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Characterizing the role of built environment stocks in human development and emission growth

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ABSTRACT

The built environment stocks such as buildings and infrastructures are key to human development: they provide the fundamental physical settings that the provision of basic human needs such as food, shelter, and transport rely on, but also contribute to anthropogenic greenhouse gas (GHG) emissions throughout their construction, operation, and end-of-life management phases. These stocks usually exist in societies for relatively long time, from years to over a century, therefore their dynamics have long term impacts on human development and emission growth. Several recent studies, including the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), have discussed the lock-in effects of infrastructure stocks on emission pathways. However, there is still a lack of quantitative analysis and evidence to support this claim. Here, based on an empirical regression model and a new dataset that determines built environment stocks, we affirm the effect of built environment stock variable on CO_2 emission by proving that considering built environment stock variable can eliminate the asymmetric effect of GDP per capita growth and decline on CO_2 emission. These results quantitatively underline the role of built environment stocks in human development, future emission pathways, and relevant climate policy.

1. Introduction

The built environment stocks, such as durable goods, buildings, and infrastructures, are key to human development (Müller et al., 2013). They provide the fundamental physical settings that the provision of basic human needs such as food, shelter, and transport rely on and thus reflect the development level of a society (e.g., urbanization and industrialization). These stocks also link the services enjoyed by humans to industrial material production and energy use in the societal metabolism (Pauliuk and Müller, 2014).

In economics, these stocks in industrial sectors are referred as fixed capital (monetary units) or fixed assets (physical units). Fixed capital accumulation is a main source of economic growth. The investment on infrastructure not only can lead to an increase in effective demand in the short-term, but also supports the economic growth in the long run. Therefore, it was considered as an important development strategy for many developing economies (Démurger, 2001).

These built environment stocks, however, normally exist in societies for relatively long time, from years to decades to over a century, and cause greenhouse gas (GHG) emissions throughout the main phases of their life cycle from construction, use/operation, to end-of-life management. For example, Liu and colleagues demonstrated in a case study for the aluminium industry that in-use stock patterns set essential boundary conditions for future emission pathways and have significant implications for mitigation priority setting (Liu et al., 2013). They also found that a globalization of Western infrastructure stocks using current technologies would cause approximately 350 Gt CO_2 from materials production, which corresponds to about 35–60% of the remaining carbon budget available until 2050 if the average temperature increase is to be limited to 2 °C (Müller et al., 2013). The recently released Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has highlighted such lock-in effect of infrastructure and built environment stocks on energy and emission pathways (IPCC, 2014).

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This assertion appears built upon earlier concepts such as "infrastructural momentum" (York, 2008), a process where material infrastructure entailed by urbanization and industrialization does not go away immediately and continue to drive emissions when the economic development is reversed. Davis and colleagues called this phenomenon "infrastructure inertia" and have quantified the significant amount of committed future GHG emissions of existing energy infrastructure (Davis et al., 2010; Davis and Socolow, 2014). The inertia characteristics of built environment stocks are also in agreement with the observations in economic recession time, for example, the change of CO_2 emissions did not correspond with the post-Soviet deindustrialization (York, 2008) or post-2008 global financial crisis (Peters et al., 2011).

In a recent study, York (York, 2012) has used the nation-year panel data and identified an asymmetric effect of GDP per capita growth and decline on CO_2 emission. In other words, in years where GDP per capita shrinks, CO_2 emissions per capita do not decline in equal proportion to the amount by which they increase with economic growth. His postulate, similarly as the abovementioned studies, is that durable goods and infrastructure are not removed by economic decline and continue to contribute to CO_2 emission even after growth is curtailed. However, there is still a lack of quantitative analysis and evidence to analyze the relation between built environment stocks and GHG emissions.

In this paper, we aim to characterize the role of built environment stocks in human development and emission growth based on empirical datasets covering all the world countries and the past several decades. We developed an empirical regression model to quantitatively investigate, for the first time to our own knowledge, the relation between built environment stocks and emission growth, particularly to answer if considering built environment stock variable can eliminate the asymmetric effect identified earlier by York (York, 2012).

2. Materials and method

2.1. Data

Due to the lack of bottom-up cross-national built environment stock data, we approximated them by aggregating the stock of three key infrastructural materials (cement, aluminium, and steel). We calculated the stocks for these materials using a top-down approach based on country-specific historical data for production, international trade of the materials along the entire supply chains, and assumptions about the lifetime distribution of the main product categories (such as buildings and construction, transportation, machinery and equipment, and packaging).

Details on the system definition, model approaches, and primary data used for stock estimation can be found in our previous studies (Liu and Müller, 2013; Pauliuk et al., 2013b; Müller et al., 2013). In short, for each material (cement, aluminium, and steel), we simulate its cycle from production to use and end-of-life management and quantify all relevant stocks and flows within the cycle for the past century. Starting points were either production or domestic shipment, which were further adjusted by international trade flows of materials in semis and final products (for aluminium and steel) to calculate the flows entering the use phase. Different end-use categories were considered and their corresponding lifetimes following a normal distribution were assumed and differentiated by category and by country to simulate the stocks in use and flows exiting from the use phase.

We use the Human Development Index (HDI) published by the United Nations Development Programme, which is a composite statistic of life expectancy, education, and income per capita indicators and is widely used to rank the human development level of countries, as an indicator for human development from 1980 to 2008 in this analysis. CO_2 emission per capita and GDP per capita data from 1960 to 2008 for all countries are taken from the database of World Bank's World Development Indicators (WDI).

In total, there are 4,162 valid observations covering 108 countries/territories and at most 48 years for each of the countries. Table 1 lists the sample means, standard deviation, and sample size of the material stocks, CO_2 emission, and GDP per capita data sets we used at six points in time. Table 1 also illustrates that we are dealing with a panel that is unbalanced: the sample size of in-use stocks that are available over time varies. The dataset of in-use stocks covers a great amount of countries. During the period from 1960 to 2008, the in-use stock of aluminium averagely accumulates much faster than that of steel, i.e., the in-use stock per capita of aluminium increased by more than three times, while that of steel by only more than one time. This is because aluminium is a much younger metal than iron. Its application in building and transportation starts to kick off only after the 1950s.

2.2. Regression analysis

We introduce built environment stock as a new explanatory variable, *ceteris paribus*, into York's regression model. We use the same time-series cross-national GDP and CO_2 emission data as York, and the abovementioned new dataset that determines built environment stocks using three key materials, cement, aluminium, and steel as a proxy. Two dummy variables are used to test the asymmetric effect. One takes only positive value and the other one takes only negative value of the change in GDP per capita (and otherwise as 0). In other words, the former coefficient shows the GDP elasticity of CO_2 for economic growth and the latter represents the GDP elasticity of CO_2 for economic decline.

All variables are converted to natural logarithmic form before first-differencing, so the slopes on the explanatory variables can be considered as elasticity. Because GDP and other macroeconomic time series may be an integrated variable, differencing the data will eliminate potential stochastic trends in the series. The first-order differencing is conducted on all the variables including flow variables (CO_2 emission and GDP) and stock variables. Therefore, the first-order differencing does not change the fact that we are still discussing the relation among CO_2 emission, GDP and stock variables.

Random-effects and fixed-effects model are used for the panel data. The regression equation is as follow:

$$\Delta\ln\left(E/P\right)_{it} = \alpha + \beta_1\Delta\ln\left(S/P\right)_{it} + \beta_2\Delta_{pos}\ln\left(GDP/P\right)_{it} + \beta_3\Delta_{neg}\ln\left(GDP/P\right)_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

where E refers to CO_2 emissions, S denotes in-use stocks, GDP represents real GDP, and P refers to the population. $\Delta_{pos}\ln\left(GDP/P\right)_{it}$ is the dummy variable which takes the value of $\Delta\ln\left(GDP/P\right)_{it}$ if positive, and equals 0 if negative; $\Delta_{neg}\ln\left(GDP/P\right)_{it}$ is the dummy variable which takes the value of $\Delta\ln\left(GDP/P\right)_{it}$ if negative, and equals 0 if positive. These data sets have two dimensions which we index by i for the country and t for the time period. In the random-effects model $\mu_i^{'}$s are assumed to be realizations of an i.i.d. (independent and identically distributed) process and to be independent of the independent variables. In the fixed-effects model $\mu_i^{'}$s are assumed to be fixed parameters. A Hausman test is then used to differentiate the fixed-effects model and the random-effects model. The result shows that in our case the random-effects model is better than the fixed-effects model. Please refer to the Appendix for details.

York's model used a generalized least squares model with AR(1) disturbance. We tested our data set with stock variables by using Wooldridge test for autocorrelation in panel data. The results