Challenges in the Transition to a Low-Carbon Economy for Developing Countries: Estimating Capital-Use Matrices and Imported Needs

Abstract

The low-carbon transition in developing countries requires large investments in new technologies, which will generate a high demand for imported machinery and equipment. To account for the important role of investment in the transition, we endogenize fixed capital in the input-output (IO) framework, estimating capital-use matrices for six developing countries in Latin America and the Caribbean within the Gloria sectoral framework from 1990 to 2020. Our findings suggest that the inclusion of capital in the IO framework reveals a substantial deepening of the external constraint for developing countries. For every dollar invested, on average more than 45% leaks directly and indirectly to foreign producers through imports. Some socio-economic benefits of green investment, such as employment generation, are absorbed by the rest of the world, rather than fostering domestic job creation. Thus, as developing countries embark on their low-carbon trajectory, they will face an increased external constraint and substantial socio-economic imbalances.

Keywords: Low-carbon transition, Macroeconomic challenges, Gross fixed capital formation, Input-output.

1. Introduction

With the signing of the Paris agreement in 2015, the international community collectively recognized the increasingly destructive impacts of human activity on our ecosystems (Persson et al., 2022; Ripple et al., 2020), committing 196 countries to limit global warming to below 2.0 degrees Celsius compared to preindustrial levels (UNFCCC, 2015). To abide by this target, countries are increasingly adopting Nationally Determined Contributions (NDC), which require large-scale green investments in advanced and technology-intensive capital goods (Hidalgo, 2021) to promote the decarbonization of the economy (UNCTAD, 2021).

However, the nature and composition of green investment is complex. First, the impact of the transition on sectors such as Agriculture, Energy, Electricity, Transportation, Telecommunication, and Water will be much more transformative than on other sectors of the economy producing a set of multi-dimensional and sector-specific challenges (ECLAC, 2022, 2023). Second, the structure of investment, the sectoral capital-intensities, and the respective investment requirements in terms of capital assets crucially determine a country's capacity to decarbonize. Third, including developing countries in the decarbonization agenda requires a thorough consideration of their specific productive, technological, and financial characteristics. Given their lower technological and productive capabilities and their dependent position in the international financial system, the low-carbon transition will present developing countries with additional multidimensional challenges (Gramkow and Porcile, 2022; Magacho et al., 2023).

While green capital goods with high technological content are essential to achieve the decarbonization (Mealy and Teytelboym, 2022), their production is concentrated in only a few developed countries (Mutreja et al., 2014). Developing countries have less diversified economies and are less competitive in the production of these high-tech green capital goods (Boleti et al., 2021; Hidalgo, 2021). Moreover, they are characterized by a concentrated production structure specialized in low-value-added industries (Cimoli and Katz, 2003; Cimoli et al., 2019; Dosi et al., 2022). Thus, by embarking on their low-carbon trajectory, these economies create a high demand for advanced capital goods such as Machinery, Transport Equipment, and Software (Hoyos et al., 2021; Gisbert, 2023) that are necessary, not only to green future production processes, but also to reduce the environmental footprint of current production activities (Magacho et al., 2023; Porcile, 2024). Accordingly, the decarbonization strategies in developing countries and the associated external constraints will have important socio-economic implications, in particular for employment generation and income distribution (Lynch et al., 2024; Saget et al., 2020).

The very nature of green capital goods is both country- and sector-specific. It requires a detailed sectoral approach to capture the structure of green investment necessary to master the low-carbon transition. In this context, Input-Output (IO) analysis (Leontief, 1936, 1941) emerges as one of the most useful tools to model structural and sectoral dynamics, in particular related to dynamics of the low-carbon transition (Lenzen et al., 2022; Wiedmann and Lenzen, 2018; Wiedmann et al., 2015; Magacho et al., 2024). Despite its comprehensibility, versatility, and high level of detail, one of the fundamental shortcomings of IO analysis concerns the accounting of capital. Given that most IO tables are constructed from supply and use tables on the basis of national accounts, capital assets are treated as exogenous to the model (Södersten et al., 2018a,b). Therefore, in the context of the pivotal role of investment for the decarbonization strategies of developing countries, the IO system that focuses exclusively on inputs may underestimate the degree to which a country's productive capacity depends on the import of capital goods, hence underestimating the challenges faced by developing countries during their low-carbon transition.

While endogenizing capital in IO models is gaining attention, previous studies have focused almost exclusively on the assessment of the environmental footprint of fixed capital and have done so largely in the context of developed countries. Based on the method developed by Södersten et al. (2018b), this paper aims to contribute to the recent methodological developments within input-output analysis by constructing an adjusted flow-matrix method to estimate capital-use matrices for six developing and emerging countries in Latin America and the Caribbean (i.e., Colombia, Costa Rica, Dominican Republic, Honduras, Mexico, and Peru) within the Gloria sectoral framework (Lenzen et al., 2022, 2017) from 1990 to 2020.[1]

Based on these estimates, we show how the endogenization of capital in the IO framework can offer a nuanced sectoral perspective on the multi-dimensional challenges faced by developing countries during their low-carbon transition. Our findings suggest that the inclusion of capital in the IO framework reveals a substantial deepening of the external constraint for developing countries. With a substantial share of imported capital goods, the decarbonization strategies and the associated replacement of productive capacity in these countries will be strongly constrained by their dependence on foreign-produced capital goods. For every dollar invested to maintain current productive capacity, more than 45% leak directly and indirectly to foreign producers on average, with sectoral leakages reaching almost 80%. The need for imports can create constraints from a balance-of-payments perspective. Although new investments may increase production and create jobs, a relevant share of this demand leaks to other countries, and hence the most prominent impact of an increase in investment is the increase in demand for foreign exchange. We find substantial differences across sectors, with key transition-sectors, such as Utilities (i.e., Waste, Water, Gas, Electricity), Transportation, Telecommunications, and Information Services being very capital-intensive, highly dependent on imported Machinery and Equipment, and hence with limited positive effects on employment multipliers. In this context, our findings exemplify the multi-dimensional and multi-sectoral challenges faced by developing countries during their low-carbon transition.

The structure of the article is as follows. In the next section, we will provide a detailed literature review on the methodological developments in the field of capital endogenization. In section 3, we will present our methodology on the construction of capital-use matrices. Section 4 will then present our results, showing the impact of the capital-endogenization on import dependencies and employment multipliers. The final section will then discuss these results by relating them to the sustainable development strategies, the challenges

[1]Note that we compute a time-series of capital matrices from 1990-2020, with differing time series across countries, due to data availability. However, for visualization purposes we present the results only for 2015. The selection of these six countries is based on the data availability in the LA KLEMS database, preventing us from including additional countries at this time.Moreover, because of data limitations, we exclude Chile and El Salvador from our analysis, despite the fact that data is available in the LA KLEMS database. Note that, because of data limitations, we exclude Chile and El Salvador from our analysis, despite the fact that data is available in the LA KLEMS database.

faced by developing countries during their low-carbon transition and the methodological developments in the field of input-output analysis.

2. Capital Endogenization in the IO system

In the IO framework, fixed capital is treated as an exogenous variable denoted either as gross fixed capital formation (GFCF) or as the consumption of fixed capital (CFC): the GFCF is usually presented as a column-vector within the final demand, while the CFC is integrated as a row-vector as part of value-added (Södersten and Lenzen, 2020). The GFCF constitutes the flow of long-term investment designated to maintain, replace, or build-up production capacity. The CFC constitutes the consumption of fixed capital, which represents the expected decline of the current value of the capital stock during the accounting period due to physical deterioration, normal obsolescence and normal accidental damage (OECD and UN, 2009). Given that, both of these measures are available only in a one-dimensional form, aggregated by product (for GFCF) and industry (for CFC) – there is no information on the inter-industrial use of capital in the IO framework. The structure of IO databases treats capital goods not as inputs to the production system, but as goods destined for final consumption, disregarding the fact that capital goods are predominately purchased to be used repeatedly in production processes (Södersten et al., 2020; Ye et al., 2021; Wu et al., 2021a).

Given the high data requirements on the use of capital by industry and asset type, only a limited amount of studies have attempted to endogenize capital in the MRIO framework. The two most prominent methods that emerged are the augmentation method and the flow matrix method (Lenzen and Treloar, 2004). With the augmentation method, fixed capital is incorporated as a separate sector of homogeneous capital goods that is added to the intersectoral matrix. This sector is constructed by using the GFCF vector as producing and the CFC vector as consuming industries. The flow-matrix method on the other hand relies on the disaggregation of capital by sector and asset type to produce a separate capital-flow matrix, which is added to the regular intersectoral flow matrix forming a total flow matrix, which incorporates both fixed capital flows and intermediate inputs (Södersten et al., 2018b; Ye et al., 2023). Upon a comparison of these two methods, Lenzen and Treloar (2004) conclude that, while the augmentation method is easier to implement, its application produces substantial and systematic distortions of the factor multipliers, which is largely due to the uncertainties in the allocation of fixed capital. On the other hand, the flow-matrix method produces much more accurate and reliable results. However, it is constrained by its high data requirement on product-by-industry capital flows.

Initial studies focused primarily on the augmentation method both on a global (Hertwich and Wood, 2018; He and Hertwich, 2019) and national level (Cao et al., 2019, 2020; Hata et al., 2022; Sajid et al., 2021) to quantify the carbon (Wu et al., 2021a; Chen et al., 2018, 2023), the energy (Chen et al., 2022) and the material-related carbon footprint (Hertwich, 2021) of countries.

However, studies applying the augmentation method treat fixed capital as a homogeneous commodity. To solve this issue, scholars increasingly applied the flow-matrix method to account for different types of capital assets. In particular, given the emergence of the KLEMS project (Timmer et al., 2007; Bontadini et al., 2023) that provides detailed data on capital stocks by industry and asset type (Södersten et al., 2020, 2018a,b; Vivanco, 2020; Wu et al., 2021a; Ye et al., 2023), one could estimate detailed capital use-matrices on a global scale, which substantially improved the accuracy and reliability in MRIO analysis. These studies show that the endogenization of capital in MRIO models has led to a substantial increase in the environmental footprint of industrial production, as well as a significant redistribution of environmental impacts across industries and countries (Ye et al., 2021, 2023; Södersten et al., 2020, 2018a; Xu et al., 2023; Hertwich and Wood, 2018; Södersten et al., 2018b).[5]

While these studies substantially advanced the literature on capital endogenization, some scholars have recently argued that the extended footprints based on the static MRIO models fail to account for the intertemporal feature of fixed capital. That is, these methods assume that the capital consumed today was produced by today's technology, ignoring that capital goods are produced in different age cohorts with different technologies (Wu et al., 2021b). Consequently, a few recent studies restored to assessing the dynamic footprint of fixed capital using the production structure and the environmental intensities of the production year of the fixed capital to quantify the historical emissions for a target year. These studies conclude that the traditional footprint tends to overestimate the environmental impact of fixed capital as dynamic models allocate emissions to future consumption (Ye et al., 2021; Wu et al., 2021b).

Despite these methodological advancements, previous research has focused almost exclusively on developed countries. The few studies that focus explicitly on developing countries show that the inclusion of capital had a stronger impact on the carbon (Chen et al., 2018; He and Hertwich, 2019; Wu et al., 2021a), the energy (Chen et al., 2022), and the material-related carbon footprint (Södersten et al., 2020) of developing countries than on developed countries. The impact was strongest for fast-developing countries, highlighting the recent capital stock expansions in those regions, but also the fact that developing countries use capital investments to accumulate productive capacity, while developed countries use capital investment to replace the existing depreciated capital (Chen et al., 2022, 2018). Moreover, Södersten et al. (2018a) argue that, while overall capital-augmented emission multipliers decreased, indicating that production processes have become cleaner, this trend was less profound in developing countries, suggesting that developing countries still have a larger share of dirty capital assets embodied in their capital stock (Shahbaz et al., 2013). In addition, by allowing for the distinction between capital assets, these studies were able to show that developing countries tend to invest in more resource-intensive assets, such as Infrastructure and Machinery, while developed countries invest in less-resource intensive assets such as Computers, Software, and Services (Ye et al., 2023).

These studies have predominantly focused on the environmental footprint of fixed capital, with none of them specifically examining the role of green investment in developing countries and its multi-sectoral, multi-dimensional, and macroeconomic consequences. This paper aims to address these limitations by expanding the analysis of sectoral capital needs for developing countries. We seek to contribute to the IO literature by providing estimates for capital-use matrices for six Latin American countries from 1990 to 2020. We adapt the method developed by Södersten et al. (2018b) to construct these matrices and analyze the imported needs for these countries to achieve a low-carbon transition, given the need for investing in specific industries. Furthermore, we aim to identify the consequences of these leakages (due to the import of Machinery, Equipment, and inputs) on employment generation. This analysis is particularly relevant for developing countries due to their limited capacity to produce most of the green products necessary for achieving their NDCs (Mealy and Teytelboym, 2022).

3. Methodology

3.1. Data

For this study, we rely on the GLORIA global multi-region input-output (MRIO) database (Lenzen et al., 2022, 2017). Contrary to most databases such as WIOD and Exiobase, which offer a high sectoral resolution only for a limited amount of developed countries, the GLORIA database covers 120 sectors for 164 countries accounting for more than 99% of the world's GDP and the bulk of global supply-chains.

Given that data on capital stock by industry and asset is not available within the MRIO database, we rely on the external database LA KLEMS (Gu and Hofman, 2021; Fernández-Arias et al., 2021) to complement our analysis. The LA KLEMS Growth and Productivity Accounts are a set of databases that contain inputs and outputs of capital, labor, energy, materials, and services for eight developing countries in Latin America and the Caribbean (LAC). They provide information on the purchase of different capital assets, making it a useful and valuable complement to Gloria. While databases such as EU KLEMS or World KLEMS provide highly aggregated capital formation matrices, the LA KLEMS database had to settle for a lower level of industry and asset type detail. Moreover, the data availability and consistency differs substantially across countries.

Given these variations in data availability, we rely on two different methods to extract the capital accounts from the external databases. For Peru and Colombia, for which data on GFCF (by asset k and sector s) was equally detailed as data on capital stock (by asset k and sector s), we rely on the capital stock data from KLEMS.[2] For Mexico, Costa Rica, Honduras, and the Dominican Republic, for which data on GFCF was available with a higher level of sectoral disaggregation, we estimate the capital stock using the time series of gross fixed capital formation in volumes, applying the permanent inventory method (PIM) with the depreciation rates provided by the LA KLEMS database (Fernández-Arias et al., 2021).

[2] Note that we refer to this method as *Direct Capital Stock* method (DCS).

Table 1: Data availability by asset and sector for each country

Country	Assets x Sectors	Database	Extraction Method
Colombia	8x9	LA KLEMS	DCS
Costa Rica	8x9	LA KLEMS	PIM
Dominican Republic	6x9	LA KLEMS	PIM
Honduras	5x9	LA KLEMS	PIM
Mexico	9x25	LA KLEMS	PIM
Peru	7x9	LA KLEMS	DCS

3.2. Estimating capital-Use matrices in GLORIA

Following the comparison by Lenzen and Treloar (2004) and building on the method developed by Södersten et al. (2018a), we propose an adjusted flow-matrix methodology to estimate the capital-use matrix for six developing countries, available in the LA KLEMS database, in the Gloria MRIO framework.[3]

Therefore, in order to combine the capital accounts provided by LA KLEMS with the detailed sectoral and environmental accounts of Gloria, we adjust and expand the KLEMS capital accounts to make them compatible with Gloria. Before that, we execute some modifications to the existing data structure to guarantee the compatability with the IO tables.

First, we separate the asset Residential Investment from the original KLEMS capital-use matrices. In cases where Residential Investment is consumed by multiple sectors, we extract the value for Residential Investment consumed by the Construction sector k_{ri}^{con} and aggregate Residential Investment and Non-Residential Investment. This is justified for two reasons. First, given that the sectoral classification of Gloria entails both Building Construction and Civil Engineering Construction, while the KLEMS dataset only provides one Construction sector, the exclusion of Residential Investment allows us to differentiate between the two. Secondly, we argue that the Property and Real Estate sector is almost exclusively consuming Residential Investment and in order to account for this dynamic, we have to seperate residential and non-residential capital assets. Moreover, we aggregate the KLEMS assets Computer equipment and Communication equipment as both assets match to only one Gloria sector. Furthermore, we seperate the cell that specifies the Cultivable Assets consumed by the Agricultural sector k_{ca}^{agr}. We then distribute k_{ca}^{agr} diagonally across all of the Agricultural sectors in GLORIA to account for the fact that each capital asset produced by the Agricultural Sector is uniquely consumed by the same Agricultural sector (see Equation 8 below. Finally, we distribute the KLEMS assets Computer Equipment, Communication Equipment, Software, Transport Equipment and Machinery and Equipment across the seven Trade and Transport sectors of the Gloria database to account for differences in trade and transport margins, as the KLEMS data is provided in purchasing prices and GLORIA in basic prices. We use their total capital stock values from the KLEMS data as a distribution proxy. Finally, this yields our modified initial KLEMS-based capital matrix $\tilde{\tilde{\mathbf{K}}}_{k,s}$ with *k* assets in rows and *s* sectors in columns

[3]The countries include Colombia, Costa Rica, Dominican Republic, Honduras, Mexico, and Peru.

with differing dimensions across countries (see Table 1)

After these initial modifications, we aim to expand the KLEMS-based capital matrix to the GLORIA structure. To do so, we first disaggregate the *k* asset types into the 120 sector categories of Gloria, using a basic concordance matrix $\mathbf{G}_{k,j}$ matching KLEMS assets k (rows) to Gloria sectors j (columns). The matrix contains ones for the corresponding KLEMS-asset to Gloria-sector combinations and zeros for the rest. For the resulting matrix, there is no rule for rows summation, but columns should sum-up to one. When KLEMS-asset match to more than one Gloria sector, the values are disaggregated and distributed among the sectors using a proxy vector $\mathbf{p}_i$. The weighted correspondence matrix is thus given by

$$\mathbf{G} = (\widehat{\tilde{\mathbf{G}}\mathbf{p}})^{-1}\tilde{\mathbf{G}}\hat{\mathbf{p}} \tag{1}$$

where the proxy $\mathbf{p}$ is the column-vector of GFCF of the domestically produced and imported goods, obtained from GLORIA, hats indicate vector diagonlization and $(\widehat{\tilde{\mathbf{G}}\mathbf{p}})^{-1}$ denotes matrix inversion of $(\widehat{\tilde{\mathbf{G}}\mathbf{p}})$. Note that we normalize the concordance matrix, such that rows sum-up to one, while columns cannot sum up to more than one. This avoids double counting as the sum of the shares that each KLEMS asset assigns to the Gloria sectors amounts to one.

Conversely, to disagregate the KLEMS sectors into the Gloria sectors we rely on a second concordance matrix $\mathbf{H}_{j,s}$ that matches KLEMS sectors *s* (columns) to Gloria sectors *j* (rows). As above, the matrix contains ones for the corresponding KLEMS-sector to Gloria-sector combinations and zeros for the rest. All rows should sum-up to one with no rule for row-summation. As above, when KLEMS-sectors match to more than one Gloria sector, the values are disaggregated and distributed among the sectors using a proxy vector $\mathbf{d}_j$. The weighted correspondence matrix is thus given by

$$\mathbf{H} = \hat{\mathbf{d}}\tilde{\mathbf{H}}(\widehat{\mathbf{d}\tilde{\mathbf{H}}})^{-1} \tag{2}$$

where the proxy vector $\mathbf{d}$ is the row-vector of CFC obtained from GLORIA. As above, the concordance matrix is normalized to avoid double-counting such that all columns should sum-up to one, while rows cannot sum up to more than one. Thus, the KLEMS based capital-use matrix $\tilde{\tilde{\mathbf{K}}}_{k,s}$ can be opened into a Gloria structure to yield a new capital-use matrix $\overline{\mathbf{K}}_{i,j}$ as

$$\overline{\mathbf{K}} = \mathbf{G}'\tilde{\tilde{\mathbf{K}}}\mathbf{H}' \tag{3}$$

where $\mathbf{G}_{k,j}$ and $\mathbf{H}_{i,s}$ refer to the corresponding concordance matrices, $\tilde{\tilde{\mathbf{K}}}_{k,s}$ to the original KLEMS capital matrix, and ′ indicates matrix transposition. Following its initial removal, the value for the consumption of *Cultivable Assets* by the Agricultural sector denoted as k_{ca}^{agr} is distributed diagonally across the Agricultural sector based on the proxy $\mathbf{p}^{agr}$, which considers only the Agricultural sector of the GFCF column-vector of the domestically produced and imported goods. This yields the new capital-stock matrix $\overline{\mathbf{K}}_{i,j}^{agr}$ of the agricultural sector with weighted values in the diagonal only for the Agricultural Sector and zeros for the rest.

$$\overline{\mathbf{K}}^{agr} = k_{ca}^{agr} \begin{bmatrix} \widehat{\mathbf{p}^{agr}} \\ 0 \end{bmatrix} \tag{4}$$

Thus, the capital-use matrix, denoted as $\overline{\overline{\mathbf{K}}}_{i,j}$ is obtained as the summation of these two matrices and the matrix of residential investment, $\overline{\mathbf{K}}_{i,j}^{res}$, which is a matrix of zeros for all cells except the one for Building Construction production (row) for Property and Real Estate consumption (column) given by k_{ri}^{con}.

$$\overline{\overline{\mathbf{K}}} = \overline{\mathbf{K}} + \overline{\mathbf{K}}^{agr} + \overline{\mathbf{K}}^{res} \tag{5}$$

In order to ensure consistency between the CFC data of Gloria and the obtained data on capital stock from KLEMS, we first transform the KLEMS depreciation matrix $\delta_{k,s}$ to the Gloria structure, by using the same concordance matrices $\tilde{\mathbf{H}}_{i,s}$ and $\tilde{\mathbf{G}}_{k,j}$ to obtain a new depreciation matrix $\boldsymbol{\delta}_{i,j}$. Note that the cell corresponding to Construction production (row) for Property and Real Estate consumption (column) is replaced by the depreciation value of residential assets $\tilde{\boldsymbol{\delta}}_{pre}^{con}$.

$$\delta = \tilde{\mathbf{H}}\tilde{\delta}\tilde{\mathbf{G}} \tag{6}$$

We then estimate a hypothetical CFC based on the previously obtained $\overline{\overline{\mathbf{K}}}$ using this newly obtained depreciation matrix $\delta_{i,j}$ by

$$\overline{\mathbf{d}} = \boldsymbol{\iota}'[\delta' \odot \overline{\overline{\mathbf{K}}}] \tag{7}$$

where $\boldsymbol{\iota}$ is the summation column-vector. We then calculate an adjustment matrix $\tilde{\mathbf{d}}_{i,j}$ for the CFC given by

$$\tilde{\mathbf{d}} = \widehat{\mathbf{d} \oslash \overline{\mathbf{d}}} \tag{8}$$

where $\oslash$ is the element-wise division. The final time series of the capital-stock matrix $\mathbf{K}_{i,j,t}$ adjusted to be coherent with CFC data from Gloria with assets i in rows and sectors j in columns is obtained as follows:

$$\mathbf{K} = \overline{\overline{\mathbf{K}}}\tilde{\mathbf{d}} \tag{9}$$

To obtain a capital *requirement* matrix **B**, we proceed similarly as when calculating the matrix of technical input coefficients $\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1}$. Thus, the matrix of capital requirements to produce one unit of output is obtained as

$$\breve{\mathbf{B}} = \mathbf{K}\widehat{\mathbf{x}}^{-1} \tag{10}$$

where **x** is the output column-vector and **K** our newly obtained Gloria-based capital matrix.

$\breve{\mathbf{B}}$ is thus the matrix of direct capital coefficients, where each element $b_i^j = b_i^j / x_i^j$ represents the direct capital requirement from sector *i* per unit of total output for sector *j* and where the horizontal vector of the row-sums represents the capital-output ratio by sector *j*.

Note however, that this matrix indicates the depreciated capital-stock and does not take into account the capital stock necessary to maintain productive capacity at its current level. Thus, we adjust our newly obtained $\breve{\mathbf{B}}$ matrix by an adjustment vector to build a capital-stock matrix that captures the capital-stock needed to sustain productive capacity.

To compute this adjustment vector, we first calculate a hypothetical Investment matrix $\bar{\mathbf{I}}$ that captures the investment necessary to replace depreciation, using the following formula and the newly obtained matrix $\breve{\mathbf{B}}$ as

$$\bar{\mathbf{I}} = \widehat{\delta}\breve{\mathbf{B}}\mathbf{x} + \breve{\mathbf{B}}\dot{\mathbf{x}} \tag{11}$$

where $\dot{\mathbf{x}} = g\mathbf{x}$ with *g* being a scalar representing the desired growth rate, which is given by the average long-term logarithmic growth rate. Conversely, the investment necessary to replace the existing capital stock is given by $\mathbf{I} = \widehat{\delta}\mathbf{B}\mathbf{x} + \mathbf{B}\dot{\mathbf{x}}$, where $\mathbf{B}$ represents the matrix of the new capital stock to be estimated. Given that $\mathbf{I}$ is equal to gross fixed capital formation, it is given by the GFCF-vector $\mathbf{p}$ of the IO table. Using this vector, we are able to calculate an adjustment vector β that indicates the difference between the capital stock necessary to replace the depreciated capital and the capital stock needed to sustain productive capacity. Thus, since $\mathbf{I} = \widehat{\beta}\bar{\mathbf{I}}$, where $\mathbf{I}$ is given by $\mathbf{p}$, the adjustment vector β is calculated by

$$\boldsymbol{\beta} = \mathbf{I} \oslash \bar{\mathbf{I}} \tag{12}$$

Using this adjustment vector, we can calculate the new B matrix that considers the capital stock needed to maintain productive capacity at a given desired growth rate g:

$$\mathbf{B} = \widehat{\beta}\breve{\mathbf{B}} \tag{13}$$

Ultimately, the sum of **A** and **B** shows the total production requirements of capital and non-capital goods, which allows us to calculate a new Leontief inverse as

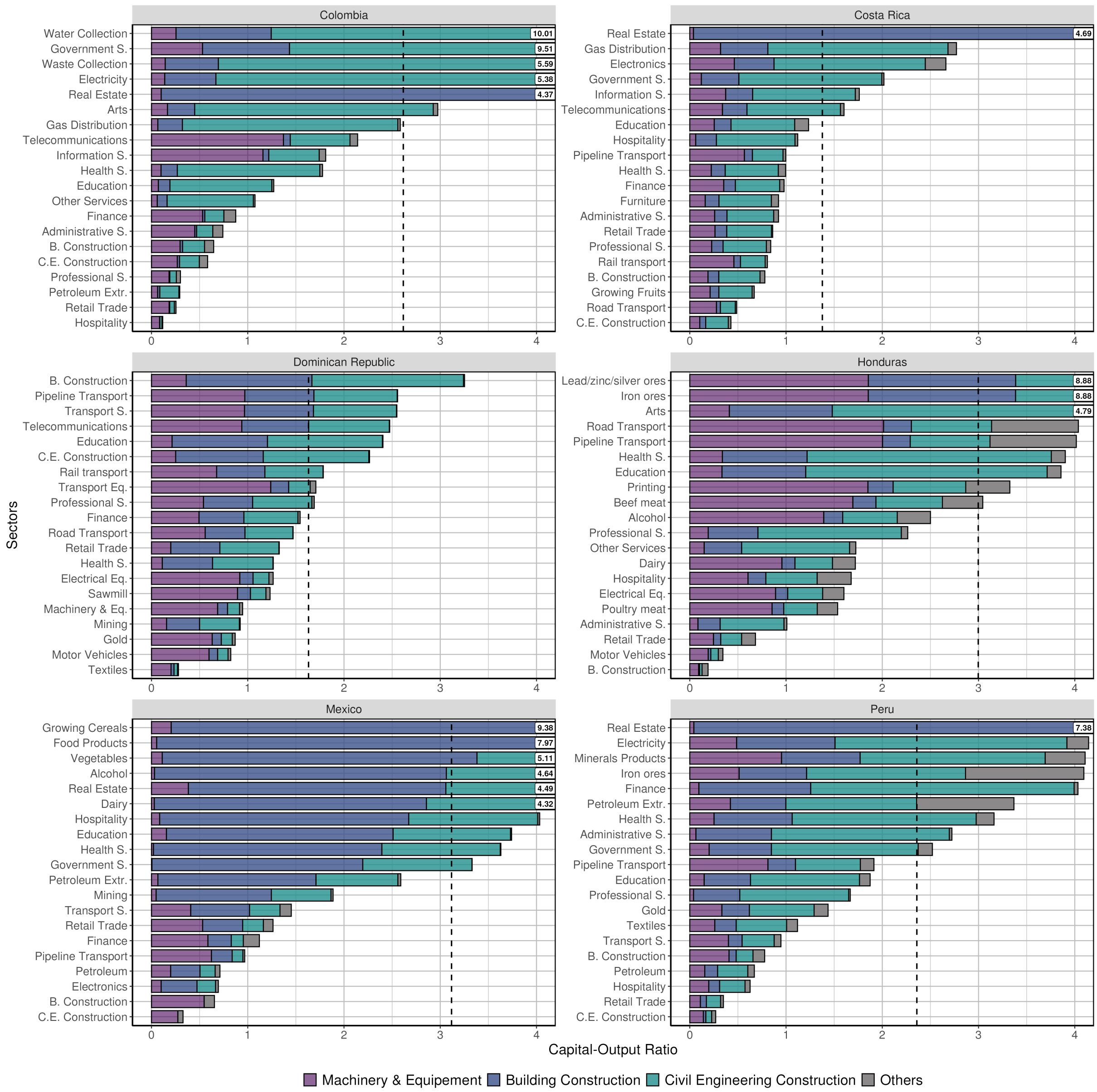
$$\mathbf{L}^{\mathsf{K}} = (\mathbf{I} - (\mathbf{A} + \widehat{\delta}\mathbf{B}))^{-1} \tag{14}$$

whose element $l_{i,j}^k$ denotes not only the the direct and indirect inputs, but also the direct and indirect capital assets of sector *i* needed by sector *j* to produce one unit of industry *j* output. Note that **B** is multiplied by the matrix of annual depreciation rates $\delta_{i,j}$. Note that the interpretation of this new Leontief Inverse differs from the common Leontief matrix as it includes not only the embodied inputs, but also the direct and indirect capital goods required to produce both inputs and capital goods (Södersten et al., 2018a).

4. Results

4.1. Sectoral investment requirements

Figure 1: Sectoral Capital-Output Ratios by Asset



Note: The black dashed line represents the average capital-output ratio across the largest 20 sectors (in terms of total capital-stock).

The endogenization of capital into the IO system allows us to understand sectoral differences, not only in terms of their respective capital-output ratios, but also in terms of their disaggregated investment needs in terms of capital asset. To provide a more accurate account of these sectoral differences, Figure 1 compares the sectoral capital-output ratios of the 20 largest sectors (in terms of total capital stock) of each country disaggregated by four primary asset types Machinery and Equipment, Building Construction, Civil Engineering Construction, and Others. More specifically, it presents the sectoral investment disaggregated by asset type that is necessary to maintain the current productive capacity in this sector.

In accordance with the literature, we find the capital-output ratios of the six analyzed countries to vary between 1.4 (Costa Rica) and 3.1 (Mexico) with Dominican Republic (1.6), Colombia (2.6), Peru (2.4), and Honduras (3.0) falling within this range (Feenstra et al., 2015; Inklaar et al., 2019).[4]

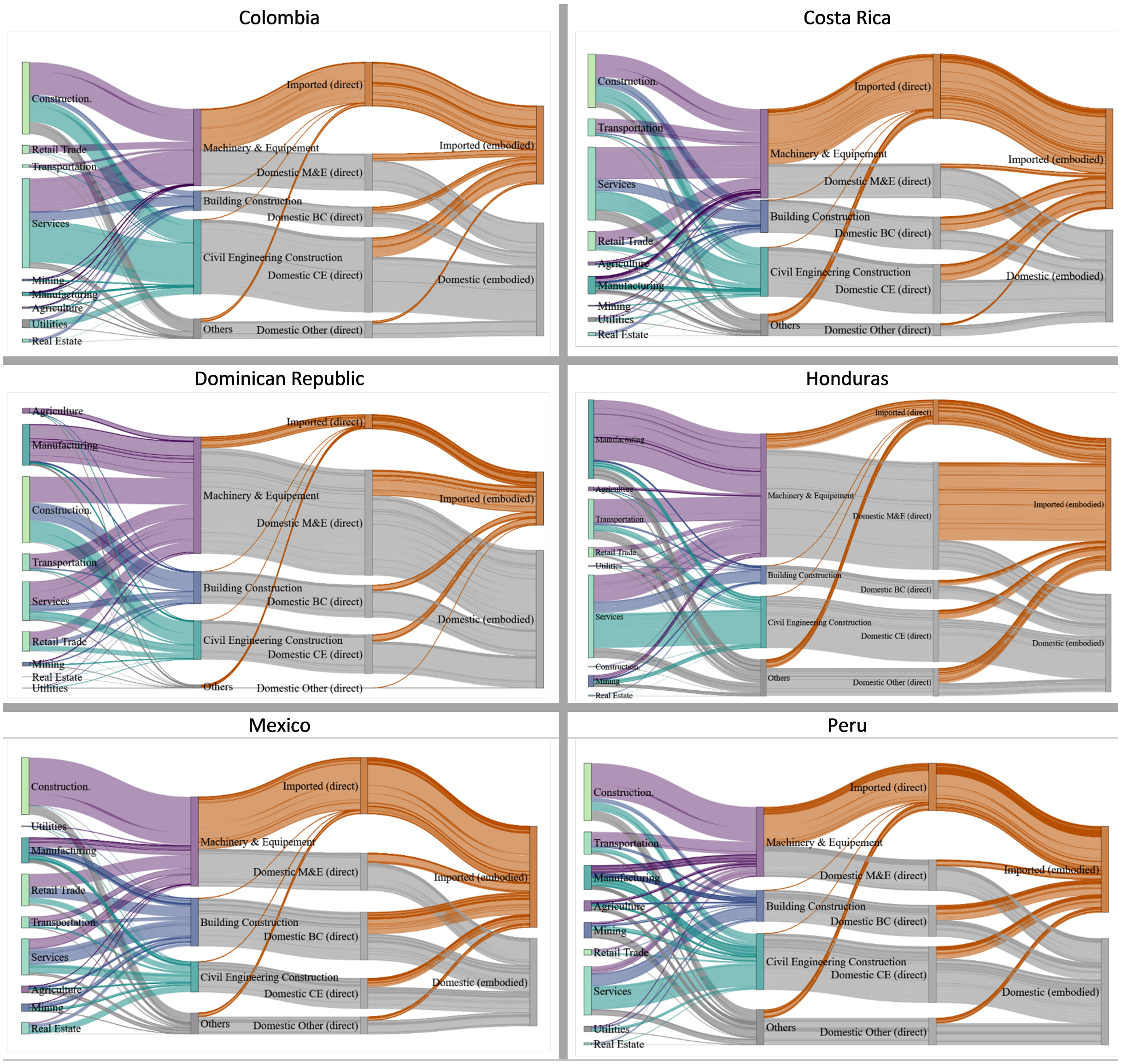
We further find the capital-output ratios to vary substantially between sectors within the same country. In particular, sectors such as Utilities (i.e., Waste, Water, Gas, Electricity), Transportation, ICTs (Telecommunications, Information Services, Electronics) and Education tend to have high capital-output ratios across countries, suggesting that they are capital-intensive sectors. Large sectors (in terms of monetary output) such as Motor Vehicles, Construction, or Retail Trade tend to have lower capital-intensities across countries, requiring less capital to produce an equivalent unit of output. Nevertheless, we find that similar sectors have very different capital-output ratios across sectors. For example, Petroleum Extraction in Mexico (2.6) and Peru (3.4) has a relatively high capital-output ratio, while for Colombia it has a very low capital-output ratio (0.25). Conversely, while Arts ranks among the more capital-intensive sectors in Colombia (4.37) and Honduras (4.79), it is much less capital-intensive in other the other countries. In addition, food producing sectors such as Growing Cereals, food Products, Vegetables, Dairy, and Alcohol are very capital-intensive in Mexico (4.32-9.38), while for the rest of the countries, similar sectors tend to be less capital-intensive.

Figure 1 also demonstrates large differences across sectors and countries in terms of their respective investment structures, as the capital assets that are required to maintain productive capacity in the respective sector differ between sectors. While Service Industries, Agricultural Industries, and Utilities depend largely on Building and Civil Engineering Construction, sectors such as ICT's, Manufacturing, Transportation, and Construction tend to be much more dependent on Machinery and Equipment. Furthermore, it becomes apparent that the structure of investment of the most capital-intensive sectors differs between countries. For example, while Machinery and Equipment plays an important role in Honduras and the Dominican Republic, Mexico and Costa Rica tend to be more dependent on Construction, with Colombia and Peru's investment structure being relatively balanced across capital assets.

[4]Note that these studies find slightly higher capital-to-output ratios as they use GDP as a measure of output, which discounts intermediate consumption as opposed to our measure of output that includes intermediate consumption.

4.2. The import-intensity of investment

Figure 2: Comparing Monetary Flows of Capital Goods Demand



Underlying these sectoral investment needs are monetary capital flows that start from capital-investing sectors undertaking the investment to build up their capital stock, to capital producing sectors that provide the necessary capital assets. These flows are then either captured by foreign producers (i.e., through imported capital goods) or by domestic producers (i.e., through domestically produced capital goods). They also flow indirectly to foreign and domestic producers who produce the necessary inputs and capital goods that are required to produce the domestic capital goods. Given developing countries' dependence on the import of foreign technology, in particular capital goods, the objective is to understand how the endogenization of the capital stock into the IO system may reveal an increased dependence on imported capital goods, that may be underestimated by previous IO analyses that focused exclusively on inputs.

To this end Figure 2 plots Sankey Diagrams for each country, presenting their direct and embodied sectoral dependence on imported inputs and capital goods. The first flow represents the investment allocation ($\mathbf{K}$) from the capital-demanding to the capital-producing sector. The second flow represents the origin of the capital supply, distinguishing between the imported ($\mathbf{K}^M$ in orange) and the domestic ($\mathbf{K}^D$ in grey) investment allocation, with the domestic investment requirements being disaggregated by asset type. The final flow describes the origin of the embodied inputs and capital goods in capital, differentiating between the imported ($\mathbf{L}^{K^m}$ in orange) and the domestic ($\mathbf{L}^{K^d}$ in grey) content of domestic production.

First, coherent with Figure 1, we observe that across countries, Manufacturing is a large capital-investing sector, investing predominately in Machinery and Equipment. In particular for Honduras, Mexico, and Dominican Republic, the Manufacturing sector, but also the Transportation sector, have high capital requirements, despite accounting for only a small share in total output. Apart from Services, who rely predominately on Construction with Machinery and Equipment playing a supplementary role across countries, we observe substantial variations across countries in terms of their sectoral investment needs.

Analyzing the monetary flows necessary related to this capital-stock reveals that more than 50% of Machinery and Equipment are directly imported. This means that for every dollar spent on Machinery and Equipment more than half leak to foreign producers through imports. On the contrary, Building Construction and Civil Engineering Construction are primarily produced domestically with, more than 99% originating from domestic production and negligible shares being directly imported. On the contrary, across countries, Other capital assets, such as Cultivable Assets and other Manufactured capital goods, despite constituting a minor share in total consumption, present non-negligible levels of direct imports of between 15% and 20%.

However, when considering the embodied imports, namely the imported inputs and capital goods necessary to produce the domestic capital stock, we observe that the country's dependence on foreign produced capital goods increases significantly. Figure 2 reveals that across countries a substantial share of the domestic production of capital goods and inputs depends on the import of inputs and capital goods. For most countries up to 50% (Honduras) of the domestically produced capital stock are indirectly imported. Accordingly, when considering the direct and indirect embodied inputs and capital goods, countries import on average of 45.8% with countries like Honduras (55.8%), Mexico (53.6%), and Costa Rica (52.1%) being even more import-dependent and the Dominican Republic being less import constraint than the other countries (27.8%). This suggests that for every dollar invested to sustain productive capacity, more than 45% of the monetary flows leak directly and indirectly to foreign producers. Note that this share varies substantially, depending on the capital-investing sector and the capital-asset used with Machinery and Equipment being much more import intensive than Building Construction and Civil Engineering Construction., suggesting that the replacement of productive capacity in Machinery and Equipment-intensive sectors is more import-intensive than in Building Construction- or Civil Engineering Construction-intensive sectors.

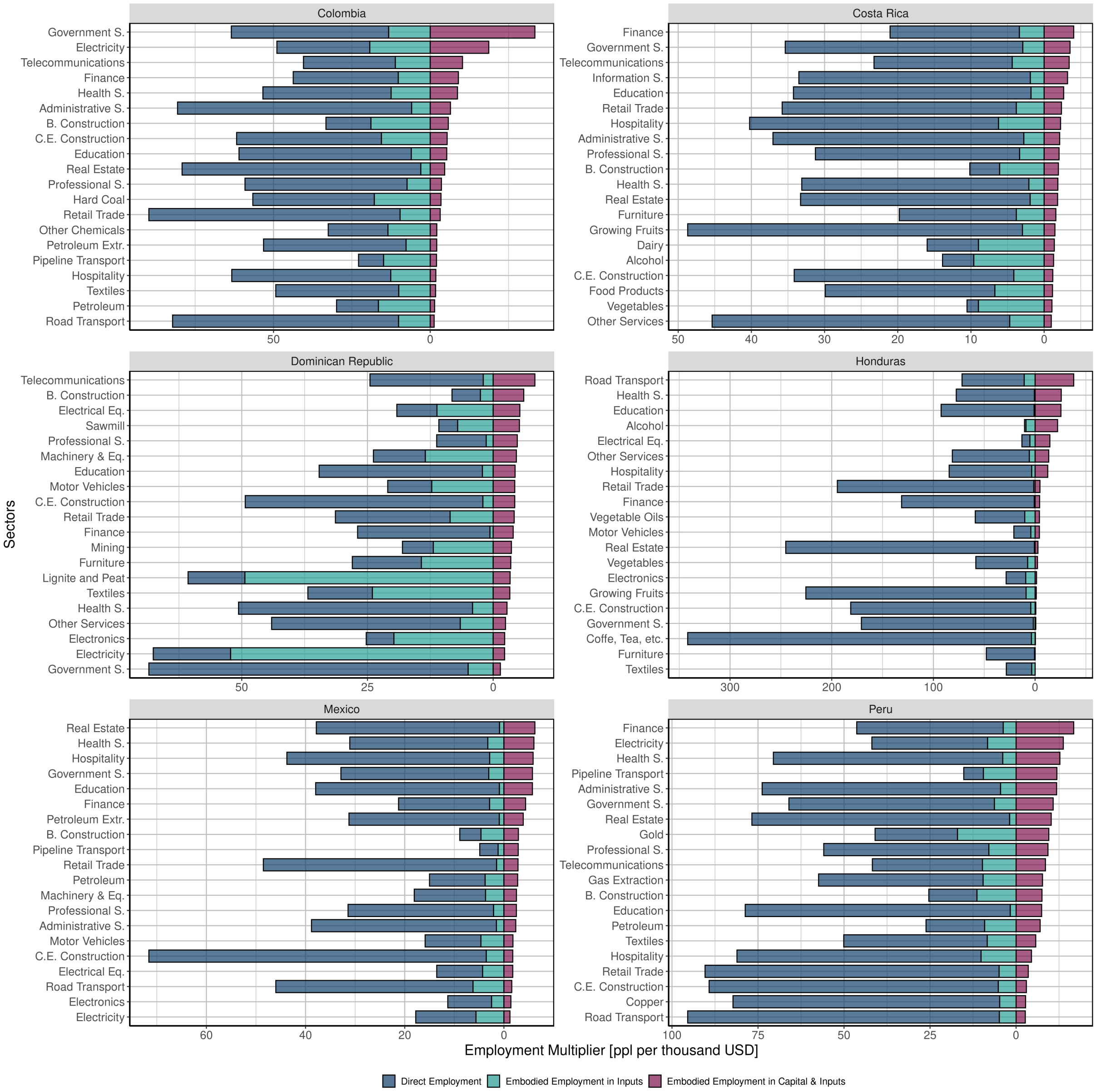
4.3. The employment-intensity of investment

While the endogenization of fixed capital into the IO system reveals positive multiplier affects across the economy, the strong dependence on foreign produced capital goods suggests that socio-economic benefits (e.g., employment) are predominately absorbed by foreign producers. To this end, Figure 3 compares the direct employment ($\mathbf{n}$), the embodied employment in inputs ($\mathbf{nL}$) and the embodied employment in capital goods ($\mathbf{nL}^K$) of the 20 largest sectors in terms of monetary output (see Appendix A for explanations on the equations).

As above, we observe substantial differences across countries and sectors, with respect to the employment multiplier effects embodied in capital goods (see Figure 3). Importantly, across countries, while direct employment intensities are largest across most sectors, embodied employment in capital tends to be equal or larger than embodied employment in inputs. Moreover, we observe substantial differences across countries, as capital-intensive sectors such as ICTs, Government Services, Finance, Electricity have high employment multipliers embodied in capital in Colombia, Costa Rica, and Peru, but low employment multipliers embodied in capital in Mexico and the Dominican Republic. On the contrary, sectors such as Transportation and Retail Trade have very low employment multipliers embodied in capital in Mexico, Peru, and Colombia, but very high multipliers in Costa Rica or Honduras.

Note further that while for Peru, Mexico and the Dominican Republic, and Costa Rica employment embodied in capital is relatively well distributed across industries, for Honduras and Colombia, employment is concentrated in only a few leading sectors with the rest of the sectors having comparably low employment multipliers.

Figure 3: Comparing Employment Multipliers

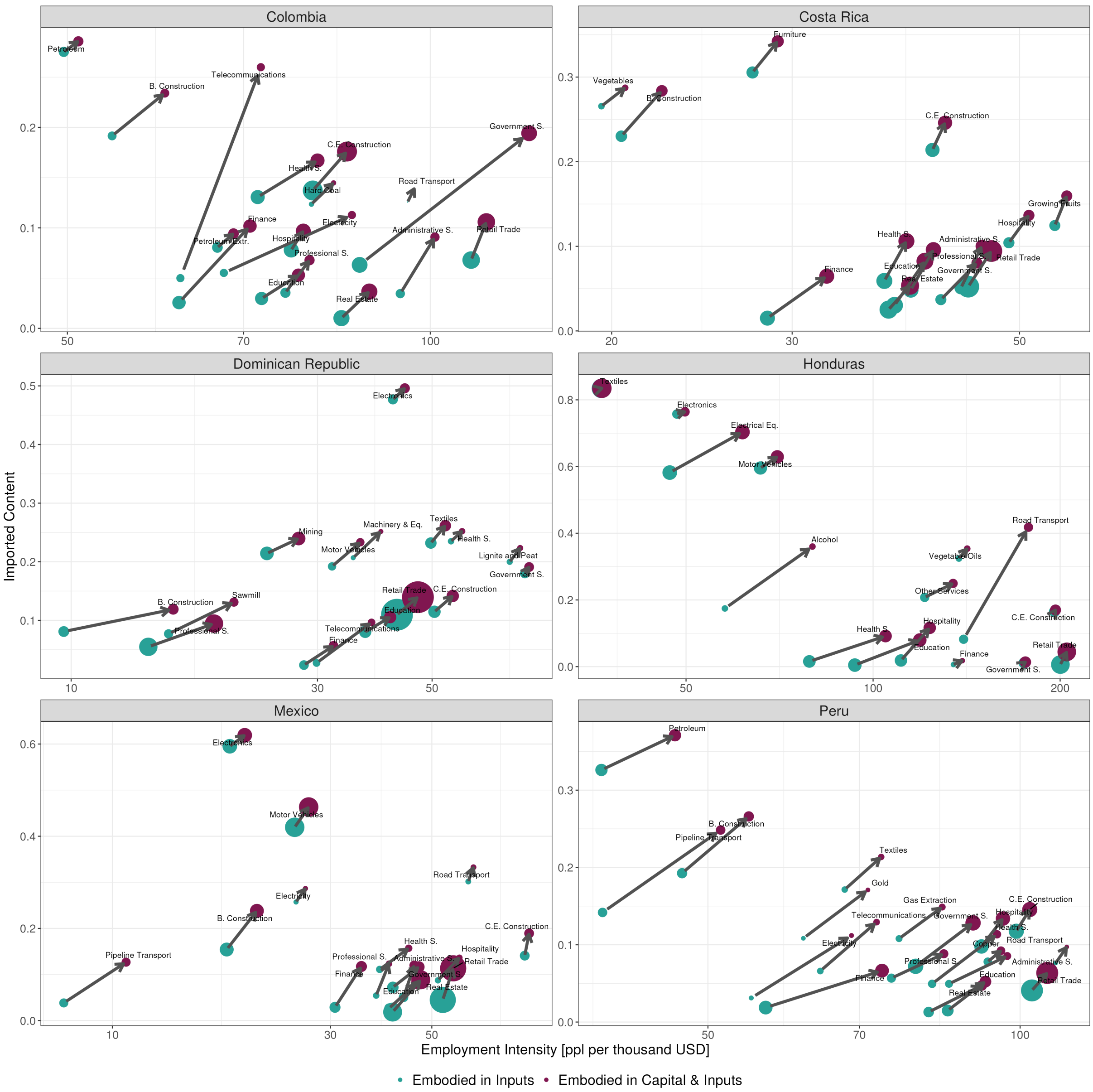


Note: The grey dashed line represents the average direct and indirect employment in inputs, while the black dashed line represents the average embodied employment in capital goods.

4.4. The multi-dimensional challenge of investment

While the build up the of the capital-stock is dependent on foreign capital goods, suggesting low employment generation, Figure 3 has shown that investment directed at replacing the existing capital stock entails positive employment effects across the economy. To understand the respective degree of both effects Figure 4 maps a country's multidimensional impact by considering not only the embodied imports in capital, but also the employment embodied in capital of the country's leading economic sectors.

Figure 4: Comparing Imported Content and Output Multipliers



Note: The length of the arrow suggests the total increase accruing from the inclusion of capital. The size of the points refers to the share in total output.

It is evident that the endogenization of fixed capital in the IO system reveals an increase in both employment and imported content for most of the leading sectors of the economy. While the average imported content of the economy, as shown in Figure 2 reveals a high import-dependency of roughly 45%, the sectoral perspective suggests that import-intensive sectors such as Electrical Equipment or Electronics import up to 80% and generally more than 45% of their investment.

The comparison of sectors within countries suggests that both the imported content and the embodied employment increased strongest for high-technology sectors such as Telecommunication, Electrical Equipment, Electronics, and Transport sectors, as well as capital-intensive sectors such as Building and Civil Engineering Construction.

For example, the imported content of the Telecommunication sector in Colombia increased almost four-fold and the Road Transport sector in Honduras almost seven-fold following the inclusion of fixed capital. On the contrary the impact on employment of the same sectors was rather small with increases of 1.1 and 1.4 respectively. The impact of the inclusion of fixed capital was smallest for Electronics, which is nonetheless characterized by very high import-needs and very low employment generation.

5. Discussion

5.1. Summary of Results

In this study we built on Södersten et al. (2018b) and applied the flow matrix method to endogenize capital in the IO framework for six LAC countries. We analyzed how the endogenization of investment impacts developing countries' dependence on imported capital goods as well as its impact on employment multipliers.

Our results suggest that the endogenization of capital had a substantial effect on the external constraint of developing countries with an average of up to 45% of inputs and capital goods being directly or indirectly imported for every dollar invested. Sectoral leakages for import-intensive sectors such as Telecommunication, Transportation, Construction, or Electronics are even stronger with values as high as 80%. This implies that developing countries, being far from the technological frontier, do not possess the productive capabilities to produce the capital goods such as ICTs, Machinery and Equipment, Transport Equipment, Electronics, and other specialized capital goods. Furthermore, our results suggest that the inclusion of capital has a positive effect on employment multipliers across most of the leading sectors. However, our findings suggest that, given very high levels of imported content, most of the demand for capital goods is leaking to foreign producers such that the positive socio-economic effects produced by the domestic employment generation are limited.

Lastly, we find substantial differences across sectors in terms of their capital intensities, their sectoral import dependencies on capital goods, as well as the sectoral employment multipliers. Sectors, such as Utilities (i.e., Waste, Water, Gas, Electricity), Transportation, ICTs (Telecommunications, Information Services), and Education tend to be not only very capital-intensive, but also very import-intensive. Moreover, we find substantial differences regarding the respective sectoral investment needs in terms of their capital assets distribution with some sectors (i.e., Real Estate, Utilities) relying primarily on Building and Civil Engineering Construction, while others such as Manufacturing, Transportation, Telecommunication, and Construction rely strongly on Machinery and Equipment. As such, we find substantial differences with respect to sectoral import dependencies, as sectors that rely predominately on Machinery and Equipment tend to be more import-intensive than sectors that rely primarily on Building Construction and Civil Engineering Construction. Finally, our results show that similar sectors have very different capital intensities and investment requirements in terms of capital assets across countries. These sectoral differences highlight the importance of bringing a detailed sectoral approach to the analysis of investment, but also the shortcomings and limitations of aggregating or uniformly distributing capital requirements across regions, sectors, or assets (Lynch et al., 2024).

5.2. The role of investment for the low-carbon transition in developing countries

The findings of our study are crucial for understanding the trajectory of the low-carbon transition in developing countries. The transition will confront developing countries with the profound challenge not only to achieve a successful decarbonization of their economy, but with the need to master this process with growing equality and a reduction in the asymmetries of the international system (Gramkow and Porcile, 2022). Central to this transition is the investment that is necessary to green the economy, reduce the environmental footprint of current production processes, generate employment and income, promote structural and technological change, as well as close the gap in GDP per capita between the developing and the developed world.

However, the nature and composition of green investment is complex, encompassing both sophisticated manufactured capital goods with a high technological content such as Machinery and Equipment and on the other hand green infrastructural investments, composed primarily of capital assets such as Construction. Conversely, the impact of the decarbonization efforts in developing countries on sectors such as Agriculture, Energy, Electricity, Transportation, Telecommunication, and Water will be much more transformative than on other sectors of the economy (ECLAC, 2022, 2023).

For example, the Agricultural sector, with both one of the highest climate and biodiversity impacts faces the two-fold challenge of providing affordable food for a growing population, while simultaneously reducing its environmental impact by reducing its GHG emissions and limiting its land-use (FAO, 2017; Vos and Bellù, 2019). In this context, sophisticated capital goods to reduce or replace chemical fertilizers and infrastructural investments to promote agroforestry practices and silvapasture systems are indispensable for a sustainable transition (Searchinger et al., 2019; Bhattacharya et al., 2019).

In the Energy sector, the transition to renewable energy sources such as solar power, green hydrogen, and wind energy, demands high-tech capital goods. Substantial infrastructure investments are needed to support the generation, transmission, and distribution, of green electricity and natural gas, which will require the construction of renewable energy plants, grid upgrades, and energy storage systems (Grottera, 2022; IEA, 2024). In the Transport sector, the shift towards electrification, particularly through an increased production of electric vehicles, demands advanced capital goods. Moreover, the scaling up of public transportation infrastructure, the expansion of rail networks, and emission-reductions in the road, maritime, and air transport sectors necessitate substantial infrastructural investments (Zhang and Fujimori, 2020; IEA, 2024; Bataille et al., 2020).

In the context of the digital transition of the economy, the Telecommunication sector also requires sophisticated capital goods alongside a substantial need for infrastructural investments to ensure comprehensive coverage across urban and rural areas (ECLAC, 2022). Finally, investments in high-tech to enhance water security and equitable access to clean water, as well as substantial infrastructure investments for managing extreme weather events such as floods and droughts are indispensable to ensure a successful decarbonization of the economy (Rozenberg and Fay, 2019).

Thus, the very nature of green capital goods and the associated green investment requirements necessary to master the low-carbon transition are diverse, sector specific and carry with them a multifaceted set of challenges depending on the sector's role during the transition and its associated investment needs.

As countries embark on their low-carbon trajectory and the pressure to transform the key sectors of the economy will increase, they will create a large demand for imported capital goods - both in the case of advanced capital goods, as well as in the case of green infrastructural capital goods. Our findings suggest that in the former case, this occurs directly through the import dependence on foreign-produced, high-technology capital goods. In the latter case, it occurs indirectly, since green infrastructural goods, despite being primarily produced domestically, rely indirectly on the import of advanced capital goods. Ultimately, with a strong import dependency of investment and capital goods, developing countries face an increased balance-of-payment constraint, with domestic capital accumulation being suppressed by the constant need to attract foreign currency that is necessary to pay for foreign-produced capital goods. This pushes developing countries to rely on their static competitive advantage and intensify their production and exportation of primary commodity, low-value added, and often emission-intensive products to ensure the necessary capital inflows.

With this concentrated and undiversified production structure and a large pool of workers employed in low-skilled industries or even informal activities, the socio-economic consequences of the low-carbon transition will be profoundly more challenging for developing countries. In particular, it will constrain the ability of developing countries to redistribute the income generated by the positive effects of employment (Hartmann et al., 2017) and will require a profound restructuring of the labour market including a substantial re-allocation and re-training of workers (Pollin, 2020). This process will likely be associated with a decline in living standards due to its impact on high job destruction and low job creation, particularly in developing economies that depend on carbon-intensive industries (Rozenberg and Fay, 2019).

In this context, our findings suggest that the low-carbon transition will produce additional socio-economic pressures in developing countries. With a growing demand of investment for foreign-produced capital goods, socio-economic benefits are absorbed by the rest of the world, rather than creating employment domestically. Hence, while green investment projects are likely to bring some positive effects on employment, in particular if they are directed to sectors with lower import propensities (Perrier and Quirion, 2018), the associated creation of employment in low-emitting (sunrise) and the destruction of employment in high-emitting (sunset) industries, may create socio-economic imbalances (Lynch et al., 2024; Saget et al., 2020).

Thus, as developing countries transition toward a low-carbon economy, they face severe challenges with their dependence on foreign-produced capital goods not only delaying the decarbonization process, but possibly hampering employment generation and the associated distribution of income across society.

5.3. Limitations

Finally, our study fails to address the inter-temporal feature of the capital-stock. As capital goods are bought to be used repeatedly in production processes, the existing capital-stock is ultimately the product of a historic accumulation process (Keynes, 1936). Effectively, we assume that the capital-stock of today was produced using today's technology, today's production structure and paid for by today's money. However, hereby, we ignore the fact that the current capital stock has already been paid for and was produced using different technologies during different age cohorts and on the basis of different productive structures (Wu et al., 2021b). This is particularly biased when interpreting the indirect impacts on employment and imports, as we attribute these impacts to a capital stock that has already been produced, and thus already been imported or generated employment. While we cannot fully abstract from these assumptions, as the structure of the input-output framework (e.g., data published on an annual basis) does not allow us to capture the historical dynamics of the capital stock, they have to be taken into account when interpreting the results.

Furthermore, since we adjust our for the CFC data from Gloria, our results are sensitive to the sectoral CFC values. In addition, using CFC as a proxy for the physical use of capital is highly debated given that it remains an economic concept designed to describe the estimated loss in value as a result of use and obsolescence (Södersten et al., 2018a). It has been previously suggested to use capital services as a more adequate measure for capital stock as inputs to production, however their estimation is highly debated and sectoral data for many countries remains scarce (Ahmad, 2004; Oulton and Srinivasan, 2003; Jorgenson, 1999).

Moreover, for our study, we rely on the depreciation rates published by the LA KLEMS database (Gu and Hofman, 2021), who rely on the same depreciation rates as the EU KLEMS database that are based on the official estimates of US Bureau of Economic Analysis (Fraumeni, 1997). As such, we implicitly assume that depreciation rates are uniform across countries and most importantly that they are similar between developed and developing countries. This has been contested both on empirical and theoretical grounds. While some studies simply suggest that depreciation rates are generally higher in developing countries (Bu, 2006; Schündeln, 2013), other studies suggest that high-technology capital assets such as ICTs, Transport Equipment or Machinery and Equipment have lower depreciation rates in developing countries, while durable capital assets such as Construction goods tend to have higher depreciation rates (Pyo, 2008; Yilmaz and Kiliç, 2021). This implies that our results may overestimate the role of Construction goods and underestimate the role of Machinery and Equipment in the capital stock structure of the analyzed countries. This in turn may cause us to underestimate the external constraint of the analyzed countries, as advanced capital goods such as Machinery and Equipment are much more import-intensive than Construction goods. In addition, the sensitivity of capital-stock estimates to the implicit assumptions made about the depreciation rates used to construct the capital-stock (Pritchett, 1999; OECD, 2023) raises important questions about the accuracy and predictability of capital-stock estimates in the context of capital endogenization. It also restates the eminent need to construct robust measures of depreciation rates across different regions of the world.

6. Conclusion and Political Implications

Our study contributes to the ongoing debate on sustainable development in developing countries, integrating sectoral investment needs and analyzing the import and employment dynamics that are associated with green investment strategies. Hereby, we are moving beyond existing studies on capital endogenization that focused almost exclusively on the environmental footprint of fixed capital. We show that including capital in the IO framework reveals that as countries transition to a low-carbon economy, they will face an increased external constraint and substantial socio-economic imbalances.

The capacity to overcome both the resulting balance-of-payment constraint and attain sufficient employment generation crucially depends on the different strategies adopted by countries to master the low-carbon transition. Evidently, it would be fatal for developing countries to continue their reliance on static competitive advantages by intensifying the export of primary, resource-intensive commodities. As most of the leading export industries tend to be very emission-intensive, an intensification in these industries may perpetuate existing environmental inequalities (Althouse et al., 2020) and substantially delay the decarbonzation process, risking permanent environmental damage, lock-in of polluting socio-technical pathways, and socio-economic and financial losses caused by stranded assets (Pegels and Altenburg, 2020).

On the contrary, our results suggest that policies that promote sustainable development in developing countries should be aimed at increasing export elasticity by raising the degree of sophistication of the export basket. Rather than using the revenues accruing from the exportation of emission-intensive industries to intensify production in those industries, countries should direct the revenues to diversify, green, and increase the degree of sophistication of their export structure (Gala et al., 2018). Such strategies are inevitable for developing countries to achieve sustainable development and build a resilient economy that can address the challenges produced by the low-carbon transition. First, with the exportation of goods that enjoy a higher demand on the international market, developing countries can ensure sufficient capital inflows to pay for the foreign-produced capital goods, with the potential to increase the balance-of-payment constrained growth rate. This may hold, despite the fact that building-up new export industries and increasing export complexity will drive demand for foreign-produced capital goods, which increases import elasticity and thus lowers the balance-of-payment constrained growth rate. Secondly, the build-up of new export industries with higher levels of productivity may increase employment and promote the establishment of a resilient labor market that can absorb the profound restructuring produced by the transition (Lynch et al., 2024; Saget et al., 2020; Pollin, 2020). Third, directing resources away from emission-intensive industries will increase environmental sustainability and reduce the socio-economic, fiscal, and external dependence on emission-intensive industries (Magacho et al., 2023). Importantly, it will allow countries to build a resilient economy, preparing its economy for the declining demand for fossil-fuels and other emission-intensive industries, with the potential to increase its productive capacity in low-emission industries and boost technical change and non-price competitiveness in green industries (Porcile, 2024).

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