CAF DEVELOPMENT BANK
OF LATIN AMERICA
AND THE CARIBBEAN

Challenges and
opportunities for
participating in
global value chains

VALUE CHAINS FOR **THE ENERGY TRANSITION** OPPORTUNITIES FOR **LATIN AMERICA** IN A CHANGING LANDSCAPE

POLICY PAPER #30

VALUE CHAINS FOR THE ENERGY TRANSITION: OPPORTUNITIES FOR LATIN AMERICAN COUNTRIES IN A CHANGING LANDSCAPE

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Executive summary

This paper proposes a comprehensive framework for identifying and analyzing opportunities for Latin America and the Caribbean (LAC) to integrate into global clean value chains (CVCs). The analysis finds that opportunities for LAC countries to participate in CVCs exist, but they are highly concentrated by country and industry segment—particularly in wind turbines and batteries. The solar industry seems to offer broader opportunities across more countries and segments, but still with a significant degree of concentration. Key to the paper's findings is the critical role of link variables like economic proximity in facilitating LAC's participation in CVCs. It argues for a policy approach that includes elements of conventional industrial policy and goes beyond traditional measures aimed at fostering macroeconomic stability and correcting market failures.

These involve encouraging collaboration with high-potential companies that could act as anchors in crucial CVC areas and addressing challenges like geographical distance through strategic interventions in logistics and connectivity. Finally, the paper aims to contribute methodologically to the understanding of the dynamics governing industrial opportunities in clean energy. The proposed framework can be applied to investigate other technologies and value chains and can set the stage for a more nuanced discussion on how to refine strategies, policies, and interventions to enhance LAC's effective insertion into CVCs.

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Introduction

The energy transition has become a focal point of discussion in Latin America and the Caribbean (LAC). Although energy accounts for less than half of the region's greenhouse gas (GHG) emissions, and the share of fossil fuels in primary energy consumption has remained largely unchanged at almost 70% for the past three decades, almost all LAC countries have announced their intention of becoming carbon neutral by 2050[1].

The region is a net energy exporter, with fossil fuels playing a large role in macroeconomic stability. Valued at today's prices, reserves amount to 18 years of government spending and to 8 times the region's gross debt[2]. LAC's fiscal revenue from nonrenewable resources has reached 8 percentage points of GDP[3] with price levels similar to current ones, and those revenues continue being a fundamental source for the investment required to lift the 160 million Latin-Americans living in poverty and to improve the pervasive income inequality that has historically afflicted the region[4].

Transitioning to a low-emissions energy matrix is a challenging proposition for the region. Fiscal revenues, public investment needs, the pervasiveness of inefficient consumption technologies, chronic underinvestment and significant institutional weaknesses make reducing the region's dependence on fossil fuels particularly difficult.

But the energy transition also brings significant opportunities. First, in investment and innovation. Changing the way countries produce and consume energy requires a shift to new technologies like wind and solar generation, electricity storage, low emissions hydrogen, bioenergy and Carbon Capture Usage and Storage (CCUS), which, in turn, require massive investments in efficient consumption equipment and transmission and distribution networks. Investment and technological change open the opportunity to create higher quality jobs, increase productivity and foster economic linkages.

It also opens the possibility of developing the deposits of minerals like copper, silver and lithium. They are critical for the energy transition and represent minerals where the region's share of global reserves is significant. The energy transition will put a renewed focus on mining that poses the challenges common to any extractive industry, but it can also open a path to improving standards, greater efficiency, and a focus on increasing the value added to raw minerals.

Third, it requires stronger and more effective institutions. The energy sector has traditionally been heavily regulated due to the pervasiveness of natural monopolies and market failures, and the subject of multiple subsidies and strong government intervention. Ideally, the energy transition should prompt countries to develop energy market regulation that fosters innovation, increases investment, secures access, and promotes efficient price formation. Governments will also need to move away from fossil fuel subsidies while investing in clean energy, reduce fiscal dependence, and ensure protection for vulnerable groups that lose with the energy transition. A significant opportunity to modernize government.

Finally, in a world where the fight against climate change, disruptions to energy markets and the rise of populism and anti-globalization sentiments are changing the geopolitical landscape, new opportunities emerge for trade and integration in LAC. The United States, for example, is responding to these challenges with initiatives like America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition aimed at ensuring the country can be a clean energy superpower in the long run. The need to increase raw material availability; the need to invest in in diverse, secure, and

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[1] Oxford University, Our World in Data (OWD).

[2] Own calculations with British Petroleum (BP) and International Monetary Fund (IMF) data.

[3] Organization for Economic Cooperation and Development (OECD).

[4] The World Bank

socially responsible foreign supply chains; and the need to attract and support a skilled workforce[5] are key components of this seven-pillar strategy that offers significant opportunities for the region's economies.This paper examines the opportunities for LAC countries to become a part of the global value chains associated with the energy transition. Two types of opportunities are at hand: new value chains emerge associated with technological developments in the energy sector, and geopolitical vulnerabilities require nearshoring of existing value chains. We propose and apply a framework to describe the value chains, identify the changing links and propose strategies for LAC countries to insert themselves in the chains.

We follow a three-step process to determine opportunities for the region in critical value chains (CVCs) for the energy transition. The first is to identify CVCs by analyzing the required changes in the global energy matrix to enable carbon neutrality by 2050 and selecting those critical in enabling that change.

Second, an adaptation of traditional analysis at the country level to include broader factors that influence value chain (VC) competitiveness like institutional framework, geography, and broader economic policy. Using publicly available data that compares these factors among countries we identify the drivers behind the observed choice of geographic location of the value chains.

Finally, based on the observed data, we design and calibrate a score associated with the drivers of value chain location. We examine the score of non-observed value chain locations that include LAC countries to identify the most likely nearshoring opportunities for CVCs and policy actions needed to materialize them.

Although the primary goal of this paper is to explore opportunities for the region to take advantage of the changing landscape of clean energy, we also aim to make a methodological contribution. We do this by developing a framework to (i) determine the drivers of location for the different components of individual value chains, (ii) rank the relative strength of unobserved, but possible, value chain configurations, and (iii) do so in a way that facilitates the identification of policy options needed to increase their chances of materializing.

Modeling key value chains for the energy transition

Value chains entail the various business activities and processes involved in creating a product. As such they can be divided in two sets of complementary activities as is traditionally done in the VC analysis originally proposed by Michael Porter. The first, primary activities, comprises all that go directly into the creation of the product, like inbound and outbound logistics, manufacturing, marketing and after sale services. The second, secondary activities, include supporting activities that make primary activities more efficient like infrastructure, human resources or technological development. Our model focuses on the primary activities of a value chain.

A directed-graph model of value chains

We focus on the existing value chains critical for the energy transition: solar photovoltaic (SPV) panels, wind turbines (WT) and batteries (EVB), as other key technologies for the energy transition like green hydrogen (GH2) production and use, and for carbon capture and utilization (CCUS), are not yet well established and thus the corresponding value chains are not well defined[6].

Moreover, we simplify our depiction of value chains to focus on variables relevant for nearshoring decisions and policy. While a full-fledged value chain description may go into the detail of each primary activity as in Figure 1, value chains in our model are directed graphs as in Figure 2. The nodes represent resource extraction, mining or electricity generation, or transformation, industrial processes, and they are situated in a specific geographic location, a country or region. The directed links are movements of goods and services from one process to the next, which may involve international trade.

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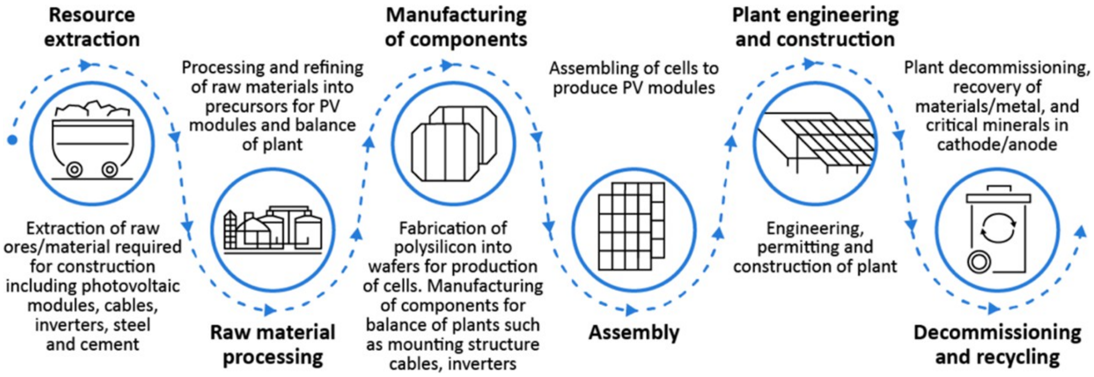
[5] Taken directly from the strategy document.

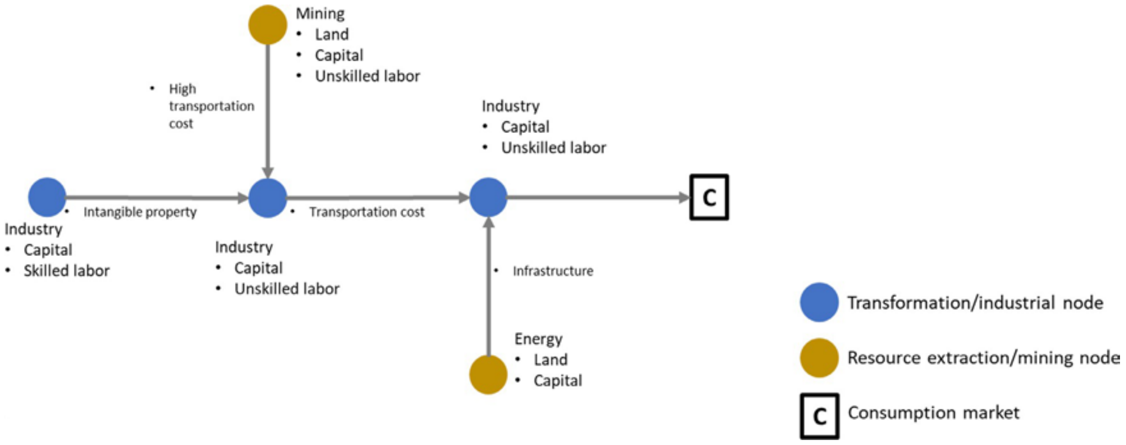
[6] It is not clear what one would want to nearshore of the alternative GH2 and CCUS value chains.

Figure 1: Solar PV value chain



Source: IEA

Figure 2: A Generic Value Chain



Both nodes and links have associated properties relevant for our analysis. For nodes, these properties identify the industrial processes' critical requirements: beside the goods and services incoming, each node has requirements of land, capital, labor and intangible assets.

Also associated with a node is its geographic location, country or region, and the corresponding environment. Country properties like intensity of social conflict, availability of labor, labor market flexibility or taxes are common to all nodes in each country and help determine whether the requirements for the industrial process to be in the country are met.

The movement of goods and services between two processes is associated with a link. It is influenced by geographic and institutional features of the environment: distance between the location of the processes, logistics, political stability, among other things.

Links may then connect nodes in different countries. If the two processes linked are in different countries the movement is considered international trade, and trade costs and barriers become a relevant institutional feature of the link. We also consider features associated with the pair of countries engaging in trade that may signal cultural or political closeness that facilitate trade.

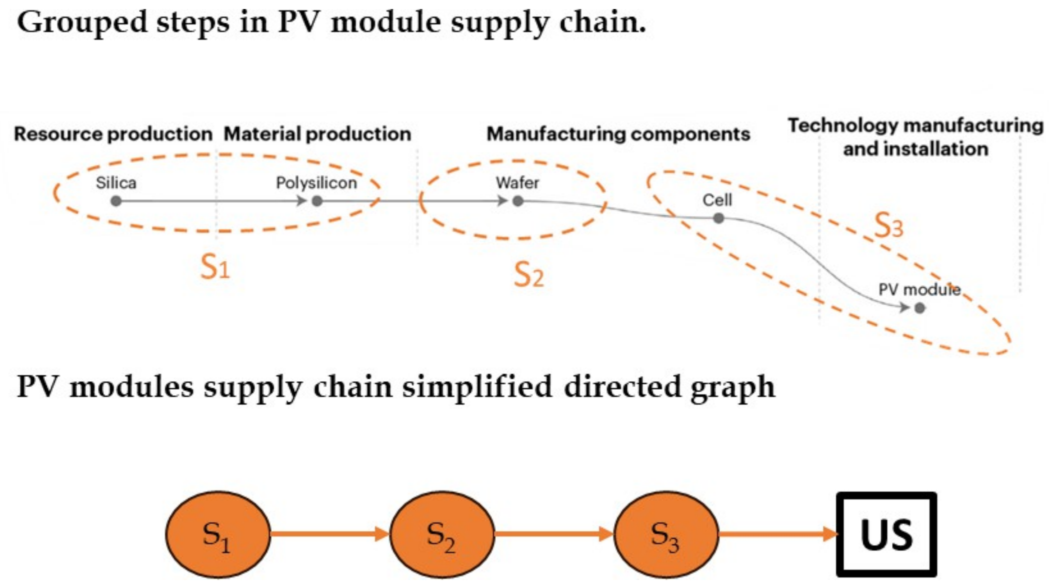
We distinguish between a value chain, a directed graph that is oblivious to the geographic location of its nodes, and a Walk, a value chain where the location of each of the nodes is identified, and the links between them include trade-related variables whenever international trade is involved. For example, as we will discuss later, our model of the value chain for SPV is linear and has four nodes, but there are four different corresponding observed Walks, depending on whether the first three nodes are in China, the Asia-Pacific region or Europe. The last node is where the panel is used, for our purposes always the United States. Of course, not all possible Walks are observed for a given value chain.

Simplified value chains for SPV, wind turbines and EV batteries

In characterizing the observed CVCs for SPV, WT and EVB, we use IEA (2023) as the starting point, and then simplify those chains to obtain our modeled VCs.

For SPV, IEA (2023) has five nodes in the value chain; for the purposes of our analysis, we collapse them into three distinct nodes and add the final demand node (always the United States).

Figure 3: Simplified Model of the Solar PV Value Chain

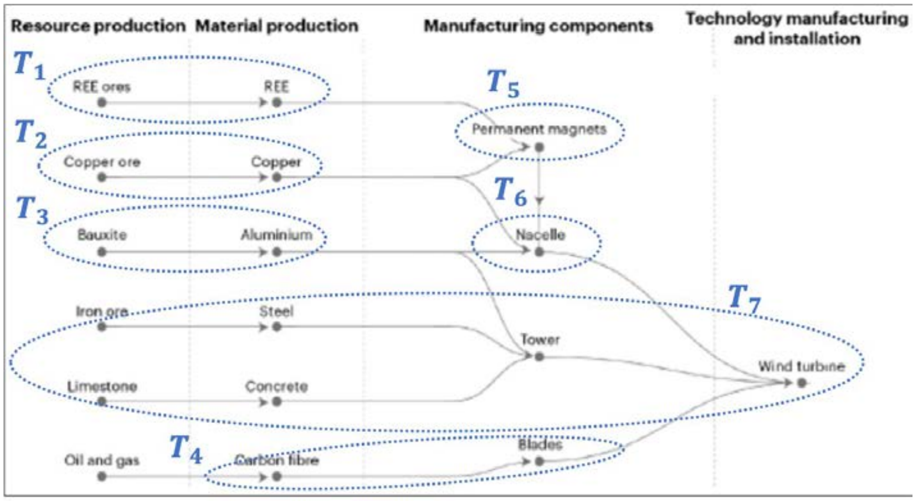


Source: Adapted from IEA (2023).

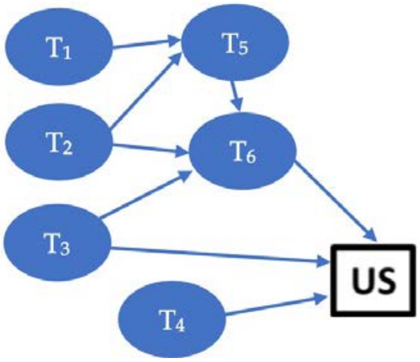
Collapsing nodes into one simplifies our analysis. Based on the observed Walks, we collapse adjacent nodes of the CVC if in all observed Walks those nodes share the same geographic location. Economically, this may be because the product transferred from the first node to the second would be prohibitive to transport at long distances; or alternatively because the process in the first node is easy to implement or very common and found anywhere. Strategically, this may be because the product in the first node is a critical bottleneck and needs to be in a near shore to avoid cross-country dependence. In any case, collapsing one or more nodes into one reflects the assumption that those nodes will always be necessarily present in the same region/country, that is, that they will necessarily be geographically adjacent and, if relocated, they will be relocated together. This is a strong assumption[7].

Figure 4: Simplified Model of the Wind Turbine Value Chain

Grouped steps in wind turbine supply chain



Wind turbine supply chain simplified directed graph



Source: Adapted from IEA (2022).

For wind turbines, Figure 4 shows the simplified value chain we use in our model. While the logic is the same as for the SPV CVC, this case also illustrates its implications for the processes that must be carried out at the site of final installation, that is, at the final consumer node, which for our purpose is always the United States. The observed Walks for this value chain all feature the production of iron ore and limestone, their transformation to steel and concrete, the manufacturing of the tower and the assembly of the wind

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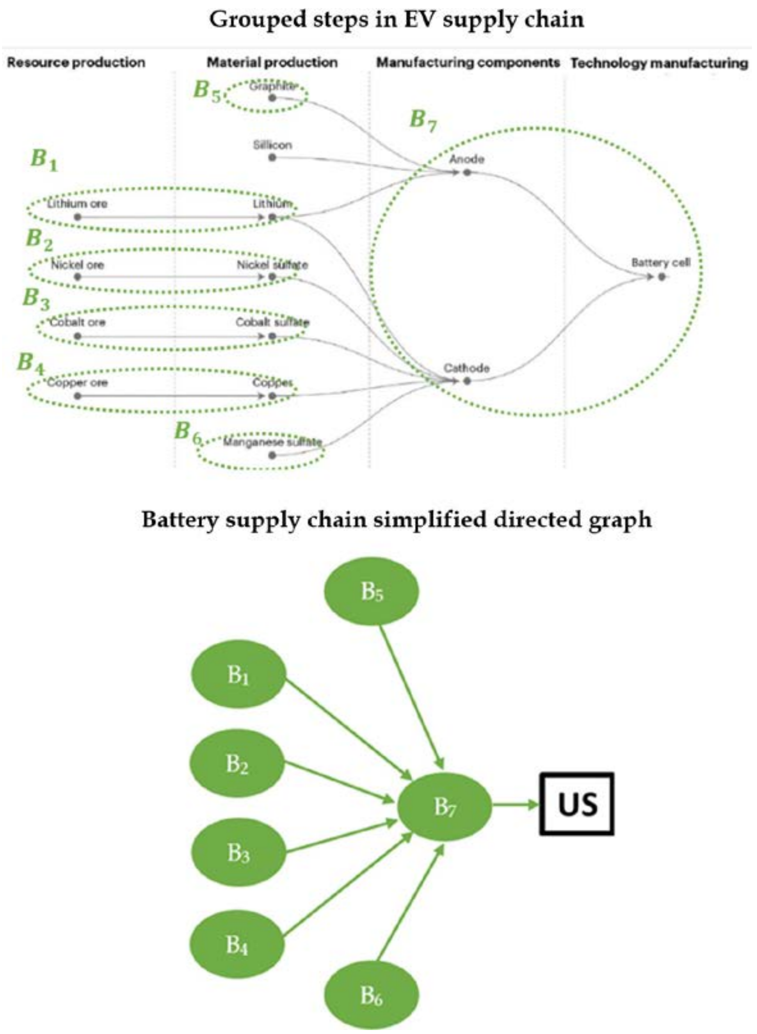
[7] See Appendix 1 for a detailed explanation of the decision to collapse nodes in each simplified value chain.

turbine at the same geographic location–the country or region of the final consumer. All these nodes are then collapsed into the final consumer node.

Finally, Figure 5 depicts the original and simplified value chains for batteries.

Figure 5: Simplified model of the EV batteries value chain



Source: Adapted from IEA (2022).

The score of a walk

Score function

Value chains can materialize in any number of locations—they could spawn different Walks. The focus of this paper is precisely to determine which Walks are more likely to materialize. Thus, in our analysis each observation is a Walk instead of a value chain.

We consider a model where a particular Walk $W_i(V)$ of a value chain V is more likely to be observed if its score function $S(W_i(V))$ is higher:

$$S(W_i(V)) = A * [ATT_{node}]^{\beta_N} [ATT_{country}]^{\beta_C} [ATT_{transport}]^{\gamma_T} [ATT_{political}]^{\gamma_P}$$

Or using the shorthand notation $x \equiv log(X)$:

$$s(W_i(V)) = \alpha + \beta_N * att_{node} + \beta_C * att_{country} + \gamma_T * att_{transport} + \gamma_P * att_{political}$$

ATT_{node} are proxies for relevant technical attributes of the production processes in the value chain, so they are node-specific; $ATT_{country}$ are relevant attributes of the countries or regions where those nodes are located, so they are country-specific.

$ATT_{transport}$ and $ATT_{political}$ are link specific. $ATT_{transport}$ stand for costs associated with the transit of the products from a node to the next. $ATT_{political}$ are proxies for the cultural/political affinity between trading countries. We further define the attribute proxies as geometric averages of meaningful variables over the Walks. Thus, if X is an attribute of a node (for instance, labor intensity of the production process), we calculate the corresponding attribute for the Walk as

$$ATT_X \equiv \sqrt[\#nodes]{\prod_{nodes\ in\ walk} [1 + X_{node}]}$$

It follows that:

$$att_X = \frac{1}{\#nodes} \sum_{nodes\ in\ walk} log[1 + X_{node}]$$

Similarly, for country-specific attributes of a Walk:

$$att_X = \frac{1}{\#nodes} \sum\nolimits_{nodes\ in\ walk} log\left[1 + X_{country}\right]$$

and for link-specific attributes

$$att_X = \frac{1}{\#links} \sum\nolimits_{links\ in\ walk} log[1 + X_{link}] \quad .$$

The final step is to train our score, which requires that we calibrate the parameters $\alpha, \beta_N, \beta_C, \gamma_T, \gamma_P$ above to best fit the data on which Walks are observed and which are not. We do this via maximum likelihood estimation of a reduced-form regression specification which closely resembles the logarithmic form of our score above. The dependent variable is a dummy indicating whether a Walk is observed or not. The details of the calibration are provided in Appendix 2.

Attributes of a walk

We use the following proxies for attributes of the Walks:

Table 1: Walk Attributes

Note: For links within the same country, the values of attributes such as shipp_connect, political_aff, and commercial_aff are uniformly set to 100, indicating maximum connection as these variables are scaled from 1 to 100. Additionally, to prevent overlap with the effects of variables measuring distance and integration, the trade_bloc attribute is assigned a value of 1 in these cases. In the case of dummy variables, they are scaled between 1 and 2 to maintain the geometric mean without distorting the overall average.

Results

Walk observations

The first step in developing the score construction is to identify observable Walks in the value chain for each technology. The approach we take is straightforward and intuitive: given the configuration of directed graphs in each technology, we start at the last node, technology product. Using 2022 bilateral trade information from the International Trade Center's (ITC) Trade Map tool, we determine which countries export each technology. We set a threshold, considering only exporters that represent at least a significant percentage of the total export market for each technology[8].

Once we identify the countries that export the technology end product, we backtrack in the directed graph to the previous node, using Harmonized System (HS) codes[9]. In other words, we identify who are the input producers supplying to exporting countries of the technologies. This logic is applied at each node until the first node is reached, once again with the constraint that each trade flow must represent the same significant percentage of the total export market for that specific input[10].

By backtracking and covering all nodes in the directed graph, we obtain all observed high-value Walks given observed trade flows. In the case of photovoltaic solar technology, this results in 76 different geographic configurations of the value chain, or 76 observed Walks. For wind turbines there are 60, and for EV batteries 288[11].

Let's consider SPV CVC as an example to illustrate the construction of observations at the Walk level. In Figure 3, the last node encompasses both cell manufacturing and final module assembly. We refer to the corresponding HS code and identify all global exporters of this product, revealing 94 countries exporting products categorized under 'HS-code '[12], with China being the largest exporter. However, we apply a threshold to include only established producers within the SPV CVC. We consider countries representing at least 1% of the total global export market.

Next, considering the preceding node (S2) containing the process of wafer manufacturing, we aim to identify who supplies this input to each of the final product exporters. Taking China as an example, we look for supplying partners exporting HS-code$_{S2}$ categorized products to this country. In this category, Japan is the largest supplying market for China. To determine which partners are relevant for our analysis, we again apply the threshold, where a flow must represent at least 1% of the total global market value of exports for products categorized under HS-code$_{S2}$.

Finally, the same logic is replicated to determine the geographical location of the first node (S1). We then consider suppliers exporting products categorized under HS-code$_{S1}$ to Japan. We take Germany for the purpose of the example (see figure 6). In this last link, the 1% threshold is also applied. Thus, for a Walk to be considered, it must meet the threshold for each of its links.

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[8] To ensure a homogeneous sample size across different technologies, percentages of 1%, 2%, and 4% were employed for PV, WT, and EVB, respectively.

[9] Standardized parities used to categorize products in international trade, ensuring a common language for customs easing commerce. In our node specification, we paired products with HS codes using data from key sources aside from the ITC's tool itself: the European Customs Portal, Volza (an export-import trade intelligence app), Transcustoms (China HS Classification Service), and Zauba (India's commercial information provider).

[10] The analysis focused only on 2022 data due to HS code revisions in that year. Including more years risks losing homogeneity as some products were part of broader categories. Limited public information hampers correction efforts.

[11] To identify Walks that are not apparent through international trade flows due to integrated nodes within the same country, a criterion was set. Given a node located in a specific country where the exports of the preceding node's material/product exceed the predetermined percentage criteria for each trade flow in each technology, nodes located in that country will autonomously source this input.

[12] The notation HS-codeS3 refers to the HS code associated with products manufactured in node S3.

Figure 6: SPV Observed Walk Example: Germany-Japan-China

Note that since there are multiple suppliers of HS-code$_{S1}$ products to Japan, there will be multiple walks for a CVC with the same geographical location in both S3 and S2, China and Japan in our example. Let's consider the CVC where China again exports the final assembled product, Japan exports polysilicon wafers to China, but this time it is South Korea that exports polysilicon to Japan instead of Germany (Figure 7).

Figure 7: SPV Observed Walk Example: South Korea-Japan-China

These two examples involve two different Walks. Therefore, the final number of Walks, 76 in the case of SPV, represents the total number of configurations observed between countries. However, no two Walks will be identical.

A table summarizing the observations is shown below. LAC's participation in the observed Walks is highlighted in bold.

Table 2: Summary of Observed Walks

Node	Name	Number of Participant Countries	List of participant countries
		Solar PV	
S1	Polisilicon	8	China; Chinese Taipei; Germany; Japan, Malaysia, Netherlands, South Korea, and United States
S2	Wafer	10	China, Chinese Taipei, Germany, Japan; Malaysia; Netherlands; Singapore; South Korea; United States, and Vietnam
S3	Cell and PV	8	China, Germany, Malaysia, Netherlands, Singapore, South Korea, Thailand and Vietnam
		Wind Turbine	
T1	REE	1	China
T2	Copper	6	Chile, Chila, Democratic Republic of Congo, Japan, United States and Zambia

T3	Aluminum	4	China, Germany, Mexico and United States
T4	Carbon fiber blades	2	Germany and United States
T5	Permanent	1	China
T6	Nacelle	1	United States
T7	Wind Turbin	2	Germany and United States
			EV Battery
B1	Lithium	2	Chile and China
B2	Nickel	2	Australia and Indonesia
B3	Cobalt	2	China and Democratic Republic of Congo
B4	Copper	3	Chile, China, and Democratic Republic of Congo
B5	Graphite	3	China, Madagascar, and Mozambique
B6	Manganese	4	Australia, Gabon, Ghana, and South Africa
B7	Battery cell	1	China.

Note: REE for Rare Earth Elements.

Next, we turn to the unobserved Walks. Having determined the observed Walks for a value chain, by default the unobserved Walks would be all possible Walks with all existing countries, minus the observed ones. With 200 countries, this approach yields huge numbers: about 8 million for the SPV value chain, 64 trillion for WT and 12.8 trillion for EV batteries. The vast majority of those are theoretical possibilities with no economic plausibility.

We thus follow a different approach, based on variations from the observed Walks. The non- observed Walks were then generated through comparative statics, involving the substitution of country attributes in any number of nodes from the chain configuration, modifying a single node and exploring all combinations until changing all nodes simultaneously. For production nodes associated with critical materials, candidates were confined to countries with production or reserves of the specific material. In the case of industrial nodes, consideration was given to countries with a minimum threshold of manufacturing exports. This process resulted in the creation of 11,634 observations for PV, 70,565 for WT, and 47,162 for EVB. A more detailed description of the construction of the non-observed Walks and a step-by-step example is provided in Appendix 3.[13]

Walk variables

To construct the proposed score, the variable selection stage involves assessing the conditions that affect production within each country and characterizing how trade between linked nodes may occur. This underscores the importance of categorizing variables into node, country level, and link, country pairs, variables. For node variables, metrics were chosen to reflect input costs, including labor, measured by

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[13] Given the manner in which we construct the observations for unobserved Walks, the observations left out of our analysis likely correspond to implausible Walks: they include countries with low industrial maturity and/or lack of critical minerals.

Nevertheless, using a specific sample of unobserved Walks has implications on the calibration of the score. The calibrated score will reflect the way differences between nodes and links in the sample of Walks correlate with the actual existence of the Walks –for the sample. The theoretically possible Walks left out of the sample may differ from the observed Walks in different dimensions, but the score will not be able to discriminate using them.

To put it differently, there are many ways to fail and perhaps only a few to succeed. Our score will discriminate based on the ways that the in- sample unobserved Walks fail, but not based on the ways that the not-included unobserved Walks fail. If one were to include them, perhaps one would identify additional Walk characteristics correlated with failure. To the extent that the not-included unobserved Walks are implausible to begin with, these additional characteristics, and the not-included Walks, are of limited practical interest for nearshoring policy.

minimum wage, and capital, valued as cost of capital, specifically WACC for energy projects. These variables provide insight into the economic landscape and

production dynamics within a country, shedding light on the cost structure and competitiveness of its industries.

The rule of law variable assesses a country's commitment to legal principles that ensure equal treatment under the law. This variable serves as a critical indicator of how the regulatory framework and adherence to legal principles influence productive activities in a country.

We also considered exchange rate volatility using the U.S. dollar as a benchmark. This variable allows us to measure the stability of investment in a given country, providing insight into the potential risks associated with macroeconomic factors and currency fluctuations.

Trade openness provides insights into a country's commitment to international trade relations. A high trade openness ratio indicates a high degree of integration with global markets, suggesting a production focus on internationally competitive sectors. It also implies that the country has the necessary infrastructure and policies to actively participate in global trade.

Finally, the population variable serves as a control for country size, recognizing the influence of population size on economic dynamics. By incorporating these variables, our score construction methodology captures multiple aspects of a country's economic environment.

Regarding link variables, the linear shipping bilateral connectivity index, as assessed by UNCTAD[14], quantifies the strength of maritime connections between pairs of countries. A higher index value suggests a more interconnected and efficient maritime trade route between specific country pairs, indicating a potential for smoother and more cost-effective trade flows.

We introduced a political affinity variable, which measures the absolute difference in EIU's[15] democracy index scores between pairs of countries. This novel metric adds a unique layer to the assessment of distance between trading partners, providing a perspective on political compatibility.

Similarly, a commercial affinity variable was formulated to calculate the weight of a country's importance in the total trade of its trading partner. The maximum weight between the two determines the strength of the commercial relationship, providing a valuable indicator of the established economic ties between pairs of countries.

Two dummy variables contribute to the characterization of links: one assesses whether the two countries share the same official language, and another identifies countries that belong to a trading bloc, for example, NAFTA, EU; both dummies reflect the capacity to reduce political and cultural characteristics to trade. In addition, the link variables include the physical distance in kilometers between the capitals of the countries as a control factor. Altogether, these variables measure different distance dimensions between countries[16].

Note that the above variables are measured at the country level. In order to extrapolate them to the Walk level, the geometric mean of the values for each country within each Walk was calculated.

Finally, an integration level variable was created. Defined at the Walk level, the numerator reflects the number of links connecting nodes within the same country, while the denominator represents the total number of links within the entire directed graph. Consequently, this variable measures the degree of node integration within one or more countries for a specified Walk. Summary statistics for each dataset are provided in tables 4, 5 and 6.

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[14] United Nations Conference on Trade and Development

[15] Economist Intelligence Unit

[16] Table 3 provides a short description for each variable, its source, the available date range and the one that was used for observation construction, together with the number of observations at the country level.

Calibration results

To estimate the score, an algorithm equivalent to maximum likelihood estimation of a reduced- form regression specification was computed for each technology. Results are shown on table 7 (See Appendix 4).

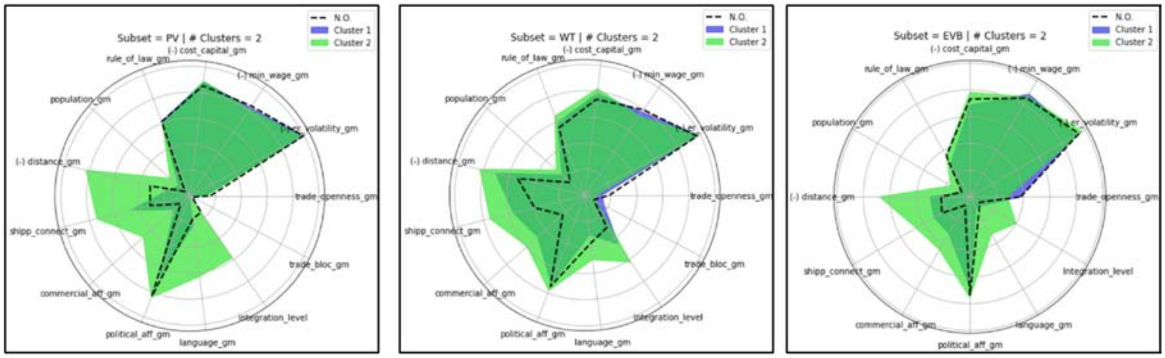
Cluster analysis and score

Since there might be competing reasons why a certain Walk configuration exists, we conducted a cluster analysis on observed Walks for each CVC. Recall that cluster analysis can help identify natural groupings in data that might not be apparent otherwise. As such, it can be a valuable tool to generate hypotheses about why such groupings might exist.

In this case, it is used to identify groupings that might reveal different paths to becoming an observed Walk. For instance, one observed Walk might incur higher input costs in production processes but face lower transportation costs, while another might face the opposite conditions, suggesting there can be more than one way to become part of the CVCs. Results of the cluster analysis are presented in Figure 8 where the mean values for each cluster are plotted together with the mean values for the unobserved Walks (N.O.).

The analysis was conducted for two clusters, as suggested by the elbow method, using a k-means clustering algorithm. Rather than pointing to trade-offs, the cluster analysis revealed two groups of observed Walks. One differs very little from the unobserved Walks (cluster 1), while the other (cluster 2) exhibits higher values in several dimensions of the spider graph[17]. They also suggest, given the variables for which such value differences exist, that link variables play a much larger role than node variables in the likelihood of observing a Walk.

Figure 8: Spider graphs and clusters of CVCs.



This is further supported by the final score outcome for each technology, where results show the scoring algorithm's predictive power to differentiate observed and unobserved Walks. Figure 9 illustrates this by contrasting the ranking on the basis of the score computed for each Walk. First, for all CVCs an average score virtually equal to zero is observed for non-observed Walks. Second, the calculated score assigns a higher average probability to observed Walks, with the magnitude differing by technology. Finally, observed Walks belonging to cluster 2 have a higher average score than those of cluster 1, providing further evidence that variables that characterize how countries within a Walk are linked play a larger role in explaining the probability of a Walk being observed.

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[17] Cluster sizes are roughly similar: for PV = C1: 30 vs C2: 46, for WT = C1: 29 vs C2: 31 and for EVB = C1: 128 vs C2: 160. Note that cluster 1 is colored in purple, cluster 2 in green and the area where they overlap has a darker green shade.

Figure 9: Predicted scores of observed and unobserved Walks for CVCs

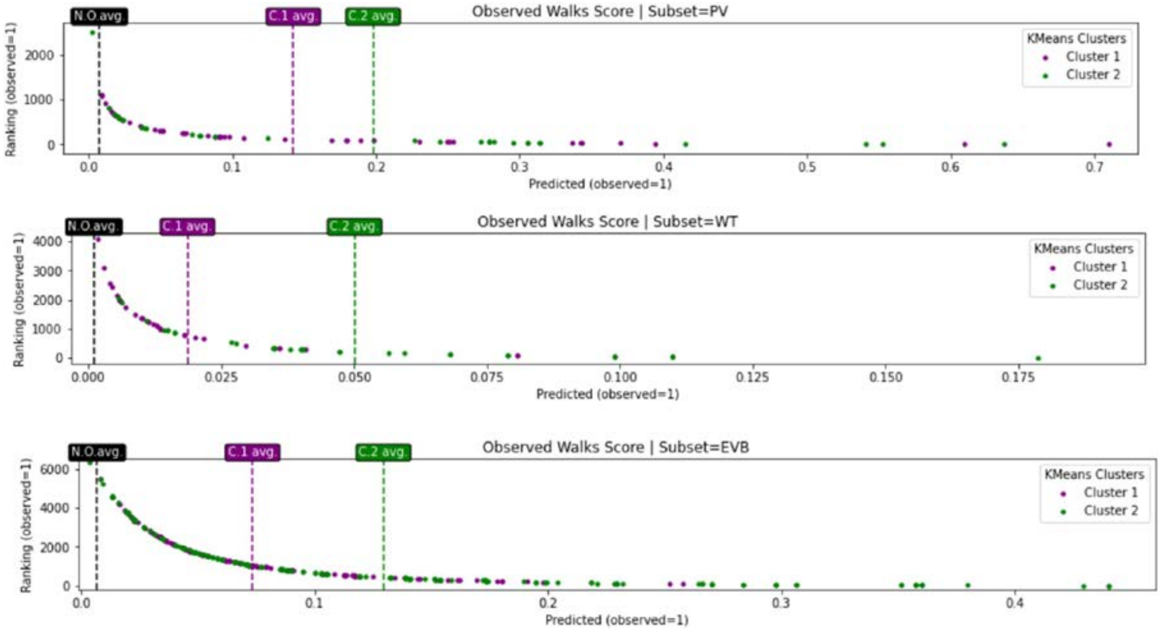

Table 3: Variables' summary

Variable Name	Full Name	Description	Source	Available Date Range (Used)	Countries
		Node Variables			
population	**Population**	Total country population	World Bank	1960-2022 **(2018-2022)**	140
trade_opennes	**Trade Openness**	Sum of a country's exports and imports as a share of that country's GDP (%).	Our World In Data	1970-2019 **(2014-2019)**	183
cost_capital	**Cost of Capital**	Country average of technology-specific real after-tax WACC	Irena	2021	100
min_wage	**Minimum Wage**	Minimum Wage regards to their minimum wage law. We've used $USD as our currency for international comparison, and have calculated minimum monthly wages, even in cases where the country in question sets only a minimum hourly or daily wage – based on information from The World Bank.	Mauve Group	2023	198
rule_of_law	**Rule of Law**	Index calculated taking into account 8 factors: constraints on government powers, absence of corruption, open government, fundamental rights, order and security, regulatory enforcement, civil justice, and criminal justice.	World Justice Project	2012-2022 **(2018-2022)**	140

er_volatility	**Official Exchange Rate**	Standard deviation of the ‘official exchange rate (LCU per US$, yearly period average).’	Own calculations, World Bank	1960-2022 **(2018-2022)**	193
		Link Variables			
shipp_connect	**Linear shipping Bilateral Connectivity Index**	Formed by the normalization of 5 components: transshipments required to get from country A to country B; number of direct connections common to both country A and B; number of common connections by country pair with one transshipment; level of competition on services that connect country A to country B; and size of the largest ship on the weakest route connecting country A to country B (quarterly observations).	UNCTAD	2006-2021Q1 **(2015-2020)**	164
political_aff	**Political Affinity**	This metric quantifies the absolute difference in democracy index values between two countries. The democracy index comprises five key categories: electoral pluralism, government effectiveness, political participation, political culture, and civil liberties.	EIU	2006-2022 **(2018-2022)**	167
commercial_aff	**Commercial Affinity**	The variable computes, for each pair of countries A and B, two ratios: the fraction of the trade with each other (exports from A to B, imports of A from B and vice versa) relative to the total trade of each country. The maximum of these ratios is taken.	ITC	2022	-
distance	**Distance between capitals**	Simple distance between capitals (capitals, km). (Transformed taking the natural logarithm (ln) of the original values and then adding a constant of 1 to better scale the data for analysis)	CEPII	-	224
langauge	**Same official language**	Variable coded as 1 when the two countries share the same official language.	CEPII	-	224
trade_bloc	**Trabe Bloc**	Dummy variable that takes a value of 1 if a link within the directed graph connects countries that belong to a trade bloc (for example, NAFTA, EU)	Own calculations	-	-
		Walk Variables			
Integration_level	**Integration Level**	The numerator represents the number of links connecting nodes within the same country, and the denominator is the total number of links within the entire directed graph.	Own calculations	-	-

Table 4: PV dataset summary statistics

	count	mean	std	min	25%	50%	75%	max
trade_openness_gm	11710	85.71	36.60	26.84	59.71	77.32	103.97	393.54
er_volatility_gm	11710	8.61	33.89	1.00	1.32	2.72	6.68	2078.53
min_wage_gm	11496	7.03	4.69	0.13	3.70	5.87	9.25	43.89
cost_capital_gm	8714	4.46	1.18	1.70	3.73	4.38	5.05	21.00

rule_of_law_gm	11710	12.34	2.20	2.96	10.80	12.30	13.82	18.24
population_gm	11710	72.19	90.65	0.37	22.42	44.57	86.62	1409.23
distance_gm	11604	7.75	3.11	1.00	3.22	9.45	10.05	10.89
shipp_connect_gm	11498	32.49	18.78	1.00	19.93	32.24	44.83	100.00
commercial_aff_gm	11710	9.56	13.82	0.00	1.63	4.73	12.18	100.00
political_aff_gm	11392	90.05	10.07	41.91	82.96	93.50	98.54	100.00
language_gm	11710	1.18	0.25	1.00	1.00	1.00	1.41	2.00
Integration_level	11710	0.15	0.24	0.00	0.00	0.00	0.50	1.00
trade_bloc_gm	11710	1.02	0.11	1.00	1.00	1.00	1.00	2.00

Table 5: WT dataset summary statistics

	count	mean	std	min	25%	50%	75%	max
trade_openness_gm	70625	46.74	10.79	27.04	38.97	44.54	52.18	131.91
er_volatility_gm	70625	2.57	3.16	1.00	1.38	1.81	2.34	60.63
min_wage_gm	69485	5.49	2.20	0.70	3.99	5.24	6.66	23.98
cost_capital_gm	56875	8.50	1.47	4.78	7.54	8.30	9.22	19.08
rule_of_law_gm	70625	11.44	1.53	4.69	10.43	11.49	12.48	16.85
population_gm	70625	210.94	119.42	3.03	125.63	195.09	273.70	1409.23
distance_gm	70085	4.21	1.00	1.00	3.21	4.20	5.26	7.85
shipp_connect_gm	69449	41.62	17.86	3.16	31.67	43.64	54.71	100.00
commercial_aff_gm	70625	22.78	13.37	0.00	12.31	20.88	31.57	100.00
political_aff_gm	68945	90.53	4.53	62.54	87.76	90.97	94.13	100.00
language_gm	70625	1.37	0.14	1.00	1.30	1.30	1.41	2.00
Integration_level	70625	0.39	0.11	0.13	0.25	0.38	0.50	1.00
trade_bloc_gm	70625	1.03	0.06	1.00	1.00	1.00	1.09	1.41

Table 6: EVB dataset summary statistics

	count	mean	std	min	25%	50%	75%	max
trade_openness_gm	47450	53.58	7.59	27.04	48.58	53.40	58.44	96.62
er_volatility_gm	47138	12.30	12.53	1.00	4.88	8.76	15.31	205.62
min_wage_gm	46058	2.95	1.33	0.68	2.02	2.67	3.56	16.18
cost_capital_gm	39050	12.25	2.46	5.86	10.53	11.98	13.69	29.58

rule_of_law_gm	47450	9.08	1.53	5.10	7.99	8.96	10.05	16.37
population_gm	47450	112.04	82.74	10.27	56.67	89.34	141.43	1409.23
distance_gm	46994	8.63	2.17	1.00	6.96	9.87	10.10	10.74
shipp_connect_gm	46706	25.19	13.57	1.00	18.37	24.93	32.77	100.00
commercial_aff_gm	47450	7.67	13.41	0.00	0.16	0.97	6.16	100.00
political_aff_gm	46586	85.27	7.68	45.06	81.09	87.05	90.87	100.00
language_gm	47450	1.13	0.16	1.00	1.00	1.12	1.26	2.00
Integration_level	47450	0.08	0.14	0.00	0.00	0.00	0.17	1.00

Discussion

The implications of these results can be better understood in the context of the energy transition (ET). According to the International Energy Agency, the scale of the shift required to move the world to a low carbon economy by 2050—in line with the Intergovernmental Panel on Climate Change's (IPCC) recommendation that global average temperatures not increase beyond 1.5°C above pre-industrial levels—is enormous. In their Net Zero Emissions (NZE) scenario[18] low- emissions energy sources must increase almost five-fold by 2050, driven mainly by electricity that will be required to meet around two-thirds of total final consumption in industry, transportation and buildings (IEA, 2022).

To do so, their estimates show the pace of new clean energy projects need to rise more than five times by 2030 to reach the levels required in the NZE Scenario, fundamentally driven by solar PV, wind and Batteries (Figure 10).

Countries around the world are effectively ramping up their efforts to expand manufacturing of clean energy technologies, but the required scale and pace is lagging[19]. To meet demand, solar must quadruple by 2030, today it accounts for 3% of generation and has annual additions of around 150GW, and planned solar capacity should be sufficient if projects materialize on time. But that is not the case for wind, where capacity by 2030 will barely meet 30% of expected demand even if projects are completed as planned. So is the case with batteries, where demand is set to increase to 5,600 GWh by 2030. To meet 75% of the expected increase for electric mobility, 150 factories with 35GWh of annual production are required, of which announced projects would cover only 85% of needs.

Critical minerals pose a similar challenge when considering the production required for NZE against current projected production for 2030. Copper, an essential component of the three technologies, has an 18% gap. Lithium, cobalt and nickel, all critical minerals for the manufacturing of batteries, face similar uncertainties. Lithium has a 45% gap, cobalt has a 5% gap in extraction and 40% in production, and nickel has a 20% gap in both extraction and production. The gap for neodymium, an essential component for wind turbine magnets, is estimated to be 10% in mining and more than 20% in production.

Figure 10: Total installed capacity and electricity generation by source in the NZE Scenario (IEA, 2022)

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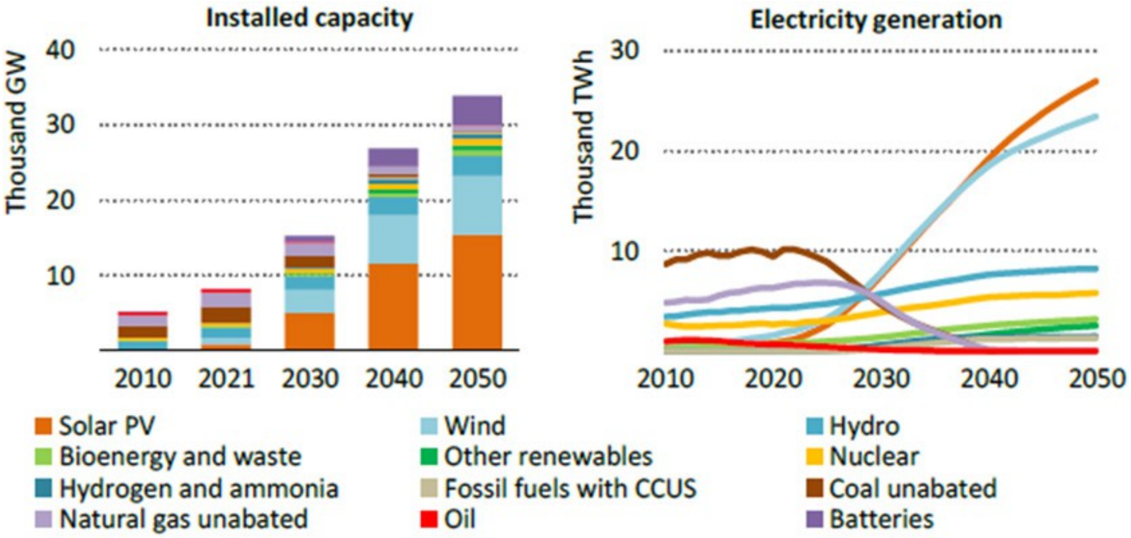
[18] The NZE scenario by 2050 is "a normative scenario that shows a pathway for the global energy sector to achieve net zero CO2 emissions by 2050. It is consistent with limiting the global temperature rise to 1.5 °C (with at least a 50% probability), in line with emissions reductions assessed in the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report". Taken from https://www.iea.org/reports/ global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze#.

[19] Estimates for this and the next paragraph taken from IEA 2022.



The scale of the expected demand for clean energy, combined with uncertainty surrounding the sources of supply, open significant opportunities for countries to improve productivity, grow and create jobs while contributing to meet climate goals. The IEA estimates there is a "global market opportunity for key mass-manufactured clean energy technologies worth around $USD

650 billion a year by 2030–more than three times today's level–[...]and that related clean energy manufacturing jobs would more than double from 6 million today to nearly 14 million by 2030, with over half of these jobs tied to electric vehicles, solar PV [and] wind."[20]

Under these circumstances it becomes critical to understand the forces behind the location of CVCs and the ways in which policy can influence them. Our results provide three important clues. The first is that the variables explaining the likelihood of observing a Walk are link variables and not node variables.

Traditional variables associated with competitiveness like cost of capital, cost of labor or rule of law don't offer significant differences between observed and unobserved Walks as was noted above, while variables that indicate the closeness of links between countries like shipping connectivity, geographical distance, commercial affinity and integration level do.

This might be the case for several reasons. One is that CVCs often involve cutting-edge technologies and a high degree of innovation that may prioritize proximity, shared technological goals and joint research efforts over traditional economic competitiveness factors. So is the case with closeness, that can facilitate effective collaboration in research, development and production. The timely and cost-effective transportation of components—essential for the efficiency and resilience of supply chains—may also lead to countries prioritizing collaboration based on logistics efficiency. Closeness can also facilitate the formation of collaborative clusters where skilled workers and research institutions help develop the entire value chain, and commercial affinity factors such as shared market goals and industry interests may be more important than traditional competitiveness factors when countries seek to access combined markets and address shared environmental challenges.

A second clue is the fact that observed Walks for each CVC can be roughly divided in two clusters. With minor differences, the first cluster closely resembles non-observed Walks for solar PV and EV batteries in

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[20] IEA 2023.

the 12 dimensions considered, while for wind turbines differences are more noticeable (figure 8). For the three technologies, however, cluster 1 is contained in cluster 2, pointing to two strategies to materialize a Walk: being not too dissimilar from non-observed Walks and substantially deepening links to potential partners in other components of the value chain.

The later strategy follows from the prior discussion: to increase the likelihood of becoming part of global CVCs, a country should focus on strengthening partnerships that can foster effective collaboration in research, logistics efficiency and shared market goals. The fact that language and population become relevant in explaining differences only for cluster 2 reinforces the significance of closeness. For Walks in this cluster—the ones with the largest average scores—differences in link variables are larger and more link variables help explain the difference with non-observed Walks. A common language can facilitate knowledge exchange, negotiation and joint decision making, while population size can influence the availability of skilled labor and the potential consumer base.

The first strategy, however, opens an important question. Among very similar Walks how can some be observed while others unobserved? An explanation could be that even if two countries have similar characteristics across the dimensions considered, elements not captured in those dimensions could lead to differences in CVC outcomes. One case could be that historical events can put similar countries on different paths of industrialization if past decisions, investments, and policies create a path-dependent trajectory that influences current economic structure. Differences in entrepreneurial culture and innovation ecosystems could be a second case if they encourage the risk-taking, entrepreneurship and innovation required for the emergence of new industries.

A third case could be the presence of established industries and their related supply chains if they create strong enough network effects to attract more investment to a particular location, that is once an industry cluster forms it can be challenging even for a similar country to replicate the same level of synergy and efficiency. Differences in the approach and effectiveness of government can also shape industrial outcomes, as could cultural factors and consumer preferences that lead to variation in the types of goods produced and consumed. A final case could be the ease with which a country is able to access and adopt knowledge that is critical to develop links of CVCs from other countries.

In other words, the specific combination of these factors and their interaction may be what ultimately determines that similar countries end up with diverging industrial outcomes.

The last clue has to do with the fact that integration level plays a significant role in explaining the likelihood of observing a Walk in the three CVCs. Recall this variable is defined as the number of links connecting nodes within the same country in relation to the total number of links within the entire directed graph, so having more links of a CVC in a single country seems to improve its chances of becoming part of the ET's global value chains.

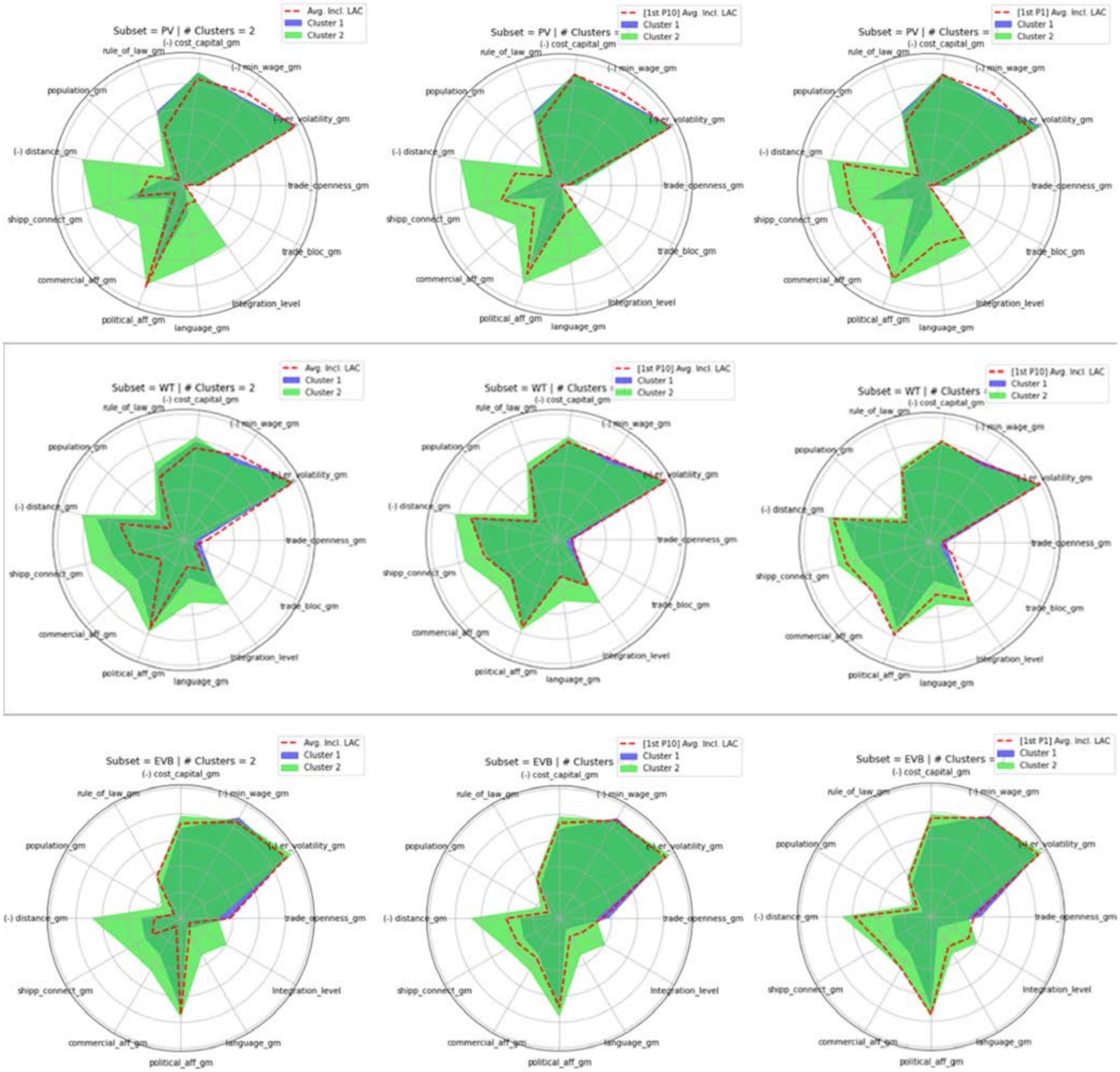
Closeness seems to be at play here too. Concentrating multiple links of a value chain in a specific country could lead to economies of scale that result in lower per-unit costs and greater cost- effectiveness. Having multiple links in proximity could also enhance supply chain efficiency by reducing transportation costs, minimizing logistical complexities and facilitating coordination.

Proximity can also foster the collaboration and knowledge exchange that promotes technological advancement, the formation of industry clusters that attract specialized suppliers and skilled labor, and may even help governments implement targeted policies to support various stages of a value chain as part of a comprehensive approach to clean energy regulation and development.

Based on these results we can turn to LAC. Figure 11 shows clusters 1 and 2 for the three technologies considered together with Walks that have LAC participation (red dotted lines), indicating the region has significant variation in its options to integrate to CVCs. Average Walks tend to coincide or fall below the observed cluster with lower predicted scores (left column), the top 10% of Walks coincide or fall above the observed cluster with lower predicted scores (middle column), and the top 1% of Walks closely resembles the observed cluster with higher predicted scores (right column). This suggests that while most of LAC's potential Walks face significant challenges to effectively become part of CVCs, there is a top tier of Walks that seem very competitive and should be easier to materialize.

Tables 8, 9 and 10 show the top 10 non-observed Walks with LAC involvement for each of the three technologies with their corresponding rankings[21]. Four facts stand out. First, how concentrated opportunities for insertion in CVCs are. For wind only Mexico appears, with one exception that includes Chile, for batteries only Chile appears, while for solar it expands to five countries—a probable reflection of the industry's greater relative maturity. Chile is the only country to appear in the top ranking for all three.

Figure 11: Clusters vs Walks with LAC participation for PV (top), WT (middle) and EV (bottom)



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[21] The ranking (last column) corresponds to the percentile in which each Walk is located according to its score in the model.

Table 8: Top 10 ranked non-observed solar PV Walks in LAC

S1	S2	S3	Percentile
Chile	**Chile**	**Chile**	0.24
United States	United States	**Dominican Republic**	0.45
United States	United States	**Costa Rica**	0.81
Colombia	**Colombia**	**Colombia**	0.92
United States	United States	**Colombia**	1.24
Uruguay	**Uruguay**	**Uruguay**	1.27
Chile	China	South Korea	1.30
Japan	China	**Chile**	1.33
Chile	**Chile**	China	1.40
China	**Chile**	**Chile**	1.41

Second, opportunities are highly concentrated by segment. In the case of wind, Chile is competitive in the production of copper ore and copper, while Mexico in the production of bauxite and aluminum. In batteries, Chile is competitive in lithium ore and copper ore; but in solar

LAC countries appear in all segments of the value chain. Having opportunities in less mature technologies so closely tied to resource endowment provides evidence on how difficult it is for the region to be competitive in manufacturing.

Table 9: Top 10 ranked non-observed WT Walks in LAC

T1	T2-T5	T2-T6	T3-T6	T3-T7	T4	T5	T6	T7	Percentile
United States	United States	United States	**Mexico**	**Mexico**	United States	United States	United States	United States	0.003
China	China	United States	United States	United States	United States	China	United States	**Mexico**	0.007
China	**Chile**	Australia	Australia	Australia	Australia	China	Australia	Australia	0.008
United States	China	United States	**Mexico**	**Mexico**	United States	United States	United States	United States	0.010
China	United States	United States	**Mexico**	**Mexico**	United States	United States	United States	United States	0.011
China	Australia	United States	**Mexico**	United States	United States	China	United States	United States	0.013
China	Australia	United States	United States	**Mexico**	United States	China	United States	United States	0.014
Australia	China	United States	**Mexico**	United States	United States	China	United States	United States	0.016
Australia	China	United States	United States	**Mexico**	United States	China	United States	United States	0.017
Australia	**Chile**	United States	United States	United States	United States	China	United States	United States	0.018

Table 10: Top 10 ranked non-observed EVB Walks in LAC

B1	B2	B3	B4	B5	B6	B7	Percentile
Chile	China	China	Democratic Republic of Congo	China	Gabon	China	0.000
China	China	Democratic Republic of Congo	**Chile**	China	Gabon	China	0.004
Chile	China	Democratic Republic of Congo	China	China	Gabon	China	0.006
Chile	China	Democratic Republic of Congo	Democratic Republic of Congo	China	Gabon	China	0.008
Chile	China	Democratic Republic of Congo	**Chile**	China	Gabon	China	0.013
Chile	China	Democratic Republic of Congo	**Chile**	China	Ghana	China	0.015
Chile	China	Democratic Republic of Congo	Democratic Republic of Congo	China	Ghana	China	0.017
Chile	China	Democratic Republic of Congo	**Chile**	China	China	China	0.019
Chile	China	China	**Chile**	China	Gabon	China	0.021
Chile	China	Democratic Republic of Congo	China	China	Ghana	China	0.023

Third, the most competitive Walks tend to favor the technology manufacturing and product installation in the same country (last node). For wind turbines it is the United States, while for EV batteries it is China. Solar again is different, with nine of the top ten Walks having the PV module manufactured and installed in a country in the region[22].

Fourth, most Walks have more than one of its links in the same country. Except for the Japan- China-Chile Walk for solar PV, all the top tier Walks are concentrated geographically. This is consistent with the previously mentioned fact that concentrating multiple links in a specific country can lead to economies of scale and lower per-unit costs that enhance supply chain efficiency.

Finally, it is important to consider how the region can take advantage of the identified opportunities to insert itself more effectively in the global CVCs. Beyond traditional competitiveness policies, general trade and FDI actions and efforts to correct market failures, there seems to be a case for structural government intervention[23]. This could involve providing direct fiscal subsidies and tax exemptions, coordinating investments in related industries and improving critical infrastructure but, as indicated above, with a focus on promoting effective links and proximity.

Specifically, governments could pursue a combination of targeted policies and strategic initiatives to promote shipping connectivity, specialization and commercial affinity and help manage geographical distance in the context of clean value chains:

- In the case of shipping connectivity, actions could focus on investing in the development of port infrastructure to facilitate the efficient movement of goods, working collaboratively with shipping companies to optimize routes and schedules to promote cost-effective

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[22] Appendix 4 shows the most competitive Walk by country for each of the three CVCs.

[23] More detail can be seen, for example, in “Strengthening value chains as an industrial policy instrument”, ECLAC United Nations 2014.

shipping connections, streamlining customs processes and reducing trade barriers and encouraging public-private partnerships to invest in and operate shipping infrastructure.

- To encourage specialization, governments can establish industry clusters or special economic zones focused on clean technologies, implement skills development programs tailored to the needs of the clean energy industry and foster research and innovation hubs that bring together industry, academia, and research institutions.
- For commercial affinity, governments can negotiate market access agreements between countries to facilitate the flow of clean energy products and its components, develop joint marketing initiatives to promote them, and facilitate trade missions and business exchanges that help build relationships between companies in different countries.
- To facilitate the management of geographical distances, governments can foster investment in digital technologies like virtual collaboration tools and IoT devices that reduce geographical barriers, strategically plan the location of key facilities and stages in the value chain to minimize transportation distances, and promote sustainable transport modes for the transportation of goods that align with clean energy goals and generate positive externalities on CVCs.

These policy actions should increase the likelihood for CVCs to materialize. But governments must also recognize when developing policy that countries pursuing energy transitions face the trilemma noted by the OECD[24]. It arises when they want to simultaneously promote the adoption of clean energy by providing incentives for the utilization of clean energy technologies, mitigate supply chain vulnerabilities by addressing concentration-related chokepoint risks, and maintain competitive neutrality by ensuring fair competition among diverse types of firms on an equitable playing field.

Chokepoints emerge when “a country or firm has such a strong control over specific stages that a reduction in their supply can endanger the entire supply chain for other countries. Geographical concentration (...) can help determine such a chokepoint by identifying the degree to which its supply is vulnerable to country-specific disruptions such as natural hazards or geopolitical events.”[25]

LAC governments must recognize this and take advantage of the fact that diversifying supply is a key component in mitigating supply chain vulnerabilities—especially since solar PV, wind turbines and EV batteries are all highly concentrated.[26] Major countries facing the clean energy trilemma will probably be willing to make cost concessions to avoid chokepoint risks that could endanger their transition strategy. This, together with well targeted policies aimed at fostering collaboration and proximity, create a unique opportunity for the region to take advantage of the surge in demand the clean energy transition is set to create.

Conclusions

This paper has focused on providing a framework to identify and analyze opportunities for LAC to become part of global CVCs in the changing landscape of the energy transition. The analysis shows such opportunities exist but are highly concentrated in terms of both country and segment, especially for less developed industries like wind turbines and batteries. Solar brings opportunities to more countries and segments, but they are still concentrated.

Our findings also highlight the predominance of link variables in shaping those opportunities. Proximity in an economic sense seems to be the key to materialize participation in CVCs and therefore a policy case to facilitate proximity and manage geographical distance can be made. It goes beyond traditional actions to foster macroeconomic stability and correct market failures to resemble a more traditional industrial-policy

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[24] “Strengthening clean energy supply chains for decarbonization and economic security”, OCDE, May 2023.

[25] OCDE (2023).

[26] See for example EIA (2023) o OCDE (2023). According to the latter all segments of the value chains have medium to high concentrations, with key parts of raw material processing and component production reaching concentration levels above 90%.

approach focused on fostering collaboration with high-potential companies, especially those that could serve as anchors in key domains of CVCs. Furthermore, managing factors such as geographical distance becomes pivotal, suggesting that strategic interventions in logistics and connectivity could enhance LAC's ability to exploit and navigate these opportunities successfully.

Finally, our analysis tries to contribute methodologically to the understanding of these dynamics. We conceptualize geographically located value chains (namely Walks) as directed graphs and characterize them through statistics of nodes and links in the graphs. Then we assign a score to each Walk, calibrated to reflect its economic viability.

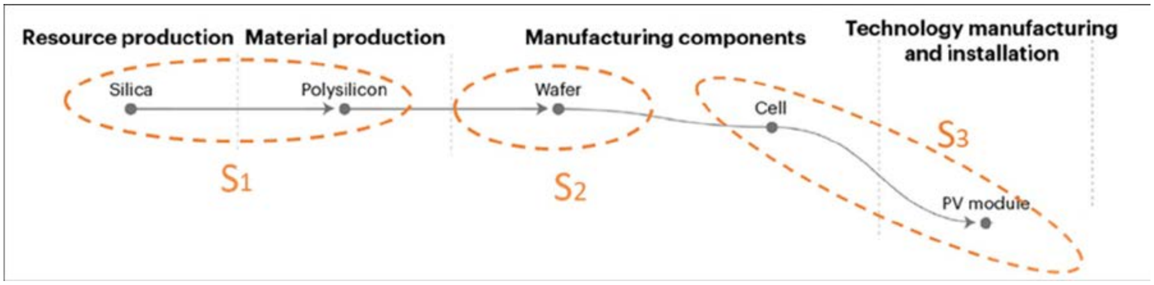
The approach employed to identify and explore variables and their impact on the likelihood of observing industrial opportunities in clean energy provides a framework for further research into other technologies and value chains, including the development of new scoring algorithms and behavioral models that can test the many hypotheses proposed. It also opens the door to discuss and refine potential strategies, policies, and interventions. Inserting itself effectively in CVCs could be one of the ways to find the sustainable growth that has eluded LAC for so long.

APPENDIX

APPENDIX 1: RATIONALE FOR NODE GROUPING AND GEOGRAPHICAL PLACEMENT SUMMARY

PV Modules:

Figure 12: Grouped steps in PV module supply chain[27]



Silicon's widespread availability in the earth's crust, as the second most abundant element after oxygen, makes its production accessible globally. This indicates that the node for silica acquisition is non-restrictive and can be disregarded for modeling purposes. Consequently, the value chain can be simplified by assuming that locations with polysilicon production also have access to primary silicon (S1). Although the standardized nature of the ingot growing and wafer cutting processes usually allows for efficient forward-integration into wafer manufacturing, we do not group polysilicon production and wafer manufacturing activities in the first node given observed trade flows of polysilicon, meaning that wafer manufacturing comprehends a separate node (S_2).

Moving further along the value chain, we group the activities of cell and module manufacturing in the third node (S_3). On one hand, this is driven by the fact that most cell manufacturers are forward integrated into module production due to the low margins in the cell business. On

the other hand, module manufacturing exhibits an almost perfect integration with the cell manufacturing business.

Wind Turbines:

Figure 13: Grouped steps in WT supply chain[28]

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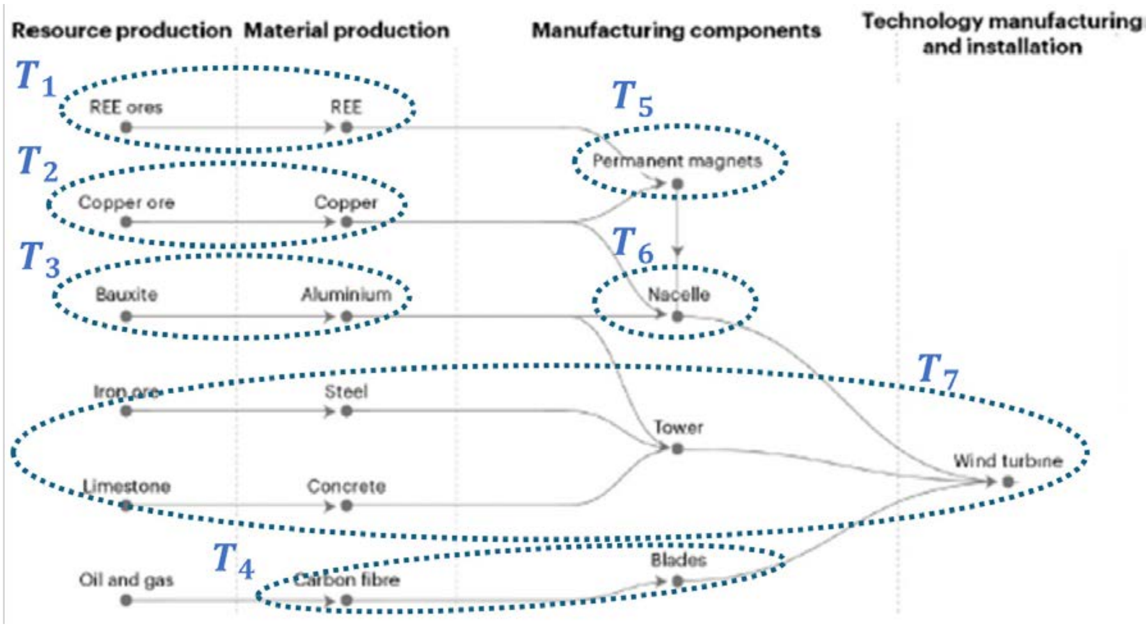
[27] Grouping logic derived from IEA (2022a, 2022c, 2023).

[28] Grouping logic derived from IEA (2022c, 2023), GWEC (2023), EY (2023) and the U.S. Department of Energy (2022).



For the initial nodes (T_1-T_3), a proposed grouping combines extractive activities of mineral ores and raw materials with their respective refining or transformation processes. However, this assumption may vary for critical minerals, as international trade flows of both rare earth elements (REE) and copper ores are recognized, indicating that their extraction and refining could be part of separate nodes. The proposed grouping represents a simplification of the chain corresponding to the current observed geographical concentration.

For the specific case of carbon fiber production, the preceding node of oil and gas is ignored as it is non-restrictive. It is assumed that a location with the capacity to produce this material already has an established supply chain for these fuels. Similarly, carbon fiber production is observed globally, except in Africa. For the purposes of this analysis, it is assumed that given a location of the blade production node, there are sufficient capacities to access this input, allowing the collapse of these activities into a single node (T_4).

Regarding permanent magnets manufacturing, it is observed that rare earth material components used to produce such magnets might well be sourced from foreign locations. Similarly, the transportation of materials for producing the nacelle is feasible, hence forming independent nodes (T_5 & T_6).

Moreover, due to the substantial weight and logistical challenges associated with transporting concrete, it is assumed that the production of this material takes place on-site where the tower will be assembled. Likewise, the production of steel is expected to occur at the location where the final turbine assembly will take place. These activities are thus grouped into one node (T_7).

Battery for EV:

Figure 14: Grouped steps in EV Battery supply chain[29]

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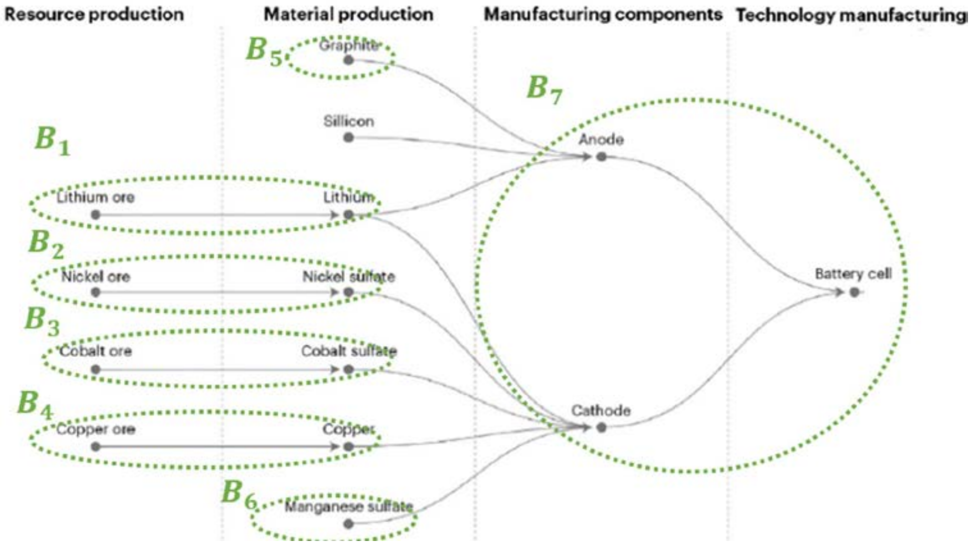
[29] Grouping logic and shares by IEA(2022b, 2022c, 2023) and McKinsey & Company (2022).



Once again, in the initial nodes, extractive activities of mineral ores are grouped with the production of their corresponding materials. It is emphasized that this assumption is flexible, and extraction and refining may correspond to separate nodes (B_1-B_4). The proposed grouping is supported by the observation of a high degree of vertical integration at a geographical level.

Subsequently, the transportation of materials for both cathodes and anodes can occur from one location to another (B_5-B_6). Finally, the cathode, anode, and battery nodes are collapsed within the model due to the inherent challenge posed by the absence of observed trade flows for these components in UNCTAD data (B_7).

Appendix 2: Score parameters calibration

Our score function $S(W_i(V))$ is of the form[30]:

$$S(W_i(V)) = A * [ATT_{node}]^{\beta_N} [ATT_{country}]^{\beta_C} [ATT_{transport}]^{\gamma_T} [ATT_{political}]^{\gamma_P}$$

Or using the shorthand notation $x \equiv log(X)$: :

$$s(W_i(V)) = \alpha + \beta_N * att_{node} + \beta_C * att_{country} + \gamma_T * att_{transport} + \gamma_P * att_{political}$$

This suggests an obvious way to calibrate the values of the parameters $\alpha, \beta_N, \beta_C, \gamma_T$ and γ_P of the score function: using regression analysis. Since we have no causal, let alone structural model, it is necessarily a reduced-form regression specification, so no clear economic interpretation is to be expected of the calibrated values. Also, the observed left-hand variable is a dummy indicating whether a Walk is observed or not, rather than the actual (unobserved) value of the score.

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[30] One should emphasize that the specific form of the score is not central to our exercise, but rather it is chosen for convenience. The variables considered can also be expanded; they are heuristically rather than theoretically motivated.

We need to define a loss function on the data and set $\alpha, \beta_N, \beta_C, \gamma_T,$ and γ_P to minimize it. For simplicity, we do this using a standard well-known algorithm: maximum likelihood estimation of a reduced-form latent variable logit model for each value chain[31]:

Each observation Vi corresponds to a Walk $W_i(V)$; the asterisk denotes the latent unobserved variable.

$$\begin{aligned} s^*_{Vi} &= s^*(W_i(V)) \\ &= \alpha + \beta_N * att_{node(Vi)} + \beta_C * att_{country(Vi)} + \gamma_T * att_{transport(Vi)} + \gamma_P \\ &\quad * att_{political(Vi)} + u_{Vi} \end{aligned}$$

u_{Vi} is assumed to have a logistic distribution.

The observed dichotomous variable is:

$$s_{Vi} = s(W_i(V)) = 1 \; if \; s^*_{Vi} \geq 0 \; and \; 0 \; otherwise$$

$s_{Vi} = 1$ means the Walk is observed, and $s_{Vi} = 0$ corresponds to non-observed Walks.

Note that, given our definition of the $att_{\square}$ variables, the constant term in the MLE subsumes the

$att_{node(Vi)}$, as the latter have no variation across Walks $W_i(V)$ of a given value chain V. Thus, dropping the att_{node} term:

$$s^*_{Vi} = \alpha + \beta_C * att_{country(Vi)} + \gamma_T * att_{transport(Vi)} + \gamma_P * att_{political(Vi)} + u_{Vi}$$

Calibrating the score is then equivalent to finding the estimates of $\alpha, \beta_N, \beta_C, \gamma_T$ and γ_P. Moreover, the (trained) score for each Walk will be the predicted value of the unobserved latent variable s^*_{Vi}:

$$\hat{s}^*_{Vi} = \hat{\alpha} + \hat{\beta}_C * att_{country(Vi)} + \hat{\gamma}_T * att_{transport(Vi)} + \hat{\gamma}_P * att_{political(Vi)}$$

Appendix 3: non-observed walks construction

The non-observed Walks were constructed using a comparative statics approach. This method involved generating new observations by changing the country attribute of every node within an observed Walk. The process included altering a single node and changing its country attribute for each candidate. Subsequently, changing each possible pair within the chain configuration to the same candidate, continuing this process until exhausting all node combinations for each number of nodes in the VC. No duplicated observations were created.

For extractive nodes related to critical minerals, candidates were limited to countries with production and/or reserves of the specific material, based on data from the US Geological Service (2022). In the case of productive nodes, candidates were economies with manufacturing exports exceeding the highest cutoff point from all three technologies, according to the World Bank. This to argue that the manufacturing economy's size was sufficient to accommodate nodes from any technology[32].

When conducting comparative statics with two or more nodes, the approach involved using the intersection between respective groups of candidates. For example, in a comparative statics analysis involving three nodes, two related to materials and one industrial, the candidates were determined by the intersection

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[31] The latent variable logit model focuses on the value of two dependent variables: a continuous unobserved (latent) variable y^* and an observed dummy y. The unobserved variable depends on observed exogenous variables x and an error term e with a logistic cdf $y^*_i = \beta' x_i + e_i \geq 0$. The materialization of a Walk is determined by the unobserved variable: if $y^*_i \geq 0$, the Walk exists, and the observed dummy takes the value $y_i = 1$. Otherwise $y_i = 0$

[32] These criteria used to filter out candidates is important for the validity of our analysis. It must reasonably weed out only implausible walks, so that the score calibration is carried out using (almost) all potentially viable walks.

between the set of candidates for mineral 1, the set of candidates for mineral 2, and the list of industrial candidates.

Let us revisit the EVB CVC to illustrate the generation of unobserved walks. As mentioned before, we start with an observed walk (an example of an EVB observed walk is provided below).

B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Chile	Indonesia	China	DR Congo	China	Australia	China

We then consider a candidate country, for example, Brazil. To change the location attribute of the first node, we evaluate whether Brazil has active lithium production or reserves (B1). In this scenario, Brazil meets this requirement, leading to the creation of a new unobserved walk that is feasible.

B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Brazil	Indonesia	China	DR Congo	China	Australia	China

This process is iteratively applied to the remaining nodes, recognizing specific mineral constraints from nodes B1 to B6, while node B7 is related to manufacturing processes and imposes no mineral constraints. This is how the subsequent unobserved walks are generated.

B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Chile	**Brazil**	China	DR Congo	China	Australia	China
Chile	Indonesia	China	DR Congo	**Brazil**	Australia	China
Chile	Indonesia	China	DR Congo	China	**Brazil**	China
Chile	Indonesia	China	DR Congo	China	Australia	**Brazil**

It is crucial to recall that in B7, being a manufacturing node, the criterion evaluated is whether Brazil, the candidate, has manufacturing exports exceeding 4% of the battery market, threshold for considering an EVB Walk. It is noteworthy that observations changing nodes B3 and B4 are not generated, as Brazil does not have significant production or reserves of cobalt or copper, respectively[33].

We then move on to changing pairs of two nodes, considering all possible combinations. To change both node B1 and node B2 at the same time, there must be significant reserves or production of both lithium and nickel. In this case, given the available resources in Brazil, the following unobserved Walks can be created.

B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Brazil	**Brazil**	China	DR Congo	China	Australia	China

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[33] According to the U.S. Geological Service (2022).

Brazil	Indonesia	China	DR Congo	**Brazil**	Australia	China
Brazil	Indonesia	China	DR Congo	China	**Brazil**	China
Brazil	Indonesia	China	DR Congo	China	Australia	**Brazil**
Chile	**Brazil**	China	DR Congo	**Brazil**	Australia	China
Chile	**Brazil**	China	DR Congo	China	**Brazil**	China
Chile	**Brazil**	China	DR Congo	China	Australia	**Brazil**
Chile	Indonesia	China	DR Congo	**Brazil**	**Brazil**	China
Chile	Indonesia	China	DR Congo	**Brazil**	Australia	**Brazil**

Now we extend the scope of change not only to three nodes, but also to the simultaneous change of all possible groups of nodes (changing 3 nodes, 4 nodes, and changing all 7 nodes simultaneously). As a result, additional viable unobserved paths are generated.

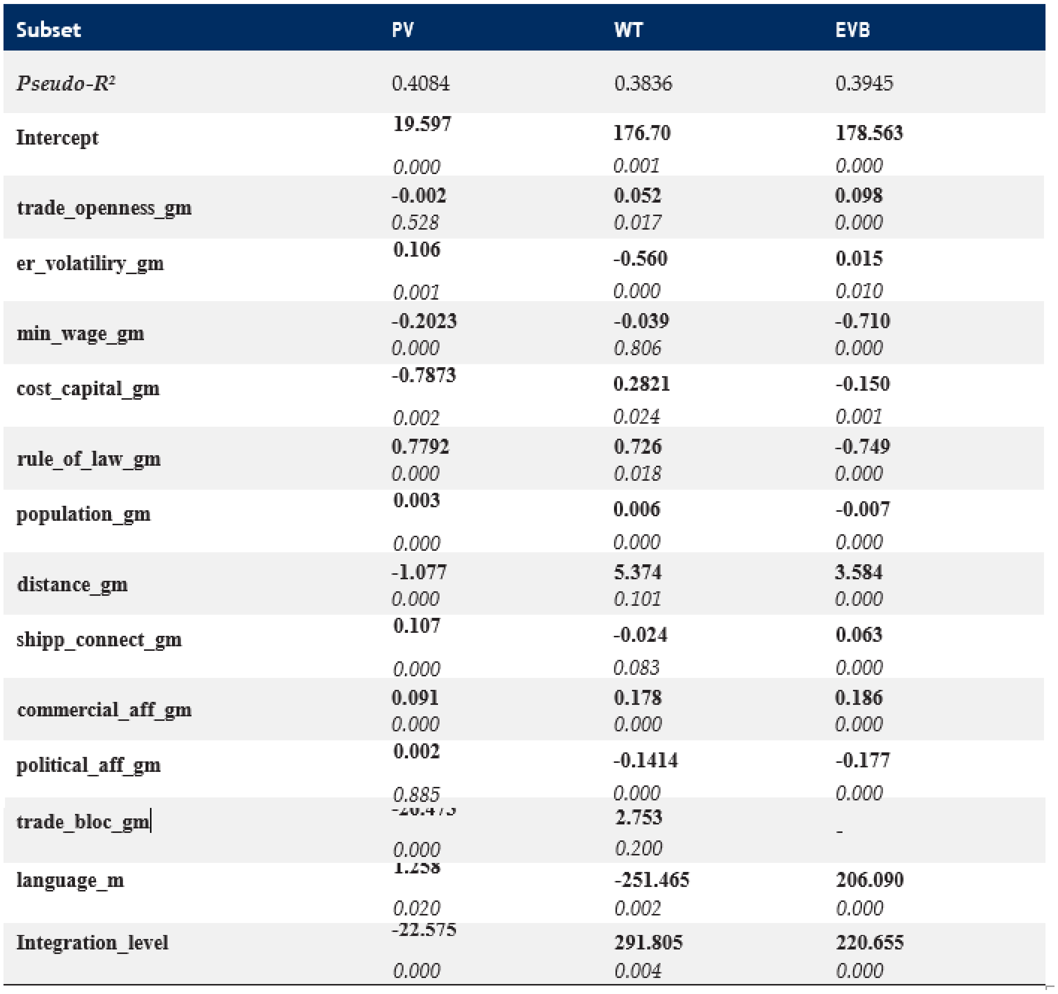
B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Brazil	**Brazil**	China	DR Congo	**Brazil**	Australia	China
Brazil	**Brazil**	China	DR Congo	China	**Brazil**	China
Brazil	**Brazil**	China	DR Congo	China	Australia	**Brazil**
Chile	**Brazil**	China	DR Congo	**Brazil**	**Brazil**	China
Chile	**Brazil**	China	DR Congo	**Brazil**	Australia	**Brazil**
Chile	Indonesia	China	DR Congo	**Brazil**	**Brazil**	**Brazil**
Brazil	**Brazil**	China	DR Congo	**Brazil**	**Brazil**	China
Brazil	**Brazil**	China	DR Congo	**Brazil**	Australia	**Brazil**
Brazil	**Brazil**	China	DR Congo	**Brazil**	**Brazil**	**Brazil**

Again, it is emphasized that a Walk in which Brazil integrates all nodes cannot exist due to mineral availability constraints.

From the generated Walks, it is ensured that none replicates an observed Walk; if such a case occurs, the Walk is not generated. This exercise is repeated for each observed Walk with each candidate country, not only those belonging to LAC, but any country in the world that meets the requirements of each node or group of nodes.

Appendix 4: Score calibration results

Table 7: Score Calibration Results[34,35]



Subset	PV	WT	EVB
Pseudo-R²	0.4084	0.3836	0.3945
Intercept	**19.597** *0.000*	**176.70** *0.001*	**178.563** *0.000*
trade_openness_gm	**-0.002** *0.528*	**0.052** *0.017*	**0.098** *0.000*
er_volatiliry_gm	**0.106** *0.001*	**-0.560** *0.000*	**0.015** *0.010*
min_wage_gm	**-0.2023** *0.000*	**-0.039** *0.806*	**-0.710** *0.000*
cost_capital_gm	**-0.7873** *0.002*	**0.2821** *0.024*	**-0.150** *0.001*
rule_of_law_gm	**0.7792** *0.000*	**0.726** *0.018*	**-0.749** *0.000*
population_gm	**0.003** *0.000*	**0.006** *0.000*	**-0.007** *0.000*
distance_gm	**-1.077** *0.000*	**5.374** *0.101*	**3.584** *0.000*
shipp_connect_gm	**0.107** *0.000*	**-0.024** *0.083*	**0.063** *0.000*
commercial_aff_gm	**0.091** *0.000*	**0.178** *0.000*	**0.186** *0.000*
political_aff_gm	**0.002** *0.885*	**-0.1414** *0.000*	**-0.177** *0.000*
trade_bloc_gm	**-20.475** *0.000*	**2.753** *0.200*	-
language_m	**1.258** *0.020*	**-251.465** *0.002*	**206.090** *0.000*
Integration_level	**-22.575** *0.000*	**291.805** *0.004*	**220.655** *0.000*

Note: No result is given for the estimated coefficient of the variable trade_bloc_gm in the EVB model, since there is no link between partners belonging to the same bloc in all the Walks (the value of the variable is equal to 1 in all observations, both at the country pair level and at the Walk level).

Regarding the explanatory power of the model, the Pseudo-R^2 is near 0.4 for the three estimations. The trade openness estimator indicates that a higher engagement in international trade contributes significantly and positively to the score, except for PV, where the estimator is not significant.

Exchange rate volatility significantly impacts the score in all three regressions. Surprisingly, in PV and EVB higher macroeconomic instability doesn't necessarily correlate with a lower likelihood of observing these

---

[34] The theoretical model specification allows for a regression model that pools all Walks for the three value chains and includes value chain fixed effects. This is an artifact of characterizing the Walks through the geometric averages of its attributes over nodes and links and implicitly ignores that those averages are over different numbers of nodes and links, which muddles the interpretation of the estimated coefficients. Hence we chose to run separate regressions for each value chain.

[35] Each variable in each subset displays the estimated coefficient in bold above and the p-value below.

value chains. This result challenges our prior that economic instability prevents involvement in transnational value chains[36].

The minimum wage and cost of capital exhibit an effect in line with the logic that productive nodes tend to be located in countries with lower input costs. For wind turbines, however, this effect is conflicting for cost of capital and non-significant for minimum wages.

Rule of law and population size both positively impact the score for PV and WT, but negatively for EVB. This indicates the productive nodes for PV and WT tend to be in more populated countries, driven by a robust regulatory framework. The opposite applies to EVB.

Regarding distance variables, shipping connectivity aligns with expectations correlating higher connectivity between countries in a Walk with a larger score, although it is not significant for WT. Commercial affinity contributes to a higher score in all three subsets while, contrary to our initial assumption, political affinity has a negative effect, ambiguous in the case of PV. The trade bloc variable presents challenging results, negatively impacting the score in PV. Furthermore, a Walk featuring countries speaking the same official language is more likely to be observed in the PV value chain, but intriguingly deteriorates the score for the other technologies. Lastly, the integration level variable indicates that a more integrated Walk is less likely to exist in PV value chains, although more likely in WT and EVB[37].

Appendix 5: top 10 ranked non-observed walks in lac by country

Table 11: Top ranked non-observed PV Walk by country

Country	Percentile	S1	S2	S3
Chile	0.24	**Chile**	**Chile**	**Chile**
Dominican Republic	0.45	United States	United States	**Dominican Republic**
Costa Rica	0.81	United States	United States	**Costa Rica**
Colombia	0.92	**Colombia**	**Colombia**	**Colombia**
Uruguay	1.27	**Uruguay**	**Uruguay**	**Uruguay**
Panama	1.76	United States	United States	**Panama**
Brazil	2.19	**Brazil**	China	China
Honduras	4.36	United States	United States	**Honduras**
Peru	4.70	China	China	**Peru**
Guatemala	7.04	United States	United States	**Guatemala**
Nicaragua	7.41	United States	United States	**Nicaragua**
Mexico	7.64	Japan	China	**Mexico**
El Salvador	9.56	United States	United States	**El Salvador**

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[36] The literature provides a candidate explanation for this result: the macroeconomic instability may capture the effect both of high-value natural resource production that is necessary for the value chain, and of institutional disarray caused by the curse of natural resources.

[37] The literature on business strategy in international investment suggests that international disintegration in the value chain is possible if transaction costs are lower across countries. Aside from the obvious transportation and trade-related costs, lower transaction costs may require a more mature value chain, where individual processes are well understood and monitored, intellectual property rights are not a critical concern, and where securing access to critical inputs does not require home production.

Ecuador	11.90	United States	United States	**Ecuador**
Argentina	17.50	Japan	China	**Argentina**

Table 12: Top ranked non-observed WT Walk by country

Country	Percentile	T1	T2T5	T2T6	T3T6	T3T7	T4	T5	T6	T7
Mexico	0.003	United States	United States	United States	**Mexico**	**Mexico**	United States	United States	United States	United States
Chile	0.008	China	**Chile**	Australia	Australia	Australia	Australia	China	Australia	Australia
Brazil	0.054	**Brazil**	China	United States	Mexico	United States	United States	China	United States	United States
Uruguay	0.144	China	China	United States	United States	United States	United States	**Uruguay**	United States	United States
Peru	0.150	China	**Peru**	United States	Mexico	United States	United States	China	United States	United States
Honduras	0.201	China	China	United States	**Mexico**	United States	Honduras	China	United States	United States
Costa Rica	0.212	China	China	United States	United States	Mexico	**Costa Rica**	China	United States	United States
Dominican Republic	0.215	China	China	United States	United States	Mexico	**Dominican Republic**	China	United States	United States
Nicaragua	0.241	China	China	United States	Mexico	United States	**Nicaragua**	China	United States	United States
Ecuador	0.486	China	China	United States	United States	Mexico	**Ecuador**	China	United States	United States
El Salvador	0.514	China	China	United States	United States	Mexico	**El Salvador**	China	United States	United States
Panama	0.528	China	China	United States	United States	United States	United States	**Panama**	United States	United States
Guatemala	0.538	China	China	United States	Mexico	United States	**Guatemala**	China	United States	United States
Colombia	0.801	China	China	United States	Mexico	United States	**Colombia**	China	United States	United States
Argentina	1.865	China	China	United States	Mexico	United States	**Argentina**	China	United States	United States
Paraguay	2.256	China	China	United States	Mexico	United States	**Paraguay**	China	United States	United States
Trinidad and Tobago	9.526	China	China	United States	United States	Germany	**Trinidad and Tobago**	China	United States	Germany

Table 13: Top ranked non-observed EVB Walk by country

Country	Percentile	B1	B2	B3	B4	B5	B6	B7
Chile	0.00003	**Chile**	China	China	Democratic Republic of Congo	China	Gabon	China
Peru	0.00195	China	Australia	Democratic Republic of Congo	**Peru**	China	Gabon	China
Brazil	0.00286	Chile	**Brazil**	China	Democratic Republic of Congo	China	Gabon	China
Mexico	0.01182	Chile	Australia	Democratic Republic of Congo	Democratic Republic of Congo	**Mexico**	Ghana	China
Argentina	0.02016	**Argentina**	Australia	Democratic Republic of Congo	China	China	Ghana	China
Costa Rica	0.07822	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Costa Rica**
Uruguay	0.07921	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Uruguay**
Panama	0.14866	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Panama**
Trinidad and Tobago	0.16583	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Trinidad and Tobago**
Colombia	0.17115	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Colombia**
Dominican Republic	0.18388	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Dominican Republic**
El Salvador	0.18829	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**El Salvador**
Honduras	0.19051	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Honduras**
Ecuador	0.19559	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Ecuador**
Guatemala	0.20391	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Guatemala**
Nicaragua	0.20974	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Nicaragua**
Paraguay	0.22445	China	Indonesia	Democratic Republic of Congo	Democratic Republic of Congo	Mozambique	Gabon	**Paraguay**

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CAF DEVELOPMENT BANK OF LATIN AMERICA AND THE CARIBBEAN GEORGETOWN UNIVERSITY GEORGETOWN AMERICAS INSTITUTE

About the project

The Georgetown Americas Institute's Latin America in the Global Economy (LAGE) program is a multiyear initiative to advance research and promote dialogue within the academy and with governments, the private sector, and civil society around the most critical economic challenges facing the region. A critical focus will be the emerging position of Latin America and the Caribbean (LAC) in a new global economic trade architecture characterized by deep structural changes.

The authors acknowledge the financial support of CAF, Development Bank of Latin America and the Caribbean, in the preparation of this document. The results, interpretations and conclusions expressed in this publication are the exclusive responsibility of its author(s), and in no way can they be attributed to CAF, the members of its Executive Board or the countries they represent. CAF does not guarantee the accuracy of the data included in this publication and is not responsible in any way for the consequences resulting from its use. The authors appreciate the comments of Fernando Branger (CAF), Carlo Pietrobelli (United Nations University UNU-MERIT & Roma Tre University), Juan Blyde (IDB), and Jorge Arbache (CAF), and an anonymous referee. We also acknowledge the project's technical coordinators Alejandro Werner (GAI), Antoni Estevadeordal(GAI), Veronica Frisancho (CAF), and Fernando Alvarez (CAF).

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