac{1}{K_C}\right)^{-1}P_{K_D}(K_D,K_C)}{P(K_D,K_C)}=\frac{C}{K_D}\frac{K_D}{K_C}\frac{P_{K_D}\left(\frac{K_D}{K_C},1\right)}{P\left(\frac{K_D}{K_C},1\right)}=ck\frac{p'(k)}{p(k)},\tag{C.1}$$

where $c:=\frac{C}{K}$, $k:=\frac{K_D}{K_C}$, $p(k):=P(\frac{K_D}{K_C},1)$ and $p'(k)=P_{K_D}(\frac{K_D}{K_C},1)$. Second, from the law of motion for K_C and K_D, we have,

$$\frac{\dot{K}_C}{K_C}=\frac{F(K_D,K_C)-C-(\dot{K}_D+\delta K_D)-\delta K_C}{K_C}=f(k)-ck-(g+\delta)k-\delta,\tag{C.2}$$

where $f(k):=F(\frac{K_D}{K_C},1)$. Finally, equalization of instantaneous marginal benefits between dirty and clean capital accumulation is given by

$$\frac{V'(P)}{U'(C)}(P_{K_C}(K_D,K_C)-P_{K_D}(K_D,K_C))=F_{K_C}(K_D,K_C)-F_{K_D}(K_D,K_C),\tag{C.3}$$

where the right-hand side of (C.3) can be rewritten as

$$F_{K_C}-F_{K_D}=\frac{F(K_D,K_C)-F_{K_D}K_D}{K_C}-F_{K_D}=F\left(\frac{K_D}{K_C},1\right)-F_{K_D}\frac{K_D}{K_C}-F_{K_D}=f(k)-(1+k)f'(k).$$

Using the Euler's theorem yields $F_{K_D}K_D+F_{K_C}K_C=F(K_D,K_C)$. Furthermore, given that $P(K_D,K_C)$ is HoD 0, the Euler's theorem yields $P_{K_D}K_D+P_{K_C}K_C=0$ and $P_{K_C}=\frac{-P_{K_D}K_D}{K_C}$, and we hence have

$$\frac{V'}{U'}P_{K_C}=\frac{C}{P}P_{K_C}=\frac{C}{P}\left(\frac{-P_{K_D}K_D}{K_C}\right)=-\frac{K_D}{K_C}\frac{C}{P}P_{K_D}=-kck\frac{p'(k)}{p(k)}.\tag{C.4}$$

Given $\frac{V'}{U'}P_{K_D}(K_D,K_C)=\frac{C}{P}P_{K_D}(K_D,K_C)=ck\frac{p'(k)}{p(k)}$ in (C.1), the left-hand side of (C.3) is rewritten by

$$\frac{V'}{U'}(P_{K_C}-P_{K_D})=-ck(1+k)\frac{p'(k)}{p(k)}.$$

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