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GREEN HUMAN CAPITAL, INNOVATION AND GROWTH

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Abstract

This paper examines why a growth process relying on both green innovation and green human capital may be responsible for higher inequality within and between skills. We propose a theoretical framework and derive some empirical observations using data from more than 2000 companies in 21 OECD countries in 2022. We discuss the policy implications of this analysis in light of the COVID-19 pandemic, which has led many governments to place green investment at the heart of their recovery plans.

Keywords: Environment, Skill Supply, Innovation-driven Growth.
JEL Codes: O33, Q50, J24.

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1 Introduction

The crisis linked to the COVID-19 pandemic has led the public authorities to place the fight against climate change at the heart of their recovery plans. The pandemic has been a stark reminder that preventing climate change from inflicting permanent harm on the global economy requires a fundamental structural change to our economy, inducing systematic changes in how energy is generated and consumed (Schnabel (2020)). It also is an opportunity for a growing number of institutional investors to question their investment practices and change their strategy.

After formally adopting a carbon neutrality objective by 2050 in March 2020, European states have adopted recovery plans in which the fight against climate change is a clearly stated objective. The European Union announced in September 2020 an issuance of 225 billion euros in green bonds to finance its recovery, or 30% of the total budget deployed to deal with the aftermath of the coronavirus crisis. France has also set itself the goal of "becoming the first major low-carbon economy in Europe with 30 billion euros, from the overall envelope of its 2020 recovery plan, devoted to four priority sectors: energy renovation of buildings, transport, agricultural transition, and energy. These investments will allow France to develop by adopting sustainable and fair growth "[1]. China, for its part, has just declared at the end of September 2020 a goal of carbon neutrality by 2060 at the latest. Those recovery plans are based on the premise that "cleaner air quality, healthier water, effective waste management, and enhanced biodiversity protection not only reduce the vulnerability of communities to pandemics and improve resilience, but have the potential to boost economic activity, generate income, create jobs, and reduce inequalities" [2].

This article investigates whether growth based on green investments and innovation can indeed be considered as a source of higher income, job creation, and lower inequality. We propose first a theoretical model of endogenous growth based on innovation in green and brown sectors, and endogenous human capital decisions. In a second step we illustrate the main prediction of the model using firm-level data on a wide set of developed and emerging countries in 2022. The main moderating factor we propose to consider in the analysis is the role of green human capital. With this approach, we show that green innovation and green growth may lead to higher inequality when relying on green motivation. Empirically, we also illustrate that policy measures relying on education policies at the firm level may effectively reduce inequality. Overall, this approach suggests that environmental concerns would be emerging as a new frontier for the social question and that public policies aimed at equity or reducing social inequalities without considering the environmental dimension would be ignoring an essential aspect of the social question. Conversely, the evolution of inequalities can reinforce certain environmental imbalances and represents a real challenge for greening growth.

We contribute to two strands of literature. The first one considers green motiva-

[1]See https://www.gouvernement.fr/en/european-aspects-of-france-s-recovery-plan
[2]See https://www.oecd.org/coronavirus/en/themes/green-recovery

tion as a mediating factor in education and labor market decisions. The green human resources management literature examines the policies and practices designed to attract, retain and motivate employees on green issues (Opatha and Arulrajah (2014)). As a signal for corporate culture, green performance can help companies attract prospective employees (Turban and Greening (1997); Albinger and Freeman (2000); Backhaus et al. (2002); Grolleau et al. (2007); Burbano (2016)). Green factors are also shown to improve employee satisfaction, and firm identification (Lanfranchi and Pekovic (2014)) and promote teamwork values and organizational citizenship behaviors and commitment (Pekovic (2015), Brammer et al. (2007), Peterson (2004)), thereby reducing employee turnover (Portney (2008)) or securing firm survival and long-term performance (Brekke and Nyborg (2008)). Interestingly, this literature highlights an ambiguous relationship between green motivation and wage levels and differentials. On one hand, green companies can be expected to offer higher wages as social entrenchment strategies, but on the other hand, green companies may want to attract employees via ethical concerns and corporate culture, thereby inducing a negative link between green motivation and wages (Crifo et al. (2023)). This element is well-known in the motivation crowding effect theory whereby monetary rewards at the roots of extrinsic motivation may crowd out intrinsic motivation at work (see Deci and Ryan (1985)). In terms of wage inequality, such a mechanism might imply a negative relationship between green production processes and wages because employees motivated by the green culture of the company would be likely to trade off monetary for nonmonetary (green) benefits and accept lower wages and/or higher wage inequality because their job would satisfy their personal value. Using a survey conducted on 300 participants from various OECD countries, Krueger et al. (2021) in fact observe that green motivation (caring about the green characteristics of their jobs) is highly prevalent, especially among skilled individuals, and individuals are willing to accept lower wages to work for greener firms, with workers in green firms earning about $9-15\%$ lower wages. Using a large employer-employee matched database of more than 15,000 French workers, Crifo et al. (2023) also shows that greener firms tend to pay lower (higher) bonuses and employee participation schemes to nonmanagers (managers). Such a mechanism would exhibit segmentation and sorting between skills, with managers (the high-skilled segment) benefiting both from green motivation and higher bonuses, while non-managers (the low-skilled segment) being faced with a trade-off between bonuses (monetary) and green (nonmonetary) incentives. We contribute to this literature by examining both theoretically and empirically the relationship between green motivation and the wage gap, focusing on the returns to education as a mediating factor (in addition to green motivation). We show, in particular, that when the returns to education decrease (and its costs increase), wage inequality will also increase.

The second strand of literature questions the contribution of green innovation to income growth and inequality. Ee et al. (2018) examines theoretically the non-linear income distributional effect of green practices at the firm level. They show notably that corporate environmental investments may raise capital rental costs and widen wage inequality between skilled and unskilled workers in the short run. In the long run, however, the wage gap could be narrowed because of an increase in unskilled wages and a reduction in skilled wages through the substitution between skilled labor and capital. Vona and Patriarca (2011) also propose a dynamic model with technological externalities driven by the emergence of a new demand for green products to explain the relationship between environmental innovations and inequality. They show that such a relationship is non-linear and depends on per-capita income, with the demand for green products (higher in richer countries) playing an important mediating factor. They also show that excessive inequality harms the development of environmental technologies especially in rich countries. We contribute to this literature by examining both theoretically and empirically the relationship between green innovation and wage inequality by focusing on the mediating role of green human capital and motivation. We show in particular that when the proportion of green workers or green motivation increases, wage inequality will rise between skills but may increase (green motivation effect) or decrease (green human capital effect) within the skilled segment. We may thus have a non-linear relationship between green innovations and inequality, explained by the share and returns to motivation of green workers (not only green demand).

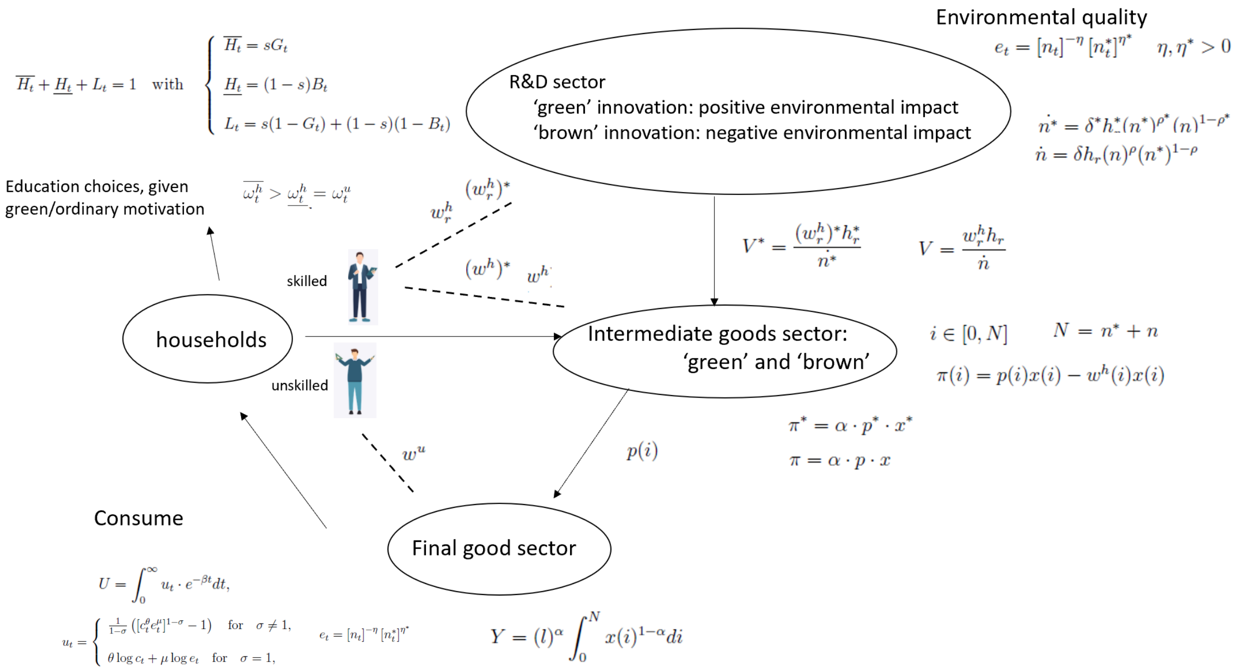
The rest of the paper is organized as follows. Section 2 presents the model and the main equilibrium results. Section 3 examines the theoretical relationship between green human capital and inequality. Section 4 proposes an empirical illustration of the results. Section 5 concludes the article.

2 The model

The model is an extended version of Romer (1990) where the economy is composed of one final good sector, one intermediate (differentiated) goods sector, and two innovative sectors: a 'green' sector which produces technologies with a positive environmental impact and a 'brown' sector which produces technologies with a negative environmental impact. Households consume the final good and choose to acquire education, based on their motivation (green or ordinary motivation) to work in the green or brown sector and the returns to education.

The basic structure of the model is shown in Figure 1 and detailed in the rest of the section (for a comprehensive list of all variables and parameters of the model, see Appendix 6.1).

Fig. 1 Basic structure of the model



2.1 The final good sector

The unique, homogenous, final good is produced competitively using unskilled labor l and a variety of differentiated intermediate goods $x(i)$, $i \in [0, N]$, according to the following production function:[3]

$$Y = (l)^\alpha \int_0^N x(i)^{1-\alpha} di, \tag{1}$$

where $0 < \alpha < 1$ and the index of different types of intermediate goods i is treated as continuous variable over the 0-N interval.[4]

The final good is the numeraire in this economy. Each final-sector producer determines the amount of unskilled labor and intermediate goods used as inputs by maximizing profit under technological constraint, according to the following problem:

$$\max_{l, x(i)} \quad Y - w^u l - \int_0^N p(i)x(i)di$$
$$\text{subject to } Y = (l)^\alpha \int_0^N x(i)^{1-\alpha} di.$$

[3]To simplify notations, time indexes are omitted when they are not necessary, and when no confusion arises.

[4]This is in line with the original Romer (1990) model.

First-order conditions give the usual equality between factor prices and marginal product:

$$p(i) = (1-\alpha)\,(l)^{\alpha}\,(x(i))^{-\alpha}, \qquad w^{u} = \alpha\,(l)^{\alpha-1}\int_{0}^{N} x(i)^{1-\alpha}di, \tag{2}$$

where $p(i)$ denotes the price of intermediate good i and w^u is the wage rate of unskilled workers.

2.2 The intermediate goods sector

In the intermediate sector, each firm i produces one variety of differentiated good i. This sector is composed of N firms which consist of two levels of technology: n^* 'green' firms and n 'brown' firms, with $N = n^* + n$. The number of green firms has a positive impact on environmental quality while the number of brown firms has a negative impact on environmental quality e_t:

$$e_t = [n_t]^{-\eta}\,[n_t^*]^{\eta^*}, \tag{3}$$

where $\eta > 0$ and $\eta^* > 0$ are the elasticity of environmental quality in the two types of goods. This function considers environmental quality as a flow variable and illustrates that society must trade off the use of the two types of goods (green and brown) in order to raise environmental quality. The potential decline in environmental quality will affect consumption (see 2.5)[5].

Note that each firm in the intermediate sector may be considered either as a purely productive firm that commercializes a new good invented in the innovative sector or as an integrated firm in which there are two distinct activities: a research activity creating a new variety of intermediate good and a production activity using this new technology. Both interpretations (separate or integrated research and production structures) are equivalent when assuming that green (resp. brown) innovators only sell their patent to green (resp. dirty) firms, without any exchange between firms of different technology levels.

Both types of intermediate firms produce their goods using skilled labor as sole input according to a one-for-one technology: one unit of skilled labor produces one unit of intermediate goods. Let $w_h(i)$ denote the wage rate of skilled labor in firm i. Green and brown intermediate firms operate as local monopolists, and their optimization program writes:

[5]For a discussion on environmental problems treated as flow variables, see e.g. Grimaud and Tournemaine (2007).

$$\max_{x(i)} \quad \pi(i) = p(i)x(i) - w^h(i)x(i)$$
$$\text{subject to } p(i) = (1-\alpha)\,(l)^{\alpha}\,(x(i))^{-\alpha}\,, \quad i \in [0, N].$$

Denoting by $(w^h)^*$ (resp. w^h) the wage rate in efficiency units of skilled labor in green firms (resp. brown firms), the first-order conditions of this optimization program imply in the green segment:

$$p^* = \frac{(w^h)^*}{1-\alpha}, \quad x^* = l\left[\frac{(1-\alpha)^2}{(w^h)^*}\right]^{\frac{1}{\alpha}}, \quad \text{and } \pi^* = \alpha \cdot p^* \cdot x^*, \tag{4}$$

and in the brown segment:

$$p = \frac{w^h}{1-\alpha}, \quad x = l\left[\frac{(1-\alpha)^2}{w^h}\right]^{\frac{1}{\alpha}}, \quad \text{and } \pi = \alpha \cdot p \cdot x. \tag{5}$$

2.3 The innovative (R&D) sectors

In each period, $\dot{N}$ new goods (or new varieties) are invented in the research sector. We assume that the research process is deterministic and uses two kinds of inputs: skilled labor (human capital) and the existing stock of knowledge. We consider intertemporal externalities in the R&D activity in that skilled workers engaged in the research activity can take advantage of knowledge accumulated in the past in both the green and the brown segment. Knowledge accumulation is assumed to exhibit constant returns with respect to green knowledge n^* and brown knowledge n (which allows for a balanced growth path) and is linear in the skilled labor input (standard assumption in Romer (1990) type framework).

The green knowledge accumulation function is linear in its skilled labor input and given by:

$$\dot{n}^* = \delta^* h_r^* (n^*)^{\rho^*} (n)^{1-\rho^*}, \tag{6}$$

where $\delta^* > 0$ denotes the efficiency of the green technology, $\rho^* \in]0,1]$ is a measure of the externalities created by green and brown knowledge and h_r^* is the number of skilled workers employed in the green research segment.

In a symmetric way, the brown knowledge accumulation function is given by:

$$\dot{n} = \delta h_r (n)^{\rho} (n^*)^{1-\rho}, \tag{7}$$

where $\delta > 0$ is the efficiency of the brown technology, $\rho \in]0, 1]$ is a measure of the externalities created by green and brown knowledge and h_r is the number of skilled workers employed in the brown research segment.

Such a knowledge accumulation function captures the fact green and brown firms are characterized by different efficiency levels δ and δ^* of their research activity and different externalities levels ρ and ρ^*.[6] In particular, if green firms have a higher (resp. lower) efficiency than brown firms, we assume that $\delta^* > \delta$ (resp. $\delta^* < \delta$).

Eqs. 6 and 7 are (standard) production function for researchers. Inventing a new variety leads to a patent with property rights (or licenses) sold to intermediate goods producers. The patent prices are denoted by $V(t)$ and $V^*(t)$; they equalize the cost and the benefit of innovation, that is, the value of the monopoly in the intermediate goods sector.

The *cost of acquiring a patent* (i.e. the cost of creating and marketing a new green and brown variety) is determined by the free-entry condition in the R&D sector:

$$\Pi_r^* = V^* \cdot \dot{n^*} - (w_r^h)^* \cdot h_r^* = 0 \qquad \text{and} \qquad \Pi_r = V \cdot \dot{n} - w_r^h \cdot h_r = 0, \tag{8}$$

where Π_r^* (resp. Π_r) is the profits and $(w_r^h)^*$ (resp. w_r^h) is the wage rate of skilled labor in the R&D sector of the green (resp. brown) segment. Given Eqs 6 and 7 these conditions lead to:

$$V^* = \frac{(w_r^h)^* h_r^*}{\dot{n^*}} = \frac{(w_r^h)^*}{\delta^* (n^*)^{\rho^*} (n)^{1-\rho^*}} \qquad \text{and} \qquad V = \frac{w_r^h h_r}{\dot{n}} = \frac{w_r^h}{\delta (n)^{\rho} (n^*)^{1-\rho}}. \tag{9}$$

The *market value of an intermediate monopolist* is given by the present value of profits earned by the intermediate monopolist over the infinite patent lifetime $\int_t^{\infty} e^{-r(z-t)} \pi^*(z) dz$ and $\int_t^{\infty} e^{-r(z-t)} \pi(z) dz$. The value of the patent is such that in each period intermediate monopolists have to decide whether to invest in the risk-free asset (priced at the interest rate r) or to buy a patent, produce an intermediate good for one period, and then sell the patent after a year at price V in the brown segment, and V^* in the green segment. Equating the return from two options yields:

[6] A similar formulation is adopted in a different framework by Berthelemy and Demurger (2001).

$$rV = \pi + \dot{V} \text{ and } rV^* = \pi^* + \dot{V}^*, \tag{10}$$

where r is the interest rate and π^* (resp. π) is the profit of intermediate producers computed in Eqs. 4 and 5.

2.4 Green human capital

The size of the population is normalized to one. Individuals differ in their job motivation: they can have either green or basic motivation. Green motivation means workers are motivated by green tasks on their job, and therefore willing to supply more efficient units of labor than workers with basic motivation either because their work satisfies their personal values (Brammer et al. (2007), Nyborg and Zhang (1996), El Akremi et al. (2018)) or because of a pure labor productivity effect (see Delmas and Pekovic (2018), Edmans (2011), Bailey et al. (2001)). Basic motivation means workers are indifferent towards green tasks, and, therefore, less efficient at those activities compared to green-motivated workers. The distribution of motivation in the population is fixed and exogenous. However, individuals can acquire education, so that the allocation of workers between skilled and unskilled labor is endogenous. Let s denote the proportion of workers that have green motivation. We denote by G_t (respectively B_t) the fraction of workers with green (respectively basic) motivation who choose to become educated. Resources constraints on the labor market then write:

$$\overline{H_t} + \underline{H_t} + L_t = 1 \quad \text{with} \quad \begin{cases} \overline{H_t} = sG_t \\ \underline{H_t} = (1-s)B_t \\ L_t = s(1-G_t) + (1-s)(1-B_t) \end{cases} \tag{11}$$

where $\overline{H_t}$ (respectively $\underline{H_t}$) is the number of skilled workers with green (respectively basic) motivation and L_t is the number of unskilled workers.

Given the distribution of motivation, the choice of becoming educated allows workers with green (respectively basic) motivation to supply $\overline{\varphi_t}$ efficiency units of labor (respectively $\underline{\varphi_t}$ efficiency units of labor). Individuals who choose not to acquire skills supply φ_t efficiency units of labor. To formalize the fact that among workers who choose to acquire education, green-motivated workers are willing to supply more efficiency units of labor (productivity effect) than workers with basic motivations at work, we have:

$\overline{\varphi_t} > \underline{\varphi_t} \geq \varphi_t$.

In this framework, green motivation, and education are complementary inputs in the determinant of human capital.[7] but firms use green production to attract and motivate green workers. There are, in fact, two types of returns to human capital in the model: returns to motivation and returns to skills. Returns to motivation are captured by inequality $\overline{\varphi_t} > \underline{\varphi_t}$, which implies that the productivity (efficiency units of labor) of individuals with green motivation who choose to become educated is higher than the productivity of individuals with basic motivation who choose to become educated. This assumption is in line with Delmas and Pekovic (2018), Edmans (2011), Bailey et al. (2001). Returns to motivation, determined by the firm's labor demand, are therefore used to attract and motivate workers on the basis of their productivity-enhancing green preferences. On the other hand, returns to skills are captured by inequality $\underline{\varphi_t} \geq \varphi_t$ which implies that unskilled workers supply lower efficiency units of labor than skilled workers. Therefore, returns to skills determined by the firm's labor demand are used to attract and motivate workers to acquire skills independently of their green preferences, which is in line with the basic theory of human capital formation (Becker (1964)).

We assume that the cost of education is such that individuals who choose to become skilled workers devote a fraction $0 < \xi < 1$ of their unit-time endowment to the formation of human capital. Individuals who choose to become skilled then supply a fraction $(1 - \xi)$ of their potential efficiency units of skilled labor. The expected incomes of each category of workers then write:

$$\overline{\omega_t^h} = (1 - \xi).\overline{\varphi_t}.w_t^h, \quad \underline{\omega_t^h} = (1 - \xi).\underline{\varphi_t}.w_t^h, \quad \omega_t^u = \varphi_t.w_t^u, \tag{12}$$

where w_t^h is the wage rate per efficiency units of skilled labor and w_t^u is the wage rate per efficiency units of unskilled labor.

2.5 Households' preferences

Households consume the final good and maximize an intertemporal utility function which is given by: $U = \int_0^\infty u_t \cdot exp^{-\beta t} dt$, with β the discount rate and where preferences are represented by the following instantaneous utility function:[8]

[7] See Crifo (2008) for a similar assumption applied to skill-biased technical change.

[8] Following Elbasha and Roe (1997), this utility function has the following properties:
(a) the elasticity of the marginal rate of substitution between consumption and environmental quality with respect to consumption, $\partial \log(u_e/u_c)/\partial \log c$ is equal to 1;
(b) the elasticity of the marginal utility of consumption is constant and equal to $1 - \theta(1 - \sigma)$;
(c) the elasticity of the marginal utility of environmental quality is constant and equal to $1-\mu(1-\sigma)$;
(d) Inada conditions: $\lim_{c\to 0} u_c = \infty$, $\lim_{c\to\infty} u_c = 0$, $\lim_{e\to 0} u_e = \infty$, $\lim_{e\to\infty} u_e = 0$.

$$u_t = \begin{cases} \frac{1}{1-\sigma}\left([c_t^{\theta} e_t^{\mu}]^{1-\sigma} - 1\right) & \text{for} \quad \sigma \neq 1, \\ \theta \log c_t + \mu \log e_t & \text{for} \quad \sigma = 1, \end{cases} \tag{13}$$

where c_t denotes per capita consumption and e_t denotes environmental quality and is defined by Eq. 3: $e_t = [n_t]^{-\eta} [n_t^*]^{\eta^*}$ with $\eta > 0$ and $\eta^* > 0$.

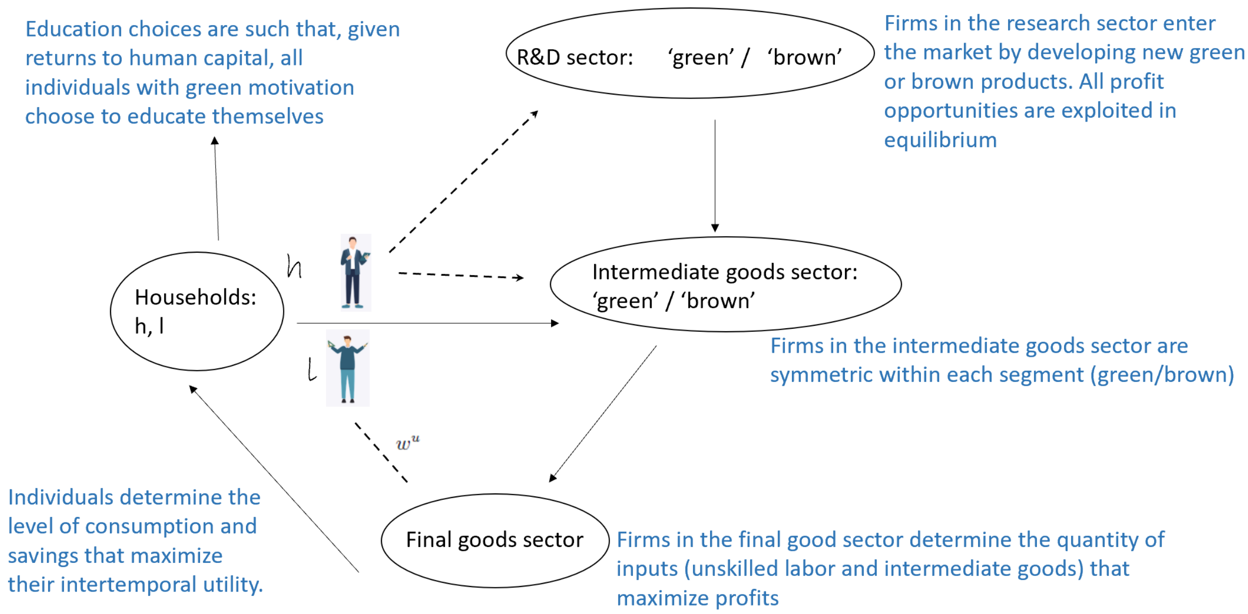
Monotonicity and strict concavity imposes the following restrictions:

$$\sigma, \theta, \mu > 0 \quad \theta(1-\sigma) < 1, \quad \mu(1-\sigma) < 1, \ \text{a,d} \ (\theta+\mu)(1-\sigma) < 1. \tag{14}$$

2.6 Competitive general equilibrium

The general equilibrium for this economy, illustrated in Figure 2, is characterized by the following conditions (see Appendix 6.2 for detailed calculations).

Fig. 2 General equilibrium of the model



• Firms in the final good sector determine the quantity of inputs (unskilled labor and intermediate goods) that maximize profits. This yields the following inverse demand functions:

$$w_t^u = \frac{\alpha Y_t}{l_t}, \qquad p_t = \frac{(1-\alpha) Y_t}{H_t}. \tag{15}$$

• Firms in the intermediate goods sector are symmetric within each segment (green and brown). Prices and quantities produced in equilibrium are given by Eqs. 4 and 5.

• Firms in the research sector enter the market by developing new green or brown products. All profit opportunities are exploited in equilibrium.

Skilled workers are indifferent between working in any intermediate firm i and in the research sector: $w_i^h = w^{h*} = w_r^h = w_r^{h*}$, leading to:

$$\frac{n^*}{n} = \left(\frac{\delta}{\delta *}\right)^{\frac{1}{\rho+\rho^*-1}}. \tag{16}$$

• Education decisions are such that all individuals with green motivation choose to become educated: $G_t = 1$, and workers with basic motivation are indifferent between becoming educated or not. The ratio $\frac{\omega_t^u}{\underline{\omega_t^h}}$ therefore satisfies the following condition:

$$\frac{\omega_t^u}{\underline{\omega_t^h}} = 1 \Leftrightarrow \frac{\varphi_t}{\underline{\varphi_t}} \frac{w_t^u}{w_t^h} = 1 - \xi. \tag{17}$$

• Equilibrium on the labor market implies equality between demand and supply in efficiency units, that is:

$$L_t^d = l_t = L_t^s = \varphi_t L_t = \varphi_t (1-s)(1-B_t), \tag{18a}$$
$$H_t^d = H_t + H_{rt} = H_t^s = \overline{\varphi_t} \overline{H_t} + \underline{\varphi_t} \underline{H_t} = \overline{\varphi_t} s + \underline{\varphi_t} (1-s) B_t. \tag{18b}$$

The number B_t of workers with basic motivation who chose to acquire education and supply labor as skilled workers is given by:

$$B_t = \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi) - \frac{\overline{\varphi_t}}{\underline{\varphi_t}} \frac{s}{1-s}}{\frac{(1-\alpha)^2}{\alpha}(1-\xi) + 1}. \tag{19}$$

The number of skilled workers employed in the green and brown research sectors is given by:

$$h_{rt} = \frac{H_{rt}}{1+\Delta}, \qquad h^*_{rt} = \frac{\Delta}{1+\Delta} H_{rt}, \tag{20a}$$

$$H_{rt} = H^d_t - H_t = \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi)}{\frac{(1-\alpha)^2}{\alpha}(1-\xi)+1}(\overline{\varphi_t} s + \underline{\varphi_t}(1-s)) - \frac{1-\alpha}{\alpha} r_t \frac{1+\Delta}{\delta^* \Delta^{\rho^*}}, \tag{20b}$$

with $\Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}}$.

• Individuals determine the level of consumption and savings that maximize their intertemporal utility

$$\max_{c_t} \quad U = \int_0^\infty u_t(c_t, e_t) \cdot exp^{-\beta t} d$$
subject to $c(t) + \dot{A}(t) = \Omega(t)L + r(t)A(t)$ and Eq. 3,

where $\Omega(t)$ is the household expected income, $\Omega(t) = \{\omega^u_t, \underline{\omega^h_t}, \overline{\omega^h_t}\}$, and $A(t)$ is the stock of assets (non human wealth) held at time t.

Solving this program leads to the following standard growth rate:

$$g_{ct} = \frac{\dot{c}_t}{c_t} = \frac{1}{\Psi}(r_t - \beta), \tag{21}$$

where $\Psi = 1 - \theta(1-\sigma) + \mu(1-\sigma)(\eta^* - \eta)$.

In steady state, N, n^*, n, c and Y all grow at the same rate g:

$$g = \frac{\delta^* \frac{\Delta^{\rho^*}}{1+\Delta} \Gamma \left[\overline{\varphi} s + \underline{\varphi}(1-s)\right] - \beta \frac{1-\alpha}{\alpha}}{1 + \Psi \frac{1-\alpha}{\alpha}}, \tag{22}$$

where: $\Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}}$, $\Gamma = \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi)}{1+\frac{(1-\alpha)^2}{\alpha}(1-\xi)}$, and $\Psi = 1-\theta(1-\sigma)+\mu(1-\sigma)(\eta^*-\eta)$.

The balanced growth path then is characterized by the following properties.

Proposition 1. Balanced growth path

Along the balanced growth path, the economy grows at a unique constant rate g^* defined by Eq. 22. This growth rate is increasing in:

- *the proportion of green motivated workers in the economy, s*
- *the efficiency rates of innovation δ and δ^**
- *and the relative share of green products in environmental quality, $\eta^* - \eta$.*

Proposition 1 tells us that growth is higher when the proportion of green workers is higher or when the efficiency of innovation is higher. This is basically because innovation is the engine of growth in this model. However, the efficiency of green innovation has a different impact on growth than the efficiency of brown innovation. In equilibrium also the equalization of the rate of accumulation in green and brown knowledge implies: $\frac{n^*}{n} = \left(\frac{\delta}{\delta^*}\right)^{\frac{1}{\rho+\rho^*-1}}$. The distribution of firms across green and brown segments hence depends on the productivity ratio between green and brown firms $\frac{\delta}{\delta^*}$ and on the externalities created by green and brown knowledge ρ and ρ^*.

Interestingly, the relative efficiency of green and brown technologies δ/δ^* also influences the demand for skilled labor h_r and h_r^*. If we compute the partial derivative of h_r and h_r^* with respect to δ/δ^* we get $\frac{\partial h_r}{\partial \delta/\delta^*} = -\frac{\partial h_r^*}{\partial \delta/\delta^*}$ and

$\frac{\partial h_r^*}{\partial \delta/\delta^*} \geq 0 \Leftrightarrow \rho + \rho^* - 1 \geq 0 \Leftrightarrow \rho^* \geq 1 - \rho$

Parameter ρ^* represents the elasticity of green new goods with respect to the number of green goods: $\rho^* = \frac{\partial \dot{n}^*/\partial n^*}{\dot{n}^*/n^*}$ (and symmetrically for brown goods: $\rho = \frac{\partial \dot{n}/\partial n}{\dot{n}/n}$). If we look at Eq. 6 and 7, $\rho^* \geq 1 - \rho$ means that the externality (benefit) of green goods on the invention of new green goods is higher than on the invention of new brown goods. In that case, h_r^* is increasing in δ/δ^* and h_r is decreasing in δ/δ^*.

The literature on green technology adoption identified that energy-saving technologies appearing cost-effective were under-utilized because of incomplete information on the returns to such innovations, as well as adoption externalities (Jaffe et al. (2005)). We can therefore consider that there is a disadvantage or an efficiency gap between green and brown firms such that $\delta > \delta^*$.

In turn, the fact that h_r^* is increasing in δ/δ^* implies that the demand for skilled labor in green R&D firms increases with the efficiency gap of green technologies compared to brown technologies δ/δ^* when $\rho^* \geq 1 - \rho$, that is when green technologies create more positive externalities for green goods than for brown goods. In other words, green firms are in a better position to attract more green-motivated talents when they generate positive innovation externalities. This is in line for instance with Muisyo and Qin (2021) who document that green human resource management needs green innovation culture to generate a positive impact.

Proposition 1 also states that growth is higher when the relative elasticity of green products in environmental quality is higher. These elasticity parameters measure the responsiveness of environmental quality e to a change in levels of either green or brown products in the quality of the environment, ceteris paribus. For example, if $\eta* = 0.45$, a 1% increase in green product usage would lead to approximately a 0.45% increase in environmental quality (and vice versa for brown products). We now turn to the analysis of inequality in this economy.

3 Green human capital and inequality

In this section, we examine how wage inequality evolves in reaction to shocks in the economy. Two inequality indexes can be defined: wage inequality within skilled workers, denoted by Σ^{within}, and wage inequality between skilled and unskilled workers, denoted by $\Sigma^{between}$. These indexes are given as follows (see Appendix 6.2 for detailed calculation):

$$\Sigma_t^{within} = \frac{\overline{\varphi_t}}{\underline{\varphi_t}} \frac{s}{1-s} \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi)+1}{\frac{(1-\alpha)^2}{\alpha}(1-\xi) - \frac{\overline{\varphi_t}}{\underline{\varphi_t}}\frac{s}{1-s}} \tag{23}$$

and

$$\Sigma_t^{between} = \frac{(1-\alpha)^2}{\alpha} \frac{1-s(1-\frac{\overline{\varphi_t}}{\underline{\varphi_t}})}{\frac{(1-\alpha)^2}{\alpha}(1-\xi)+s(1-\frac{\overline{\varphi_t}}{\underline{\varphi_t}})}. \tag{24}$$

We would like here to determine the type of relationship between educational attainment and inequality (and hence the capacity of green innovators to attract and retain green-motivated workers). Following a seminal work by Tinbergen (1974), important literature has developed on the existence of a race between education and technology in determining the wage structure, in particular in the US. Autor et al. (2020) and Goldin and Katz (2008) for instance document a non-linear relationship between inequality and the supply and demand for skills over the twentieth century in the US, with a secular growth in the demand for skilled workers induced by technology (skill-biased technical change) and a rapid, but variable, growth of the relative supply of more-educated workers, which may lead to periods of increasing and decreasing wage inequality depending on the relative magnitude of both. We analyze here whether such opposing forces might be at play between the demand and the supply of green human capital, thereby leading to a non-linear relationship between wage inequality and the supply and demand for green skills.

We then have the following propositions.

Proposition 2. Education costs and inequality

A shock increasing the cost of education (ξ) induces a decrease in the number of workers with basic motivation who choose to become educated B_t, and an increase in wage inequality both between groups $\Sigma_t^{between}$ and within skilled workers Σ_t^{within} .

Proof: Immediate from partial derivatives of Eqs. 19, 23 and 24 with respect to ξ.

The cost of education is borne by households during their work period (it is a time cost), it increases notably when firms reduce private expenses on workers' training. Proposition 2 states that when the cost of education increases (or the corporate training expenses decrease), this reduces the supply of potential efficiency units of skilled labor and the wage rate per efficiency unit of skilled labor, which reduces the number of workers with basic motivation who choose to become educated (discouragement effect due to lower productivity in acquiring education). This in turn increases wage inequality within groups due to a composition effect: the pool of skilled workers is more heterogeneous (with an increasing proportion of basic motivation workers) thereby increasing within-group inequality. The increase in the time cost of education also increases wage inequality between groups because the relative scarcity of skilled labor in the economy exerts upward pressure on its relative price.

Proposition 3. Green human capital and inequality

A shock increasing the proportion of green workers in the economy s induces a decrease in the number of workers with basic motivation who choose to become educated B_t; an increase in wage inequality between groups $\Sigma_t^{between}$ and a decrease in wage inequality within skilled workers Σ_t^{within}.

Proof: Immediate from partial derivatives of Eqs. 19, 23 and 24 with respect to s.

The proportion of green-motivated workers in the economy may increase following a rise in society's environmental awareness. Proposition 3 states that when this proportion increases, this decreases the number of workers with basic motivation who choose to become educated (supply effect) which increases wage inequality between groups (the quantity of skilled labor diminishes which increases its relative price compared to unskilled workers). On the contrary, the increase in the proportion of green workers in the economy reduces wage inequality within skilled workers because of a composition effect: the pool of skilled workers is more homogeneous (with a predominance of green-motivated skills) thereby reducing within-group inequality. The relationship between green motivation and wage inequality hence is non-linear when accounting for green motivation.

Proposition 4. Green motivation and inequality

A shock increasing the returns to green motivation $\overline{\varphi_t}/\underline{\varphi_t}$ induces a decline in the number of workers with basic motivation who choose to become educated B_t and an increase in wage inequality both between groups $\Sigma_t^{between}$ and within skilled workers Σ_t^{within} .

Proof: Immediate from partial derivatives of Eqs. 19, 23 and 24 with respect to $\overline{\varphi_t}/\underline{\varphi_t}$.

The returns to green motivation may increase when firms develop practices to attract and retain green workers, for instance through environmental management programs (see Lanfranchi and Pekovic (2014)). Proposition 4 states that when the return to green motivation increases, this reduces the number of workers with basic motivation who choose to become educated via a productivity effect. Firms find it profitable to save workers relatively less productive and increase their demand for the most productive workers. The supply of skilled labor by workers without green motivation adjusts downward. This effect is responsible for the increase in wage inequality between groups.
An increase in the returns to green motivation increases wage inequality within skilled workers via two channels: productivity and supply. A rise in the motivation ratio $\overline{\varphi}/\underline{\varphi}$ raises the productivity of green workers, with a positive impact on within-group wage inequality. But it also induces an indirect supply (shift) effect by reducing the number of workers with basic motivation who choose to become educated B. With a lower relative supply, the relative wage of green workers increases, which drives inequality within educated workers.

We now propose an empirical analysis of the main propositions derived from the model.

4 Empirical illustration

4.1 Data description

The data are obtained from MSCI ESG Ratings database. MSCI ESG Ratings aim to measure a company's management of financially relevant ESG (environment, social, and governance) risks and opportunities using a rules-based methodology to identify industry leaders and laggards according to their exposure to ESG risks and how well they manage those risks relative to peers. ESG risks and opportunities can vary by industry and company. The MSCI ESG Ratings model identifies the ESG risks or Key Issues, that are most material to a sector. The environmental key issues describe notably how a company manages its environmental risks with respect to climate change, biodiversity and raw materials sourcing, pollution and waste management, as well as the use of green technologies and renewable energy. The social dimension covers the management of risks related to health, safety, human capital development, product and consumer safety, or community relations. And the corporate governance pillar evaluates the exposure to risks of corporate governance fairness and accountability, transparency, or ethics among others.

The sample considered are companies belonging to the All Countries World Index Investable Market Index (MSCI ACWI IMI) capturing large and mid-cap representation across 23 Developed Markets and 24 Emerging Markets countries. With 2,935 constituents, the index covers approximately 85% of the global investable equity opportunity set across 11 sectors. We focus our analysis on the companies of the biggest countries by market weights in this index that is (see Appendix 6.3): US (63.6%), Japan (5.8%), UK (3.9%), Canada (3.2%), China (3%), France (2.6%), Switzerland (2.4%), Germany (2%), Australia (2.2%), Netherlands (1%), Sweden (1%), and other countries from the Europe, Middle East and Africa area (3.2%): Denmark, Italy, Spain, Israel, Belgium, Finland, Norway, Ireland, Austria, Portugal. We obtain a final sample of 2039 companies and our data are retrieved for the fiscal year 2022.

4.2 Variables and Methodology

From the MSCI database, we need three types of variables: inequality within and between skills, training and green jobs, and green motivation. Such variables are not measured as such, but we can compute some proxies to represent them.

Wage inequality between groups will be proxied by the CEO-to-employee pay ratio, which measures the ratio of the salary of a company's CEO to the median salary of the company's employees. On the other hand, wage inequality among skilled workers will be proxied by a human capital development score measuring the company's capacity to attract and retain skilled employees with the provision of benefits, development, and employee engagement. In the MSCI methodology, this score captures in particular the fact that companies that rely heavily on highly-skilled employees but show no evidence of such employee engagement score poorly on this key issue.

Regarding education and training, we use the company's expenditures on employee training and professional development programs.

To measure the green workforce, we use the number of employees at the company level multiplied by the portion of the company's revenues derived from lines of business that typically have a low level of carbon intensity.

Green motivation will be measured through the company's environmental pillar score which represents the firm's management of and exposure to key environmental risks and opportunities on the following dimensions: Carbon impact (emissions and footprint), Climate Change Vulnerability, Biodiversity and Land Use, Raw Material Sourcing, Water Stress, Toxic Emissions and Waste, Opportunities in Clean Tech, Green Building and Renewable Energy. Scores range from 10 (best) to 0 (worst).

We aggregate the information at the country level, scale the variables over the 0-10 interval and propose to analyze the main predictions of the model by representing graphically the correlation between inequality indexes and education and green motivation indexes. The corresponding graphs are the scatter plots represented in Figures 3 to 5 below.

4.3 Discussion and policy implication

From figures 3a and 3b, we can observe a negative correlation between training expenses and the index of inequality both between groups and within groups. If we consider that company-level training expenses are negatively related to individual education costs borne by workers, this negative correlation is in line with Proposition 2.

From figures 4a and 4b, we can observe a positive correlation between green workers and the index of inequality between groups and a negative correlation between green workers and the index of inequality within groups. This is partially consistent with proposition 3.

Finally, from figures 5a and 5b, we can observe a negative correlation between green motivation and the index of inequality between groups and a positive correlation between green motivation and the index of inequality within groups. This is partially consistent with proposition 4.

Fig. 3a Education cost and inequality between group

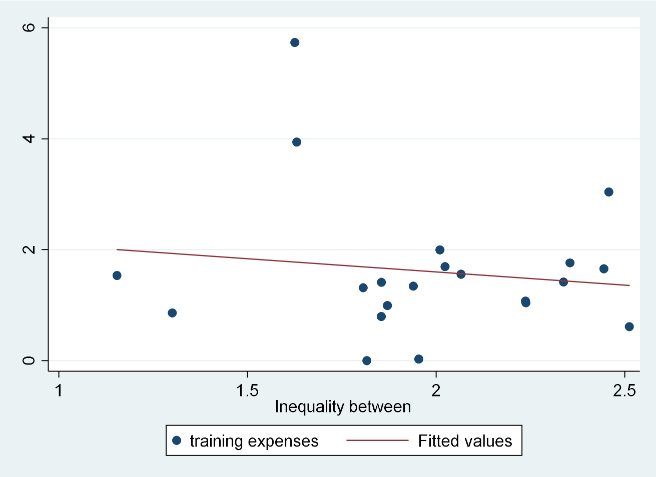


Fig. 3b Education cost and inequality within group

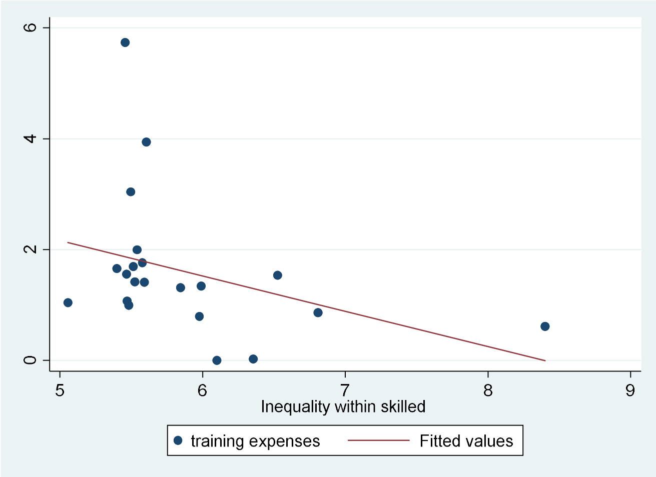


Fig. 4a Green human capital and inequality between group

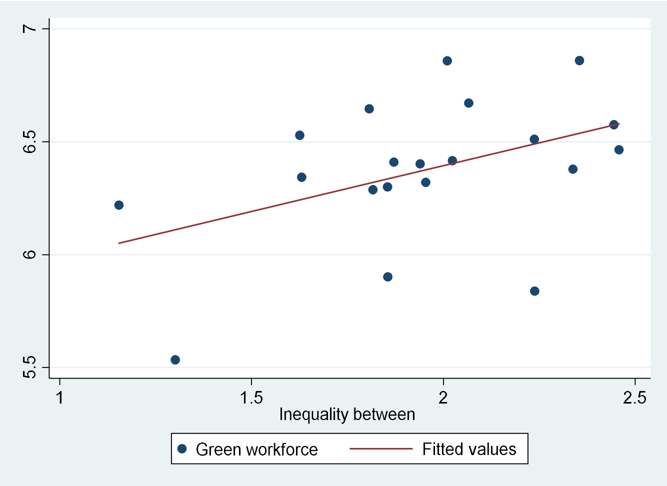


Fig. 4b Green human capital and inequality within group

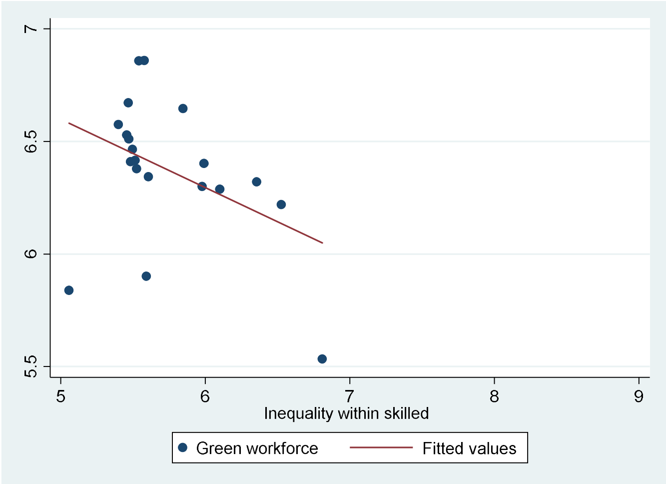


Fig. 5a Green motivation and inequality between group

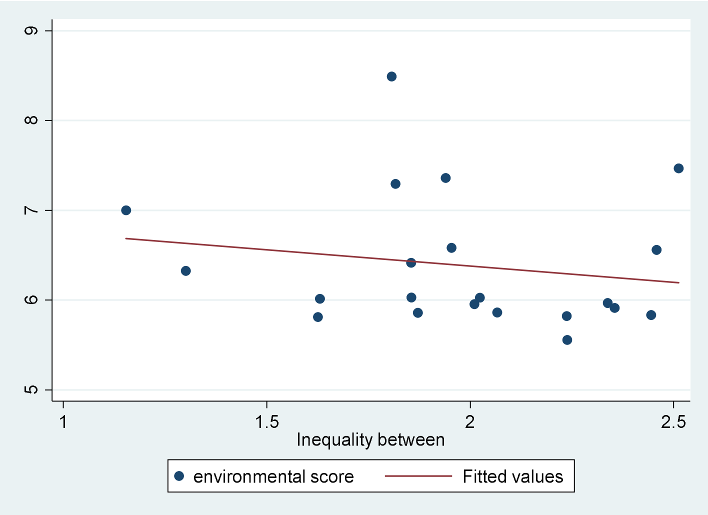
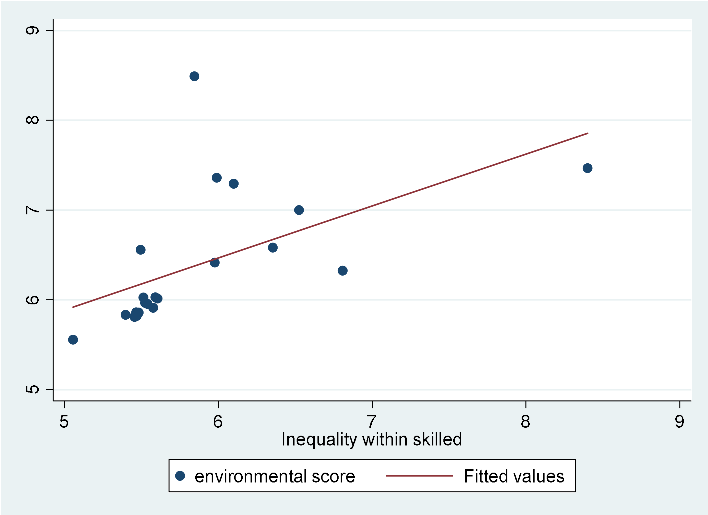


Fig. 5b Green motivation and inequality within group



Our empirical observations imply that on the one hand, inequality between groups decreases with corporate training expenses and green motivation (based on high corporate environmental score), and increases with the green workforce; and on the other hand, inequality within skilled workers decreases with corporate training expenses and the green workforce and increases with green motivation (based on high corporate environmental score).

In terms of policy implications, our observations suggest that environmental concerns are emerging as a new frontier for the social question and that the evolution of inequalities represents a real challenge for the greening of growth and the green recovery plans that have been adopted recently in most OECD countries. As this is the case with the recent recovery plans adopted at the European level (our data cover the year 2022), policies stimulating green innovation, by increasing the need for "green skilled labor", will create an upward pressure on the demand for green and skilled workers. If the supply of labor does not increase as well, this effect will translate into a mechanical pressure increasing wage inequality. Here we see that inequality between skilled and unskilled workers is higher, the higher the level of the green workforce, and inequality within skilled workers is higher the higher the corporate environmental performance. Interestingly we see that the higher the education expenses at the company level the lower the level of inequality both between and within skills. It is therefore interesting to note that to avoid these innovation policies being "absorbed" by an increase in wages, and simply resulting in an increase in inequalities, it is necessary to accompany them by training and education policies supported at the firm level. As green human capital incorporates an essential firm-specific, that is non-transferable component, corporate expenses are crucial to avoid increases in inequality.

This is all the more important as an unequal distribution of income may not intrinsically increase the demand for better environmental quality and a higher degree of inequality does not necessarily lead to higher financing of environmental protection (Baland (1999)). Indeed, the higher the income, the more the demand for the environment can be satisfied by private means, and the less need there is for recourse to public power. Added to this argument is the empirical fact that the poorest households suffer from poor environmental conditions due to the uneven distribution of environmental quality and their greater socio-economic vulnerability. These low-income households would therefore benefit more from ambitious environmental policies than the more privileged groups. Fighting income inequality through dedicated education policies may thus be a pre-requisite for the implementation of ambitious environmental policies.

5 Conclusion

This article analyzes the relationship between green human capital, innovation, and inequality in a model of endogenous growth. The model shows that innovation-driven growth is higher when the relative share of green products in environmental quality is higher and when the proportion of workers motivated by socially responsible tasks is higher. But such a growth process may create more inequality within skilled workers and between skilled and unskilled workers, depending on the variation in education or motivation cost or the supply of green human capital. The necessity of a 'just', that is fair, transition precisely emphasizes how to link these two dimensions over time: to overcome the climate risks linked to the energy transition by creating new economic opportunities while preserving social justice and limiting inequalities. This issue will be especially crucial to mitigate the socio-economic impact of the transition in regions and sectors that will be most affected because of their dependence on fossil fuels or energy-intensive industrial activities.

Author Declarations

1. Authors' contributions
   All authors contributed to the study conception and design. All authors read and approved the final manuscript.

2. Conflicts of interest/Competing interests
   The authors declare they have no competing interests.

3. Funding
   This work has received research support from IdR FDIR Sustainable finance and responsible investment 2019-2022.

4. Ethics Declaration statement
   Not applicable

5. Consent to Participate
   Not applicable

6. Consent for publication
   This study contains data agregated at the country level from the MSCI ESG database.

7. Data availability
   Data availability is subject to data user license from MSCI.

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6 Appendix

6.1 Model's variables and parameters

Symbol	Description	Value or price
Y	Final good	numeraire
l	unskilled labor	unskilled wage rate w^u
$x(i)$	intermediate good i	$p(i)$
α	output elasticity of unskilled labor	$\in]0,1[$
w^u	unskilled wage rate	
n (n^*)	number of brown (green) intermediate goods	$n + n^* = N$
π (π^*)	profit of a brown (green) intermediate firm	
w^h ($(w^h)^*$)	skilled wage rate in a brown (green) intermediate firm	
δ (δ^*)	efficiency of brown (green) technology	> 0
ρ (ρ^*)	brown (green) knowledge externalities	$\in]0,1]$
h_r (h_r^*)	skilled workers in brown (green) research	
H_r	skilled workers demand in research	$H_r = h_r + h_r^*$
H	skilled workers demand in intermediate goods sector	$H = h + h^*$
H^d	total skilled workers demand	$H^d = H + H_r$
V (V^*)	brown (green) patent price	
r, β	interest rate, discount rate	
Π_r (Π_r^*)	brown (green) profits in the research sector	null (free entry condition)
$w_{h,r}$ ($w_{h,r}^*$)	skilled wage rate in the brown (green) research sector	
s	share of green-motivated workers	$\in]0,1]$
G (B)	share of green (ordinary) workers acquiring skills	$\in]0,1[$
$\overline{H}$ ($\underline{H}$), L	number of skilled green (ordinary), unskilled workers	$\in [0,1]$
$\overline{\varphi}$ ($\underline{\varphi}$), φ	returns to human capital for skilled green (ordinary), unskilled workers	
H^s	total skilled workers supply	$H^s = \overline{\varphi}\overline{H} + \underline{\varphi}\underline{H}$
ξ	education cost	$\in]0,1[$
Ω	household expected income	$\Omega = \{\omega^u, \underline{\omega^h}, \overline{\omega^h}\}$
$\overline{\omega^h}$ ($\underline{\omega^h}$), ω^u	expected income of skilled green (ordinary), unskilled workers	
u	instantaneous household utility function	
c	per capita consumption	
e	environmental quality	
θ, μ	elasticity of utility with respect to c and e	
σ	elasticity of utility with respect to consumption growth	
η	elasticity of environmental quality with respect to n and n^*	
A	household asset (non human wealth)	
g	economy's growth rate	
Σ^h	average income of skilled workers	$(\overline{\varphi}\overline{H} + \underline{\varphi}\underline{H})w^h/(\overline{H} + \underline{H})$
Σ^u	average income of unskilled workers	φw^u
Σ^{within}	wage inequality within skilled workers	$\overline{\omega^h}\overline{H}/\underline{\omega^h}\underline{H}$
$\Sigma^{between}$	wage inequality between skilled and unskilled workers	Σ^h/Σ^u

6.2 Equilibrium and steady-state

We compute here the equilibrium of this economy.

6.2.1 Final-sector market

Each producer in the final sector determines the amount of skilled labor and intermediate goods to be used as inputs by maximizing profit under technological constraint, leading to the following inverse demand functions for unskilled labor and intermediate goods:

$$p(i) = (1-\alpha)\,(l)^{\alpha}\,(x(i))^{-\alpha}\,, \qquad w^{u} = \alpha\,(l)^{\alpha-1}\int_{0}^{N} x(i)^{1-\alpha}di, \tag{25}$$

where $p(i)$ denotes the price of intermediate good i and w^u is the wage rate of unskilled workers.

6.2.2 Equilibrium in the R&D sector

The value of the patent is such that researchers are indifferent between investing in a risk-free asset or buying a patent, producing an intermediate good for one period, and then selling the patent after a year that is from Eq. 10:

$rV = \pi + \dot{V}$ and $rV^* = \pi^* + \dot{V^*}$. Dividing by V and V^* we get:

$$r = \pi/V + \dot{V}/V \text{ and } r = \pi^*/V^* + \dot{V^*}/V^* \tag{26}$$

Along the equilibrium balanced growth path, r is constant, therefore on the right hand side of Eq. 26 π/V $\pi*/V*$, $\dot{V}/V$ and $\dot{V*}/V*$ must be constant. This implies that π, $\pi*$, V and $V*$grow at the same rate along the balanced growth path.

Note that in equilibrium, from Eqs. 4 , 5 and 29 we have $\pi^* = \pi = \alpha px = (\alpha(1-\alpha))Y/N$. Moreover, along the equilibrium balanced growth path, Y and N grow at the same rate, which implies that the growth rate of π and pi^* is null along the balanced growth path, as well as the growth rate of V and V^*). We thus have $\dot{V}/V = 0$ and $\dot{V^*}/V^* = 0$, that is:

$$rV = \pi \text{ and } rV^* = \pi^*. \tag{27}$$

From Eqs. 4 and 5 we have $\pi = \alpha px$ and $\pi^* = \alpha p^* x^*$ which leads to $rV = \alpha px$ and $rV^* = \alpha p^* x^*$

Using Eq. 9 we get $rV = rw_r^h/(\delta n^{\rho}(n*)^{1-\rho})$ and $rV^* = r(w_r^h)^*/(\delta * (n*)^{\rho} * (n)^{1-\rho^*})$. Rearranging a bit we finally have:

$$w_{h,r}^* = \frac{1}{r}\alpha\delta^*(n^*)^{\rho^*}(n)^{1-\rho^*}p^*x^* \text{ and } w_{h,r} = \frac{1}{r}\alpha\delta(n)^{\rho}(n^*)^{1-\rho}px. \tag{28}$$

6.2.3 Allocation of skilled workers between sectors

The condition which determines the allocation of skilled workers between sectors expresses that skilled workers must be indifferent between working in the research sector and in the intermediate goods sector.

The indifference condition for skilled workers between working in any intermediate firm i and between working in the intermediate goods sector and in the R&D sector implies the equality of wage rates across sectors:

$$w^h(i) = (w^h)^* = w^h = (w_r^h)^* = w_r^h \quad \text{for } i \in [0, N]. \tag{29}$$

Using Eq. 4, 5 and 28 this leads to:

$$\frac{1}{r}\alpha\delta^*(n^*)^{\rho^*}(n)^{1-\rho^*}p^*x^* = (1-\alpha)p^* = \frac{1}{r}\alpha\delta(n)^{\rho}(n^*)^{1-\rho}px = (1-\alpha)p, \tag{30}$$

that is after some simple manipulations:

$$\frac{n^*}{n} = \left(\frac{\delta}{\delta^*}\right)^{\frac{1}{\rho+\rho^*-1}}. \tag{31}$$

6.2.4 Education decisions

The population size is constant and normalized to one. Individuals choose to become skilled workers if the skilled income is higher than the unskilled one. Here, individuals with basic motivation then choose to become skilled workers as long as their expected income as skilled workers, $\underline{\omega_t^h}$, is higher than that of unskilled workers, ω_t^u. In equilibrium, this condition is binding, implying that the number of workers with ordinary ability who choose to become educated satisfies the following indifference condition: $\underline{\omega_t^h} = \omega_t^u$. Regarding individuals with green motivation, the assumption that $\overline{\varphi_t} > \underline{\varphi_t}$ (A1) implies that $\overline{\omega_t^h} > \underline{\omega_t^h}$.

Education decisions in turn satisfy the following rule: $\overline{\omega_t^h} > \underline{\omega_t^h} = \omega_t^u$ which implies that, all individuals with green motivation choose to become educated:

$$G_t = 1, \tag{32}$$

and on the other hand, workers with basic motivation are indifferent between becoming educated or not. The ratio $\frac{\omega_t^u}{\underline{\omega_t^h}}$ therefore satisfies the following condition:

$$\frac{\omega_t^u}{\underline{\omega_t^h}} = 1 \Leftrightarrow \frac{\varphi_t}{\underline{\varphi_t}} \frac{w_t^u}{w_t^h} = 1 - \xi. \tag{33}$$

Using the fact that $w_t^u = \frac{\alpha Y_t}{l_t}$ and $w_t^h = \frac{(1-\alpha)^2 Y_t}{1+H_t}$ and the equality between demand and supply of unskilled labor in efficiency units that is equalization between $L_t^d = l_t$ and $L_t^s = \varphi_t L_t$, from Eqs. 11 and 32, we therefore have $l_t = \varphi_t L_t = \varphi_t(1-s)(1-B_t)$. Thus:

$$\frac{w_t^h}{w_t^u} = \frac{(1-\alpha)^2}{\alpha} \frac{\varphi_t(1-s)(1-B_t)}{\overline{\varphi_t} s + \underline{\varphi_t}(1-s)B_t} \tag{34}$$

6.2.5 Equilibrium on the labor market

Total skilled labor demand writes $H^d = H + H_r$, where $H = h + h^*$ is the aggregate skilled labor demand in the intermediate goods sector and $H_r = h_r^* + h_r$ is the aggregate skilled labor demand in the research sector.

In the intermediate goods sector, the demand for skilled labor is such that one unit of skilled labor produces one unit of intermediate good. Hence, the demand for skilled labor in green-tech (resp. dirty-tech) firms is equal to x^* (resp. x). The aggregate skilled labor demand in the intermediate goods sector hence writes: $H = n^*x^* + nx$. Using Eqs. 4, 5, we have: $\frac{\alpha\delta}{r} n^\rho (n^*)^{1-\rho} = 1 - \alpha$. Using Eq. 31, we thus get: $h = nx = \frac{1-\alpha}{\alpha} \frac{r}{\delta} \Delta^{\rho-1}$, and similarly: $h^* = n^*x^* = \frac{1-\alpha}{\alpha} \frac{r}{\delta^*} \Delta^{1-\rho^*}$.

The aggregate skilled labor demand in the intermediate goods sector then write:

$$H = h^* + h = \frac{1-\alpha}{\alpha} r \left(\frac{\Delta^{\rho-1}}{\delta} + \frac{\Delta^{1-\rho^*}}{\delta^*} \right) = \frac{1-\alpha}{\alpha} r \frac{1+\Delta}{\delta^* \Delta^{\rho^*}}, \text{ with } \Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}} \tag{35}$$

In the research sector, the allocation of skilled workers between sectors leads to Eq. 31: $\frac{n^*}{n} = \left(\frac{\delta}{\delta^*}\right)^{\frac{1}{\rho+\rho^*-1}}$. Together with $N = n^* + n$, this equation implies the equalization of the rate of accumulation in green-tech and dirty-tech knowledge:

$$\frac{\dot{n}^*}{n^*} = \frac{\dot{n}}{n} = \frac{\dot{N}}{N}. \tag{36}$$

Substituting for (36) into Eqs. 6 and 7 leads to: $\frac{\delta h_r n^\rho (n^*)^{1-\rho}}{n} = \frac{\delta^* h_r^* (n^*)^{\rho^*} (n)^{1-\rho^*}}{n^*}$, implying $h_r = h_r^* \frac{n}{n^*} = \frac{h_r^*}{\Delta}$. Aggregate skilled labor demand in the research sector then writes $H_r = h_r^* + h_r = \frac{1+\Delta}{\Delta} h_r^*$, and we have:

$$h_r = \frac{H_r}{1+\Delta} \text{ and } h_r^* = \frac{\Delta}{1+\Delta} H_r, \text{ with } \Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}} . \tag{37}$$

Equilibrium on the labor market implies equality between demand and supply of skilled labor in efficiency units, that is between $H^d = H + H_r$ and $H^s = \overline{\varphi}\overline{H} + \underline{\varphi}\underline{H}$. Given Eq. 11 and 32 this implies $H^d = H + H_r = H^s = \overline{\varphi}s + \underline{\varphi}(1-s)B$. Using Eq. 19, we thus have:

$$H^d = \overline{\varphi}s + \underline{\varphi}(1-s) \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi) - \frac{\overline{\varphi}}{\underline{\varphi}} \frac{s}{1-s}}{\frac{(1-\alpha)^2}{\alpha}(1-\xi) + 1}. \tag{38}$$

Eq. 25 implies that $w^u = \frac{\alpha Y}{l}$.

Eq. 31 implies that $n^* = \Delta n$ and given that $N = n^* + n$, we thus have $n = \frac{N}{1+\Delta}$ where $\Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}}$.

Using Eqs. 4 and 5 we have $x = x^*$, $p = (1-\alpha) l^\alpha x^{-\alpha}$ and $Y = N l^\alpha x^{1-\alpha}$, thus: $Npx = (1-\alpha)Y$.

Eq. 9 together with Es. 27, 4 and 5 imply that $w^h = \frac{\alpha \delta^*}{r} npx \Delta^{\rho^*}$. Given that $n = \frac{N}{1+\Delta}$, we get: $w^h = \frac{\alpha\delta^*}{r} \frac{Npx}{1+\Delta} \Delta^{\rho^*}$ and therefore $w^h = \frac{\alpha\delta^*}{r} \frac{(1-\alpha)Y}{1+\Delta} \Delta^{\rho^*}$.

Substituting for $w^u = \frac{\alpha Y}{l}$ and $w^h = \frac{\alpha\delta^*}{r} \frac{(1-\alpha)Y}{1+\Delta} \Delta^{\rho^*}$ into $\frac{\varphi}{\underline{\varphi}} \frac{w^u}{w^h} = 1 - \xi$ finally leads to:

$$\frac{\varphi}{\underline{\varphi}} \frac{r}{\delta^*} \frac{1+\Delta}{\Delta^{\rho^*}} \frac{1}{(1-\alpha)l} = 1 - \xi$$

The number B_t of workers with basic motivation who choose to become educated is determined by Eq. 17, where the skill premium $\frac{w_t^h}{w_t^u}$ is obtained using $w_t^u = \frac{\alpha Y_t}{l_t}$ and $w_t^h = \frac{(1-\alpha)^2 Y_t}{H_t}$:

$$\frac{\varphi_t}{\underline{\varphi_t}} \frac{1}{1-\xi} = \frac{(1-\alpha)^2}{\alpha} \frac{\varphi(1-s)(1-B_t)}{\overline{\varphi_t}s + \underline{\varphi_t}(1-s)B_t} \Leftrightarrow B_t = \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi) - \frac{\overline{\varphi_t}}{\underline{\varphi_t}} \frac{s}{1-s}}{\frac{(1-\alpha)^2}{\alpha}(1-\xi) + 1}. \tag{39}$$

The number of skilled workers employed in the green and brown research sectors then is obtained using Eqs. 35, 37 and 38:

$$h_{rt} = \frac{H_{rt}}{1+\Delta}, \qquad h_{rt}^* = \frac{\Delta}{1+\Delta} H_{rt}, \tag{40a}$$

$$H_{rt} = H_t^d - H_t = \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi)}{\frac{(1-\alpha)^2}{\alpha}(1-\xi)+1}(\overline{\varphi_t} s + \underline{\varphi_t}(1-s)) - \frac{1-\alpha}{\alpha} r_t \frac{1+\Delta}{\delta^* \Delta^{\rho^*}}, \tag{40b}$$

with $\Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}}$.

6.2.6 Consumption decisions and steady state growth rate

Individuals determine the level of consumption and savings that maximize their intertemporal utility according to the following maximization problem

$$\max_{c_t} \quad U = \int_0^\infty u_t(c_t, e_t) \cdot exp^{-\beta t} d$$
subject to $c(t) + \dot{A(t)} = \Omega(t)L + r(t)A(t)$ and $e_t = [n_t]^{-\eta} [n_t^*]^{\eta^*}$

where $\Omega(t)$ is the household expected income , $\Omega(t) = \{\omega_t^u, \underline{\omega_t^h}, \overline{\omega_t^h}\}$, and $A(t)$ is the stock of assets (non human wealth) held at time t.

The first order condition of this program leads to the standard condition $r - \beta = -\frac{-du'/dt}{u'}$, that is

$$r = \beta - (\theta(1-\sigma) - 1)\frac{\cdot c}{c} + \mu(1-\sigma)\frac{\cdot e}{e} \tag{41}$$

After simple manipulations we get the following growth rate:

$$g_{ct} = \frac{\dot{c}_t}{c_t} = \frac{1}{\Psi}(r_t - \beta), \tag{42}$$

where $\Psi = 1 - \theta(1-\sigma) + \mu(1-\sigma)(\eta^* - \eta)$.

In steady state, N, n^*, n, C and Y all grow at the same rate $g = \frac{\dot{c}}{c} = \frac{\dot{N}}{N} = \frac{\dot{n^*}}{n^*} = \frac{\dot{n}}{n}$, that is:

$$g = \frac{\dot{c}}{c} = \frac{\dot{N}}{N} = \frac{\dot{n^*}}{n^*} = \frac{\dot{n}}{n} = \delta^* h_r^* \left(\frac{n}{n^*}\right)^{1-\rho^*} = \delta h_r \left(\frac{n^*}{n}\right)^{1-\rho}. \tag{43}$$

Using Eq. 31 and 40a, this gives:

$$g = \delta^* \frac{\Delta^{\rho^*}}{1+\Delta} H_r. \tag{44}$$

where $\Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}}$.

Combining Eqs. 40b, 41, 42 and 44 finally leads to the following steady-state growth rate:

$$g = \frac{\delta^* \frac{\Delta^{\rho^*}}{1+\Delta} \Gamma \left[\overline{\varphi} s + \underline{\varphi}(1-s) \right] - \beta \frac{1-\alpha}{\alpha}}{1 + \Psi \frac{1-\alpha}{\alpha}}, \tag{45}$$

where: $\Delta = (\delta/\delta^*)^{\frac{1}{\rho+\rho^*-1}}$, $\Gamma = \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi)}{1+\frac{(1-\alpha)^2}{\alpha}(1-\xi)}$, and $\Psi = 1 - \theta(1-\sigma) + \mu(1-\sigma)(\eta^* - \eta)$.

6.2.7 Wage inequality indexes

Two inequality indexes can be defined: wage inequality within skilled workers, denoted by Σ^{within}, and wage inequality between skilled and unskilled workers, denoted by $\Sigma^{between}$.

Within-group wage inequality is defined by: $\Sigma_t^{within} = \dfrac{\overline{\omega_t^h} \overline{H_t}}{\underline{\omega_t^h} \underline{H_t}}$.

Between-group inequality writes: $\Sigma_t^{between} = \dfrac{\Sigma_t^h}{\Sigma_t^u}$,

where Σ_t^h the average income of skilled workers is defined by the income (in efficiency units) of skilled workers, divided by the size of the skilled workforce: $\Sigma_t^h = \dfrac{\overline{\varphi_t} \overline{H_t} + \underline{\varphi_t} \underline{H_t}}{\overline{H_t} + \underline{H_t}} w_t^h$.

and where Σ_t^u, the average income of unskilled workers is given by: $\Sigma_t^u = \dfrac{\varphi_t L_t}{L_t} w_t^u = \varphi_t w_t^u$.

Using the resource constraints given by Eqs. 11 and 32 we get:

$\Sigma_t^{between} = \dfrac{\overline{\varphi_t} s + \underline{\varphi_t}(1-s) B_t}{s + (1-s) B_t} \dfrac{w_t^h}{\varphi_t w_t^u}$.

Using equilibrium conditions on the goods and labor markets Eqs. 15, 18a and 18b we obtain after some simple manipulations:

$\Sigma_t^{within} = \frac{\overline{\varphi_t}}{\underline{\varphi_t}} \frac{s}{1-s} \frac{1}{B_t}$

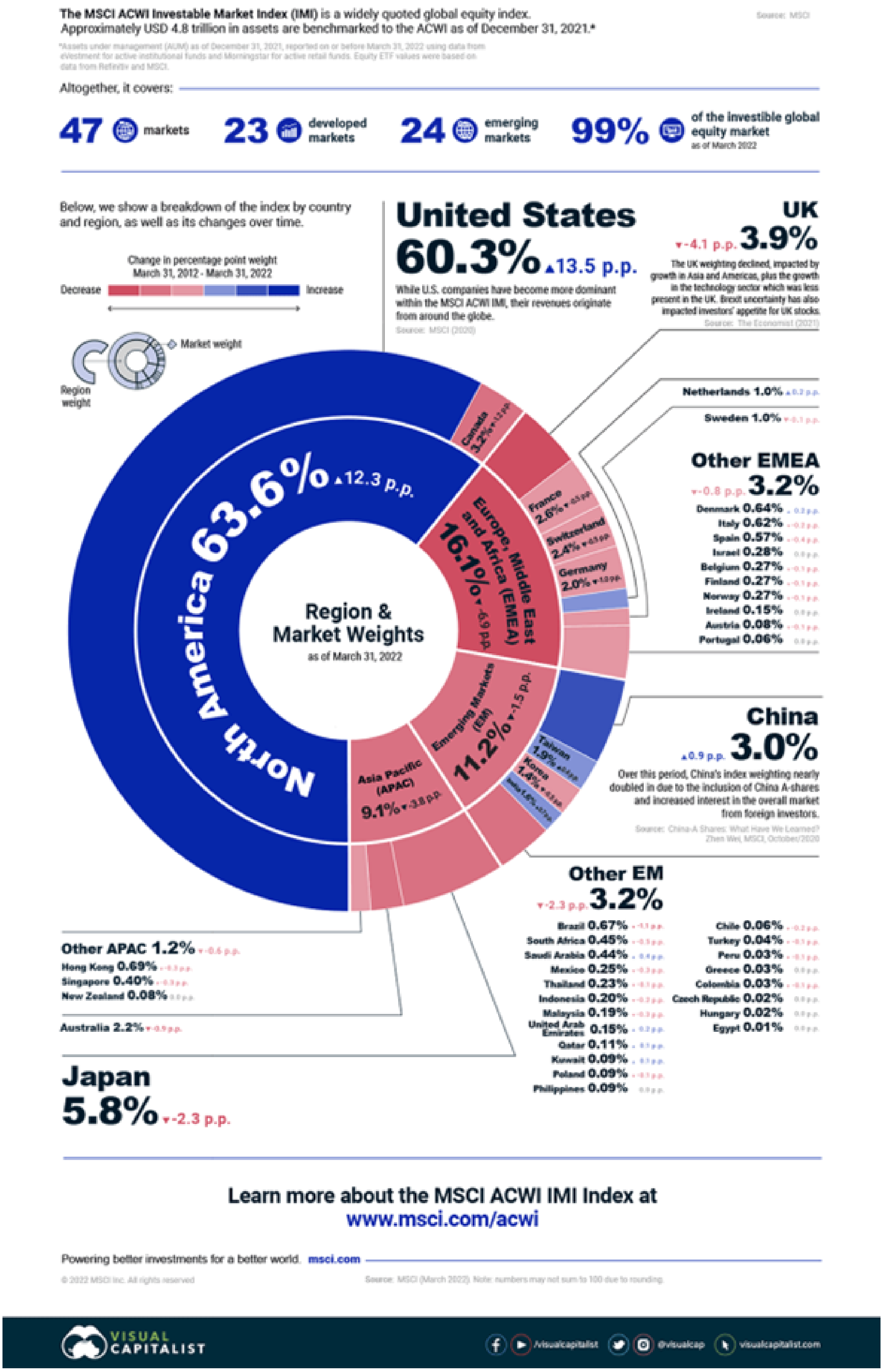
and $\Sigma_t^{between} = \frac{(1-\alpha)^2}{\alpha} \frac{(1-s)(1-B_t)}{s+(1-s)B_t}$. Substituting for Eq. 19, we finally get:

$$\Sigma_t^{within} = \frac{\overline{\varphi_t}}{\underline{\varphi_t}} \frac{s}{1-s} \frac{\frac{(1-\alpha)^2}{\alpha}(1-\xi)+1}{\frac{(1-\alpha)^2}{\alpha}(1-\xi) - \frac{\overline{\varphi_t}}{\underline{\varphi_t}} \frac{s}{1-s}} \tag{46}$$

and

$$\Sigma_t^{between} = \frac{(1-\alpha)^2}{\alpha} \frac{1-s(1-\frac{\overline{\varphi_t}}{\underline{\varphi_t}})}{\frac{(1-\alpha)^2}{\alpha}(1-\xi)+s(1-\frac{\overline{\varphi_t}}{\underline{\varphi_t}})}. \tag{47}$$

6.3 MSCI ACWI index



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