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The impact of energy sector pollution on human development and inequality amidst climate change

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Abstract

The provision of energy is a primary contributor to climate change and environmental pollution, the latter including air pollution from aerosol emissions and a broad range of other human health effects and ecosystem damages. At the same time, aerosol emissions also reduce radiative forcing, leading to a masking of part of the warming due to rising CO_2 concentrations and temporarily reducing the adverse impacts of climate change. Using an energy-economy-climate model linked to atmospheric chemistry, health impact and life cycle assessment models, we show that the societal costs of the health impacts of environmental pollution substantially exceed the economic benefits from masked warming. We further highlight the unequal burden of these issues on developing countries and explore the implications for human development, global inequality and international climate policy.

1. Introduction

Six-hundred and fifty million people are still living below the absolute poverty threshold of 1.90 dollars per day (Bank 2023). The debate over the historic root causes of global inequality ranges from theories of modernization, which link wealth disparities to industrialization practices (McClelland 1967, Rostow 1990), to dependency and world-systems theories that highlight historical exploitation and economic hierarchies (Wallerstein 1974, Packenham 1992), and Postcolonial and Marxist theories (Marx 1867, Angeles 2007). Whatever the historic cause, the majority of total inequality is still accounted for by disparities between countries rather than within them (Sala-i Martin 2002, Milanovic *et al* 2010), a pattern that persists from the preindustrial age through to the present day.

This inter-country disparity not only hinders progress but also poses significant challenges to the sustainable development goals (SDGs)—a set of 17 interconnected global objectives established by the United Nations, which serve as a blueprint for peace and prosperity for people and the planet, now and into the future. The SDGs aim to address global challenges including poverty, inequality, climate change, environmental degradation, and justice (UN General Assembly 2015).

Addressing global inequality is at the heart of SDG 10, which is dedicated to reducing inequality within and among countries. This goal emphasizes the need for inclusive social, economic, and political policies that ensure equal opportunities and reduce disparities, particularly those that affect the poor and marginalized. SDG 10's commitment to equality is fundamental and intersects with other critical goals such as ending poverty (SDG 1), achieving zero hunger (SDG 2), promoting good health and well-being (SDG 3), ensuring quality education (SDG 4), and fostering decent work and economic growth (SDG 8). Therefore, tackling these disparities is essential for fostering inclusive growth and empowering individuals and communities to overcome the structural challenges that perpetuate poverty and hinder equitable development.

Climate change further complicates achieving the SDGs and amplify inequality by disproportionately affecting poorer countries (Mendelsohn *et al* 2006, Bathiany *et al* 2018). These nations, hindered by low levels of development and high degrees of poverty, have limited adaptive capacity (Hallegatte *et al* 2018), making them particularly susceptible to the adverse impacts of climate change. They also encounter substantial obstacles when attempting to implement climate change mitigation strategies in accordance with international agreements like the Paris Agreement. Such efforts are further hindered by their vulnerability to rising energy and food prices as a consequence of climate change mitigation (Taconet *et al* 2020, Soergel *et al* 2021a).

The energy sector plays a pivotal role. On the one hand, it serves as a critical enabler for achieving a wide range of objectives aimed at reducing global inequality and fostering human development (McCollum *et al* 2018, Santika *et al* 2019). Access to sustainable energy is key to achieving SDGs 1, 2, 3, 4, and 8, addressing poverty, hunger, health, education, and economic growth, while SDG 7's focus on modern energy for all is essential in narrowing global inequality. SDG 10 targets reducing inequalities exacerbated by energy disparities, and SDG 13 emphasizes the critical role of climate action in fostering equitable development.

On the other hand it is a key contributor to climate change[1] and non-greenhouse gas pollution, including air, water, and soil contamination, which significantly affects human health and carries substantial social costs (Shindell 2015, Rauner *et al* 2020). Air pollution, for example, is a leading cause of death in low- and middle-income countries (Lelieveld *et al* 2020). This burden falls disproportionately on marginalized and low income communities, who are more likely to live in pollution-prone areas due to industrial activity and inadequate housing (Bell *et al* 2013, Jbaily *et al* 2022, Rentschler and Leonova 2023)[2]. Nevertheless, the impact of non-GHG pollution[3] on global inequality remains poorly understood, with only isolated beneficial effects of short-term climate change masking[4] of air pollution currently assessed (Zheng *et al* 2020).

This paper seeks to bridge the knowledge gap of how energy related pollution affects global inequality by providing an analysis of the effects of economic and social costs of energy-related environmental pollution. We examine the impact on income, labor productivity, and human health, as well as the counter-intuitive short-term economic benefits of air pollution-induced cooling, which can temporarily mask the growth-inhibiting effects of climate change in some regions. By aggregating these findings, we offer an overall assessment of the impact on human development, highlighting the complex interplay between environmental pollution, inequality, and the pursuit of sustainable progress.

2. Methods

Global inequality can be estimated by differences in proxies for long and healthy lives, education, and economic development. We use the human development index (HDI) develop by the United Nations as our metric of choice because it encapsulates these critical aspects of well-being and development. The HDI provides a composite measure that reflects the average achievements in a country in these key areas, offering a broader perspective on human progress than income alone.

The energy system modeling is based on the REMIND (REgional Model of Investments and Development) integrated assessment modeling system, as it describes the nexus between the energy sector, the economy and climate. The results from REMIND are then fed into the impact modeling (Baumstark *et al* 2021). The impact modeling comprises air pollution and Life Cycle Assessment-based models, which calculate the economic and public health effects. The economic effects are modeled through direct costs and social costs, as well as the cooling effects of air pollution. Public health impacts are aggregated based on their life expectancy reduction effects. Education is not directly modeled, although evidence suggests impacts of environmental pollution on cognitive abilities (The Lancet Neurology 2018, Zhang *et al* 2018). We then aggregate these impacts to the HDI as a comprehensive measure of human development. The comparison of different countries allows drawing conclusion on the effect of energy related environmental pollution on global inequality. See figure 1 for a schematic of the modeling framework and section SI 1.1 in the Supporting Information for an extended description of the methods and a discussion of uncertainties.

2.1. Energy-economy-climate modeling

The REMIND model employs a hybrid modeling approach that integrates macroeconomic drivers,

[1] The understanding of how GHG-induced climate change influences inequality is evolving, and there is a growing discourse on how climate mitigation policies can be effectively employed to counteract these disparities (Soergel *et al* 2021a).

[2] Contributing factors include lenient air quality regulations, outdated and polluting machinery, fossil fuel subsidies, congested urban transport, rapidly industrializing sectors, and agricultural burning practices (McDuffie *et al* 2021).

[3] E.g. water contamination from the discharge of toxic chemicals and heavy metals, such as mercury and lead, into water bodies from mining operations for fossil fuels and materials. Soil contamination from accidental oil spills and leakage of hazardous waste can lead to the accumulation of pollutants in food crops, affecting food safety and public health.

[4] Masking in climate science refers to the temporary cooling effect caused by certain air pollutants, such as aerosols, which can obscure the full warming impact of long-lasting greenhouse gases.

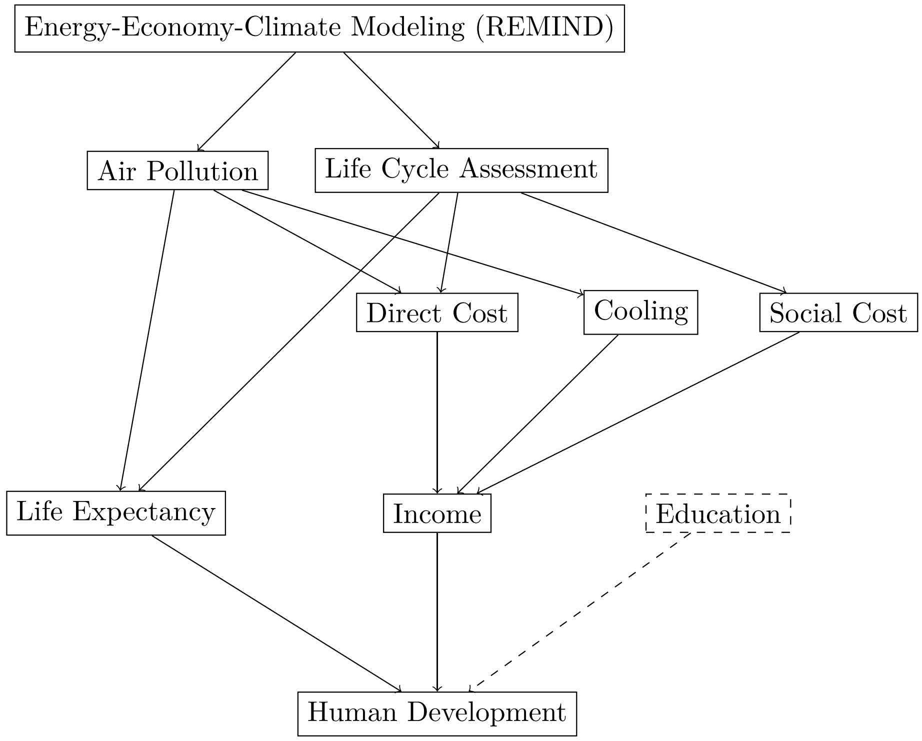


Figure 1. Schematic of the interaction between models and their cumulative impact on Human Development.

including growth, investment, and energy demand, across 12 global regions with a detailed representation of energy technologies (Baumstark *et al* 2021). This approach allows for a comprehensive analysis of the energy sector, capturing the intricacies of both supply sectors and demand sectors—such as mobility, industry, and buildings—each with their specific technological and economic characteristics. A pivotal feature of REMIND is its capacity to dis-aggregate climate emissions by region and sector, providing a detailed view of greenhouse gas sources and their distribution. Moreover, REMIND provides detailed modeling of air pollution emissions, which are of paramount concern due to their profound impact on human health and the associated social costs.

2.2. Life expectancy

The effects on human health and the environment, excluding climate impacts, are analyzed with two models:

(1) The source of air pollutant emissions, which have the largest impact on local health, are recorded in REMIND (Rauner *et al* 2019), and the resulting health effects are calculated using an atmospheric chemistry model and non-linear, disease-specific epidemiological response functions (Burnett *et al* 2018).
(2) Other health impacts and ecosystem damage are evaluated based on a life-cycle assessment of all regional energy systems, utilizing the ReCiPe methodology (see section SI 1.2 in the Supporting Information for an extended description of this method) (Goedkoop *et al* 2009). It is essential to consider the entire life cycle because the shift towards renewable energy sources changes the impacts from direct emissions, such as burning fossil fuels, to indirect emissions, such as the construction of energy infrastructure or land-use for bioenergy. Here, we include impacts of pollution on life expectancy by human toxicity, water pollution, ozone depletion, and ionizing radiation impacts associated with the direct and upstream emissions of the whole life cycle of the energy system.

2.3. Income

The effects on income in our study are evaluated through three distinct cause-effect chains: (1) the impact of aerosol-induced cooling on economic growth, (2) the impact of air pollution on direct and indirect (social) costs, and (3) the direct and indirect costs associated with other environmental pollutants, such as those affecting water and soil. The impacts of air pollution-induced cooling on economic growth are analyzed by Zheng *et al* (2020), with updated data from Burke and Tanutama (2019) (see section SI 1.4 in the Supporting Information for an extended description of this method). Aerosol cooling, which partially masks the temperature increase due to climate change, can reduce the loss in economic growth attributable to climate change for most countries. This phenomenon is considered a benefit when compared to a counterfactual scenario featuring warming without aerosol cooling. In our analysis, direct and indirect health costs are derived from two primary cause-effect chains: the health impacts of air pollution (see section SI 1.3 in the Supporting Information for an extended description) and the broader environmental impacts (such as water and land pollution) assessed through life cycle assessment modeling (see section SI 1.1 in the Supporting Information for an extended description). These impacts are quantified using the disability adjusted life years (DALY) metric, which combines years of life lost due to premature mortality and years lived with disability, adjusting for the severity of the disability. We monetize these health-related costs, including treatment costs and productivity loss, see OECD (2016), as well as the broader social costs associated with premature death and disability, using GDP per capita as a valuation basis. However, it is important to note that our current framework does not account for the feedback effects from environmental and health damages—such as workforce loss and health expenditures—on GDP.

2.4. Human development

We measure the effect of energy-related environmental pollution and aerosol induced cooling on Human Health as their effect on the HDI.

The HDI, developed by the United Nations Development Programme (UNDP), serves as a composite metric that assesses key dimensions of human development: life expectancy, education, and income per capita (Programme 2022). The HDI is widely used as a standard means of measuring well-being, especially child welfare, and it is a standard means of assessing the impact of economic policies on quality of life.

The HDI is comprised of the geometric mean of normalized indices for life expectancy, education, and income:

$$\mathrm{HDI} = \left(I_{\text{life expectancy}} \times I_{\text{education}} \times I_{\text{income}}\right)^{\frac{1}{3}} \quad (1)$$

where $I_{\text{life expectancy}}$, $I_{\text{education}}$, and I_{income} are the indices for life expectancy, education, and income, respectively, normalized to a scale from 0 to 1.

3. Results

Figure 2 shows the relationship between energy-related environmental pollution and human development in 2015. The data presents the impact of environmental pollution of the energy sector via the following three factors: (a) gross domestic product purchasing power parity (GDP_PPP[5] $2005), (b) life expectancy, and (c) the resulting effect on human development measured by the HDI. The countries are arranged (a) in descending order according to the cumulative impact on GDP, with the width of each bar representing the corresponding share of global GDP, (b) and (c) in descending order according to the life expectancy, with the width of each bar representing the corresponding share of global population. The countries are grouped according to their GDP per capita in 2010.

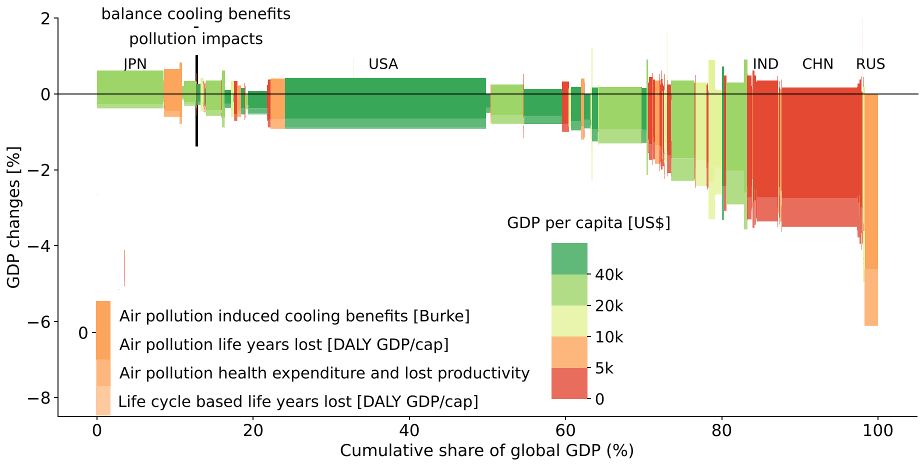
Figure 2(a) shows the economic impacts of energy-related environmental pollution relative to GDP_PPP on a country level in 2015. The figure highlights that only a few countries such as Japan have a net positive impact due to the air pollution cooling effect outweighing the negative impact. The majority of countries face a higher burden than benefits due to energy-related environmental pollution. For most countries, air pollution dominates the impacts, however, the up-stream pollution impacts are constituting a relevant share for countries such as New Zealand (26% of impact), Australia (13%) as well as the USA (6%).

Furthermore, the figure shows that low-income countries with a GDP per capita below $5000 face two and a halve times the impact (2.5% of GDP) compared to countries with a GDP per capita above $200 00. Among the worst affected areas are Russia (8% of GDP) and Hungary (6.5%) as well as sub-Saharan countries such as Chad (5%) and Burkina Faso (5%), but also China and India (4.5%, 4%), where air pollution has led to a public health crisis with around 5 million premature deaths (Rauner *et al* 2020).

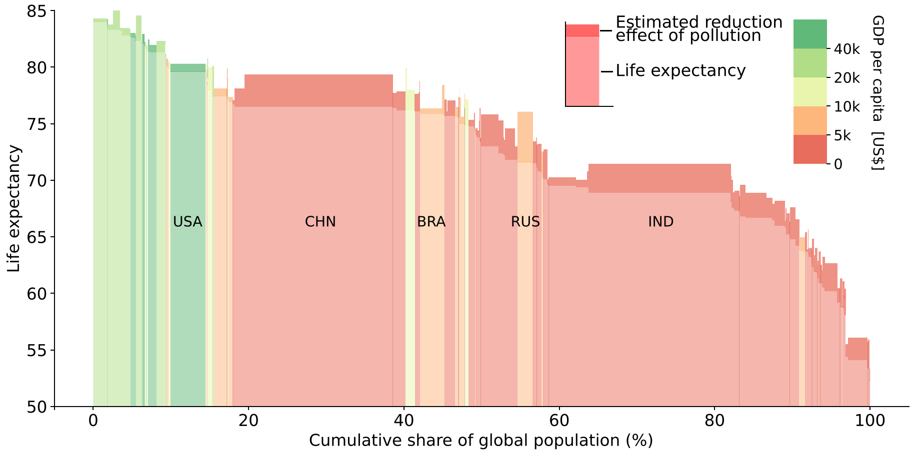
Figure 2(b) illustrates the estimated reduction of life expectancy caused by environmental pollution of the energy sector. The data shows that low-income countries with a GDP/capita below 100 00 $ have a lower life expectancy with a mean of 69 years and face the highest reduction of 1.5 years. On the other hand, countries with a higher GDP/capita above 200 00 $have a longer average life expectancy of 79 years and face a lower reduction of 0.8 years. Furthermore, China and India are among the countries facing the highest impact with reductions of 2.8 years and 2.5 years, respectively.

Figure 2(c) shows the combined effect of environmental pollution of the energy sector on human development measured by the HDI. The results indicate that the impacts of pollution on human development outweigh the benefits for all countries, regardless of their income level. Countries with a low HDI face the highest impacts. Furthermore, low-income countries with a GDP/capita below 5000 $ face trice the mean reduction of 1.5% compared to countries with a GDP/capita above 20k $. This suggests that energy-related environmental pollution has a substantial impact on the development of countries, particularly those with lower levels of economic and social development.

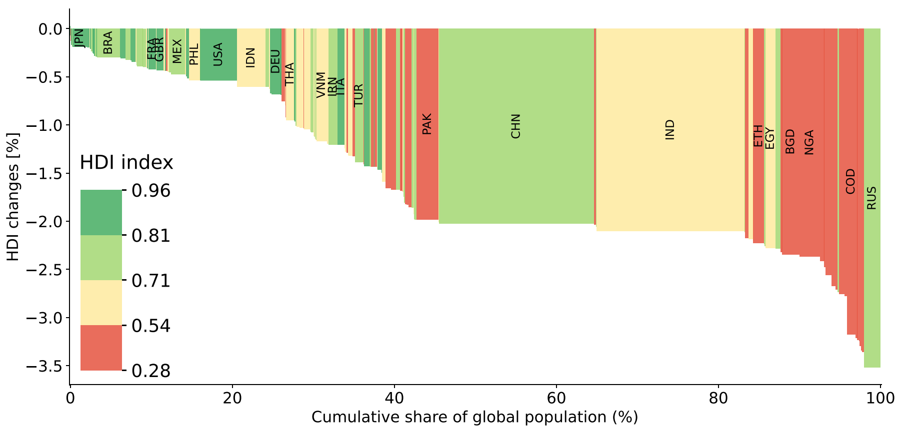
[5] Purchasing Power Parity is a method used to calculate an alternative exchange rate between the currencies of two countries that allows the same quantity of goods and services to be purchased in both countries.



(a)



(b)



(c)

Figure 2. Effect of environmental pollution of the energy sector in 2015. (a) Economic impacts of environmental pollution relative to gross domestic product expressed purchasing power parity, including potential benefits of reduced climate damages due to aerosol induced cooling and adverse impacts on human health. Human health effect are comprised of air pollution and other life cycle assessment based health impacts. Selection of countries with a high share of global GDP and or impact are labeled. (b) Estimated life expectancy reduction due environmental pollution of the energy sector. Selection of countries with a high share of global population. (c) HDI effect which is composed of the damage to income and the reduction of the life expectancy. Countries with a higher share of global population higher than 0.8% are labeled.

4. Discussion and conclusion

Our study confirms previous analysis that show the relationship between air pollution and income equality (Madhusoodanan 2023, Rentschler and Leonova 2023), a challenge that directly impacts the achievement of SDGs related to poverty (SDG 1), health (SDG 3), and economic growth (SDG 8). The relationship between energy-related environmental pollution and human development in 2015 demonstrates that air pollution has a significant negative impact on both economic output and life expectancy. Countries with lower GDP per capita face disproportionately higher economic impacts, with some nations experiencing losses up to 8% of their GDP.

Life expectancy reductions due to pollution are more severe in lower-income countries, averaging a 1.5 year decrease, while higher-income countries see a smaller reduction. We expand upon the previous findings by relating them to human development. We find that the overall effect on human development, as measured by the HDI, indicates that the adverse impacts of pollution outweigh any cooling-related benefits across all income levels, with the most substantial effects felt by countries with lower levels of economic and social development. This suggests that environmental pollution from the energy sector is a major obstacle to human development, particularly in less affluent nations.

Our analysis, which is comprehensive though not exhaustive, suggest that among the various impact factors considered, the health repercussions of air pollution emerge as the most consequential on human development, as assessed by the HDI. This adverse effect is particularly severe in low-income countries, where the repercussions include more pronounced reductions in life expectancy and disproportionately larger economic losses relative to their GDP exacerbating global inequality. The study further notes that while the temporary cooling effect of aerosols may conceal the warming impacts of climate change and could offer short-term economic gains for some regions, the overall toll of pollution is substantially higher, often by an order of magnitude, for most low-income countries.

While this study provides valuable insights into the disproportionate impact of energy-related environmental pollution on global human development and inequality, there are limitations that should be addressed by future research. In this paper, we have modeled the HDI as a proxy for human development to assess global inequality. However, it is important to recognize that real-world adaptation to environmental pollution might differ from our model assumptions. We have focused on the economic and life expectancy effects of pollution, while disregarding other critical factors such as education and mental health. These omissions are significant, as education contributes to human capital, and mental health is crucial for individual well-being. Moreover, our modeling of economic and life expectancy impacts is far from complete; for instance, migration pressure and the resulting brain drain can have economic effects, just to name one additional example. Finally, our analysis emphasizes measurable outcomes while acknowledging that there are additional emerging risks not addressed herein. For instance, research suggests a link between environmental pollution exposure and cognitive function impairment (Zhang *et al* 2018). However, incorporating the modeling of such impacts on education falls outside the purview of this study. Future research should aim to incorporate these additional dimensions to provide a more comprehensive understanding of the impacts of environmental pollution on human development and global inequality. Additionally, we focus on between-country inequality and do not consider the effects of pollution on within-country inequality, which is necessary for a complete picture.

Despite these limitations, the results suggest that given the global efforts required to mitigate climate change, support for developing regions is essential not only for mitigation but also adaptation, and recent studies have shown that technological and financial transfers are key components for climate change mitigation and adaptation and sustainable development (Wood 2011, Tavoni *et al* 2014, Bauer *et al* 2020, Soergel *et al* 2021b). Since climate mitigation efforts are generally associated with less environmental pollution over their life time, they could contribute to reducing the negative effect on global inequality. Here, future research should quantify these benefits and explore policies that jointly tackle climate change, environmental pollution and inequality. For example international transfer schemes, where richer counties (co)finance environmental protection policies, (Carraro *et al* 2006, Chancel 2021), or supply-chain laws, transferring responsibility of pollution to producers, could play a substantial role in reducing global inequality.

Furthermore, although human development measures can be enhanced through climate mitigation efforts aimed at achieving a cleaner air and environment, it is crucial to implement additional measures to address the remaining environmental burdens. Policies should be aligned to maximize co-benefits and avoid challenges, and practical measures aimed at reducing energy-related environmental pollution in developing regions should be implemented. Examples of such measures include the expansion of renewable energy sources to reduce reliance on fossil fuels, the implementation of stricter emissions standards for industries and vehicles, investment in public transportation to decrease the number of cars on the road, and the promotion of energy efficiency in buildings and appliances. Additionally, reforestation and conservation efforts can improve air quality. Education and awareness campaigns can also play a significant role in changing behaviors and promoting practices that are more environmentally friendly. Finally, technological and financial transfers and pollution control measures aimed at reducing end-of-pipe emissions in developing regions should all be considered as potential solutions to this pressing global problem.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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