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Evidence from MENA Economies and Firm-Level Insights from Turkey

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Abstract

This paper examines brown lock-in from two complementary perspectives: country-level patterns in the MENA region and firm-level dynamics in Türkiye. Brown lock-in refers to a persistent dependence on brown, low-complexity products that makes it difficult for economies and firms to shift toward greener and more sophisticated activities. Understanding both the level and the evolution of this lock-in, as well as the factors that drive it, is essential for designing effective policies that support structural transformation. To do so, first, we look at brown lock-in patterns in the MENA, a region with strong hydrocarbon dependence and high transition risks, for the period 1999-2023. Using country-level Brown Lock-In (BLI) index, we examine differences across countries and estimate how brown lock-in relates to macroeconomic outcomes through a two-way fixed effects approach. In the second part, we shift to the firm level and calculate BLI indices for Turkish exporters using detailed HS-6 product data, for the period 2013-2023. This lets us study how product complexity, export diversification, and brown intensity shape firms' exposure to transition risks, offering the first micro-level evidence of brown lock-in dynamics in a major emerging economy. To do so, we apply a Heckman two-step procedure to control for selection bias in firms' export decisions, and then identify the main factors that shape firm-level BLI scores. Understanding these determinants is important because it shows which types of firms are more vulnerable during the green transition. Our results for the MENA region show that financial globalization reduces brown lock-in, indicating that greater access to global financial markets can help countries move away from simple, resource-based export structures. In contrast, trade globalization increases brown lock-in across all country groups, suggesting that current trade patterns reinforce existing specialization in low-complexity products rather than encouraging diversification. The MENA results also differ between oil exporters and oil importers, reflecting the distinct structural constraints and export profiles of these two groups. These findings highlight the need for policies that deepen financial integration while restructuring trade incentives. Expanding access to stable, long-term international finance may support upgrading, whereas trade policies should focus on capability building and the development of higher-value export sectors. The firm-level analysis for Turkiye shows that financial conditions are central to understanding brown lock-in. Leverage consistently increases firms' BLI scores, indicating that more indebted firms remain more dependent on brown and low-complexity export products. By contrast, firm age and firm size reduce brown lock-in, suggesting that experience and a modest degree of scaling help firms gradually diversify their product mix. In manufacturing, total factor productivity also has a negative and significant effect, showing that more productive firms are better able to upgrade and move away from brown activities. Our results also differ across sectors and firm sizes, indicating that brown lock-in is not uniform but shaped by firms' structural and operational characteristics.

Key words: Turkey, MENA, brown products, product complexity, Brown Lock-in Index

JEL Classifications: Q56, D22, F14

I. Introduction

The global move toward a low-carbon economy is changing how countries produce, trade, and compete. As governments commit to cut greenhouse-gas emissions, demand for carbon-intensive or "brown" products is likely to fall, while new chances will open up in advanced green industries. Because of this shift, understanding where countries and firms stand in the transition has become an important topic in studies on economic complexity and sustainability. Research shows that productive systems change gradually, and countries that already work in areas requiring similar skills are more likely to branch into new ones (Hausmann & Klinger, 2006; Hidalgo et al., 2007). This idea supports recent attempts to map green capabilities and find potential transition paths (Mealy & Teytelboym, 2020).

In this context, the difference between green and brown products is important. Green products represent technologies expected to grow in value as the world cuts carbon emissions, while brown products are carbon-intensive goods that may lose global importance. Using the product-space approach, recent studies have created measures to evaluate how exposed countries are to brown activities and how likely they are to shift toward greener capabilities. The Green Transition Navigator introduces the Brown Lock-In Index (BLI), which captures transition risk by looking at the share of low-complexity, carbon-intensive goods—often basic or primary products—in a country's exports (Andres & Mealy, 2021). New evidence from Andres et al. (2023) shows that countries focused on a small set of simple brown goods, like crude oil or raw hydrocarbons, have far fewer nearby diversification options compared to countries exporting more complex brown goods such as engines, pumps, or petrochemical products. These results highlight that lock-in risk depends not only on how much a country relies on brown products, but also on the technological sophistication of its export mix.

Even with these advances, most research still looks only at the country level. Country-level indicators are useful for spotting broad structural risks, but they do not show how transition risks are spread among firms within the same economy. This firm-level view is especially important for middle-income countries like Turkey, where industrial skills and export complexity differ greatly across regions and industries. In addition, no study so far has calculated a Brown Lock-In Index at the firm level, leaving a key micro-level gap in both the economic complexity and sustainability transition literature.

This paper tries to fill this gap with a two-part empirical analysis. First, we look at brown lock-in patterns in the Middle East and North Africa (MENA), a region with strong hydrocarbon dependence and high transition risks, for the period 1999-2023. Using country-level Brown Lock-In (BLI) index, we examine differences across countries and estimate how brown lock-in relates to macroeconomic outcomes through a two-way fixed effects approach. In the second part, we shift to the firm level and calculate BLI indices for Turkish exporters using detailed HS-6 product data, for the period 2013-2023. This lets us study how product complexity, export diversification, and brown intensity shape firms' exposure to transition risks, offering the first micro-level evidence of brown lock-in dynamics in a major emerging economy. To do so, we apply a Heckman two-step procedure to control for selection bias in firms' export decisions, and then identify the main factors that shape firm-level BLI scores. Understanding these determinants is important because it shows which types of firms are more vulnerable during the green transition.

The remainder of the paper is organized as follows. Section 2 reviews the literature on economic complexity, green transitions, and brown lock-in. Section 3 presents the data, conceptual and methodological framework, and empirical analysis. Section 3.i focuses on MENA countries, while Section 3.ii examines Turkish firms using firm-level data. Section 4 concludes

II. Literature Review

The economic development literature has long stressed that a country's productive structure plays an important role in its long-term growth. Early studies show that countries exporting more sophisticated goods tend to grow faster (Rodrik, 2006; Hausmann, Hwang & Rodrik, 2007). Following this idea, Hidalgo & Hausmann (2009) introduced the Economic Complexity Index (ECI), which aims to reveal the underlying productive capabilities reflected in a country's export basket. Hausmann et al. (2014) later expanded this framework in *The Atlas of Economic Complexity*."

The ECI is based on a simple logic: the complexity of a product can be inferred from how many countries export it and how diverse those countries are. Products exported by only a few but highly diversified economies are seen as more complex, since producing them requires a wider and more unique set of capabilities. Alongside this, the Product Complexity Index (PCI) measures the sophistication of individual products, while the ECI captures the overall complexity of a country's productive structure (Hidalgo & Hausmann, 2009; Hausmann et al., 2014).

This complexity approach was first introduced as an alternative to earlier measures like PRODY and EXPY, which were based heavily on income levels and were often criticized for being circular. In contrast, the ECI and PCI try to identify productive capabilities without relying on income data, focusing instead on the structure of the country–product network. This change helped make economic complexity an important tool for studying industrial development, diversification, and technological upgrading.

In recent years, economic complexity has also been brought into the literature on environmental and climate transitions. This new line of work links countries' productive capabilities to their capacity to adjust to, or take advantage of, the global move toward a low-carbon economy. One of its main contributions is the identification of green and brown product groups, along with indices that measure countries' green competitiveness and their exposure to transition risks. Mealy & Teytelboym (2020) introduced the Green Complexity Index (GCI), which reflects a country's ability to export advanced green products in a competitive way. Their work created an important connection between productive capabilities and environmental outcomes by framing green technologies as capability-intensive activities that depend on specific knowledge and skills. The framework was later expanded by Andres et al. (2023), who adapted the complexity approach to measure countries' exposure to brown lock-in risks. This led to the development of the Brown Lock-In Index (BLI).

Andres et al. (2023) created detailed lists of "brown" products, meaning carbon-intensive goods that are expected to lose importance as the world decarbonizes. Based on this, they introduced the BLI, which measures how much of a country's export basket is made up of low-complexity brown products. A high BLI shows that a country is structurally dependent on carbon-heavy exports and may face limited diversification options, especially when its brown specialization is concentrated in low-PCI goods like crude oil or unprocessed hydrocarbons. Overall, their work highlights that transition risk depends not only on how carbon-intensive a country's exports are, but also on the technological sophistication behind them.

Broader research has also looked at what drives economic complexity. The literature links economic complexity to factors such as trade openness, institutional quality, innovation, and financial development (Hausmann et al., 2014; Hidalgo & Hausmann, 2009; Chu, 2020; Nguyen & Su, 2021). A smaller set of studies focuses directly on the green side. For example, Mealy & Teytelboym (2020) and Andres et al. (2023) point out that countries differ not only in their ability to produce green goods but also in their transition potential and their vulnerability to transition risks.

However, only a limited number of empirical studies examine the drivers of the green complexity. Moreover, the literature remains heavily focused on the country level. For instance, Yasar (2022) finds that stronger domestic financial systems can encourage greener and more complex production, although the effects vary between advanced and developing economies. On the other hand, empirical evidence at the firm level is limited. Although there is a growing literature on the firm-level drivers of export participation and product choice (e.g. Kaya & Gönel, 2024; Cieślik & Michałek, 2018), some recent studies have also shifted their attention toward green exports, examining how firms upgrade their products and participate in cleaner and more sustainable export activities (e.g. Singh et al., 2024; He & Cai, 2023). A related example for Turkiye is Yasar (2022), who calculates a firm-level green complexity index and studies its determinants, with a particular focus on financial development

While the green complexity literature has expanded quickly, the brown dimension has received much less attention. Although country-level BLI values are provided by the Green Transition Navigator, the index itself has not been examined empirically. To the best of our knowledge, there is no study that analyzes brown lock-in across a set of countries, such as the MENA region, or investigates the macro-level factors behind these differences. Moreover, no existing study computes a firm-level Brown Lock-in Index, leaving open questions about how micro-level productive structures influence exposure to transition risks. This gap is particularly relevant for emerging economies where firm capabilities vary widely and may not align with country-level indicators.

This study aims to contributes to this literature by looking at brown lock-in from both the macro and micro perspective. This dual perspective helps capture transition risks that may not be visible when looking only at countries or only at firms. At the country level, we assess transition risks in the MENA region, where reliance on fossil fuels is structurally high. At the firm level, we offer the first attempt to build a Brown Lock-in Index for individual exporters in Türkiye using detailed product-level data. By combining economic complexity with environmental transition indicators at different scales, this study contributes to the growing work that connects productive capabilities with climate-related risks and opportunities.

III. Methodology and Data

The methodology consists of two components: a country-level analysis focusing on the MENA region and a firm-level analysis based on exporter data from Turkiye.

III.i. Country-Level Analysis (MENA Sample)

This subsection outlines the country-level analysis focusing on the MENA region. The goal is to examine how countries differ in their exposure to brown lock-in risks and to identify macroeconomic factors associated with this variation. To do so, we combine BLI scores with a set of structural and institutional indicators.

Our sample covers 18 MENA economies for the period 1999–2023. To capture structural differences in transition risks, we classify these countries into oil exporters and non-oil exporters following the standard grouping commonly used in the MENA literature (World Bank, 2012). The oil-exporter group includes Algeria, Bahrain, Iran, Iraq, Kuwait, Libya, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, all of which rely heavily on hydrocarbons and have export baskets dominated by carbon-intensive products. The non-oil exporters are Djibouti, Egypt, Israel, Jordan, Lebanon, Morocco, Tunisia, and Turkiye and they do not depend on hydrocarbons to the same extent and exhibit more diversified export structures.

III.i.1 Country-level Data

For the country-level analysis, we do not compute the Brown Lock-in Index (BLI) ourselves. Instead, we rely on the pre-calculated BLI scores from the Green Transition Navigator[1] developed by Andres & Mealy (2021). These scores are publicly available and allow for consistent cross-country comparisons of transition risk. The Green Transition Navigator defines the BLI as "the share of low-complexity, carbon-intensive products in a country's export basket, weighted by product complexity" (Andres & Mealy, 2021; Andres et al., 2023). The Green Transition Navigator dataset includes BLI values for more than 130 countries. For this study, we use the BLI values reported in the database for all MENA economies for which data are available.

In addition to the BLI, the model includes several macroeconomic and structural variables. The definitions of these variables and their data sources are presented below.

financial_globalization (fin_glob): This variable shows the level of financial globalization (de facto). The index covers foreign direct investment, portfolio investment, international debt, international reserves and international income payments as a percentage of GDP. The data are taken from the KOF Globalisation Index, using the updated version published by Gygli et al. (2019), which builds on the original index introduced by Dreher (2006)**.**

trade_globalization (trade_glob): This variable shows the level of trade globalization (de facto), which refers multilateral trade openness. The index covers trade in goods, trade in services and trade partner diversification as a percentage of GDP. The data are taken from the KOF Globalisation Index, using the updated version published by Gygli et al. (2019), which builds on the original index introduced by Dreher (2006)**.**

gross_capital_formation (gcf): This variable reflects investment in fixed assets such as machinery, equipment, and infrastructure. It is widely used as an indicator of capital accumulation. GCF (as a percentage of GDP) is taken from the World Development Indicators (WDI) database (World Bank, 2023).

government_expenditure (gov): Government expenditure measures total public spending on goods, services, and investment. It is commonly used to capture the size and role of the public

[1] https://green-transition-navigator.org/

sector in the economy. GOV (as a percentage of GDP) is obtained from the World Development Indicators (WDI) database (World Bank, 2023).

GDP_per_capita (gdppc): GDP per capita reflects the average income level in an economy and is widely used as a general measure of economic development. The data are taken from the World Development Indicators (WDI) database (World Bank, 2023).

Population_density (pop_density): This variable measures the number of people per square kilometer and captures the demographic concentration within a country. The data are obtained from the World Development Indicators (WDI) database (World Bank, 2023)

III.i.2 Country-Level Empirical Strategy

Following Andres et al. (2023), brown products are defined as carbon-intensive goods whose global demand is expected to fall under a successful climate transition and are identified at the HS6 level. These products include crude oil, refined petroleum, natural gas, basic metals, fertilizers, cement, and other high-emission commodities.

In assessing brown lock-in, it is important to consider not only the carbon intensity of exports but also their underlying complexity. To capture this dimension, we follow Andres et al. (2023) and use the Product Complexity Index (PCI) to identify low-complexity brown products. A brown good is classified as low-complexity if its PCI score falls below the median PCI value of all brown products. This distinction matters because low-PCI brown goods—such as crude oil, natural gas, and raw minerals—tend to generate much higher lock-in risks than more complex brown products, including engines, pumps, or petrochemical derivatives. As shown in Andres et al. (2023), countries specializing in these low-complexity brown goods are more vulnerable to structural dependence and face fewer diversification opportunities during the transition.

To quantify countries' exposure to brown lock-in risk, we use the Brown Lock-in Index (BLI) as defined by Andres et al. (2023) and reported in the Green Transition Navigator database.The index captures the extent to which a country's export basket is concentrated in carbon-intensive products that require relatively limited productive capabilities.

The BLI for country c in year t is calculated as:

$$BLI_{c,t} = \sum_{p \in Brown} s_{c,p,t} \ (1 - PCI_p)$$

where $s_{c,p,t}$denotes the share of product p in country c's total exports, and $PCI_p$is the Product Complexity Index of product p. PCI provides a measure of the technological sophistication embedded in each product. It ranks products based on the characteristics of the countries that export them competitively: high-PCI products tend to be those exported by highly diversified and complex economies, while low-PCI products are typically exported by countries with more limited productive capabilities. PCI is therefore commonly used as a proxy for the capability intensity and technological sophistication associated with a given product. The PCI is normalized to range between 0 and 1, allowing products to be weighted according to their relative complexity. A higher BLI score therefore indicates that a country relies more heavily on low-complexity, carbon-intensive exports and is more vulnerable to brown lock-in.

To examine how macroeconomic and structural factors are associated with brown lock-in in the MENA region, we estimate a panel regression model using a two-way fixed-effects estimator with clustered standard errors:

$$\begin{aligned} BLI_{i,t} = \beta_1 L2.\,finance\_glob_{i,t} + \beta_2 L2.\,trade\_glob_{i,t} + \beta_3 L2.\,gcf_{i,t} + \beta_4 L2.\,gov_{i,t} \\ + \beta_5 L2.\ln gdppc_{i,t} + \beta_6 L2.\ln pop\_density_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \end{aligned}$$

where $\mu_i$denotes country fixed effects and $\lambda_t$denotes year fixed effects. To reduce potential endogeneity concerns, all explanatory variables are included in their second lag.

III.i.3 Empirical Findings for MENA Countries

We first provide descriptive statistics to give an overview of the BLI distribution and the characteristics of the key variables in the MENA sample.

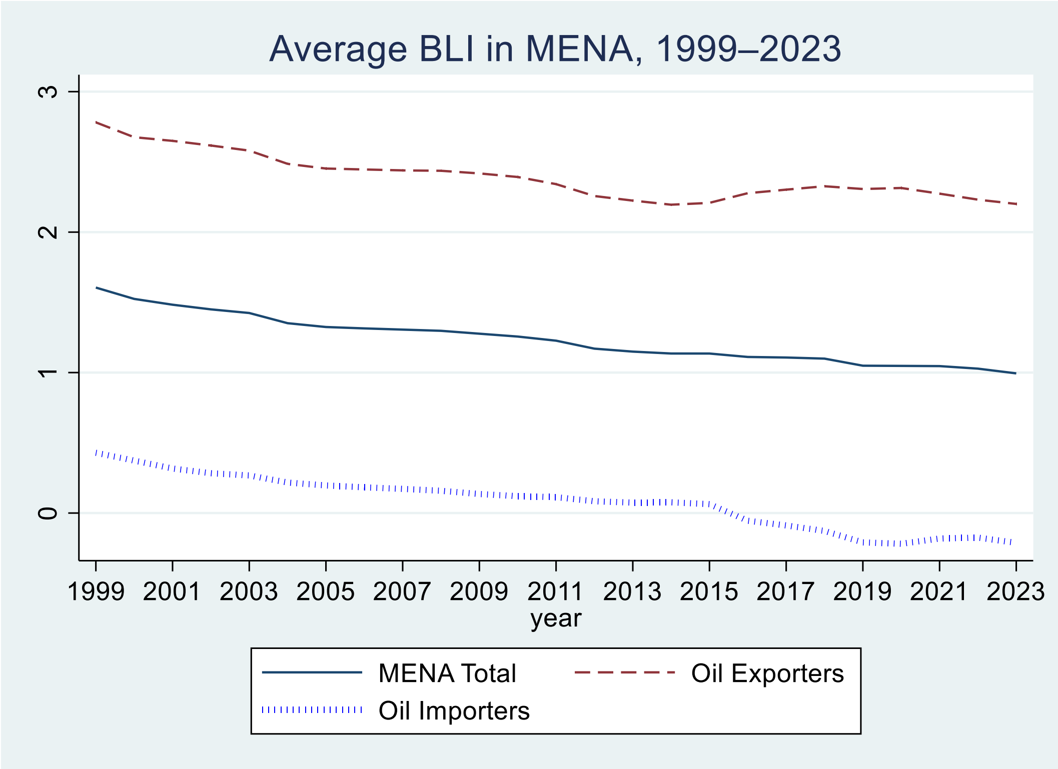
Table 1: Descriptive statistics for MENA sample

Variables	Mean	p50	SD	Min	Max	p25	p75
Brown lock_in indeks (bli)	1.24	1.26	1.48	-0.66	3.68	-0.40	2.69
Financial globalization (financial_glob)	59.65	61.40	19.62	14.16	94.56	44.97	75.25
Trade globalization (trade_glob)	60.23	60.56	17.84	16.11	99.34	49.55	73.00
Gross capital formation (gcf)	25.32	24.85	9.38	-15.68	56.91	20.17	30.68
Government expenditure (gov)	17.40	16.66	6.06	2.36	50.84	13.21	20.11
GDP per capita (gdppc)	17119	7941	17596	1935	81609	3971	24745
Population density (pop_density)	191.74	76.51	357.17	2.97	1971.32	40.18	132.37

Table 1 above summarizes the descriptive statistics for the MENA sample, covering 18 countries from 1999 to 2023. The figures indicate considerable variation across countries and over time, which is consistent with the region's diverse economic structures and broader macroeconomic conditions.

Figure 1 presents the time trend of the average BLI in the MENA region over 1999–2023, with separate lines for oil exporters and oil importers.

Figure 1: Average BLI in MENA, 1999-2023



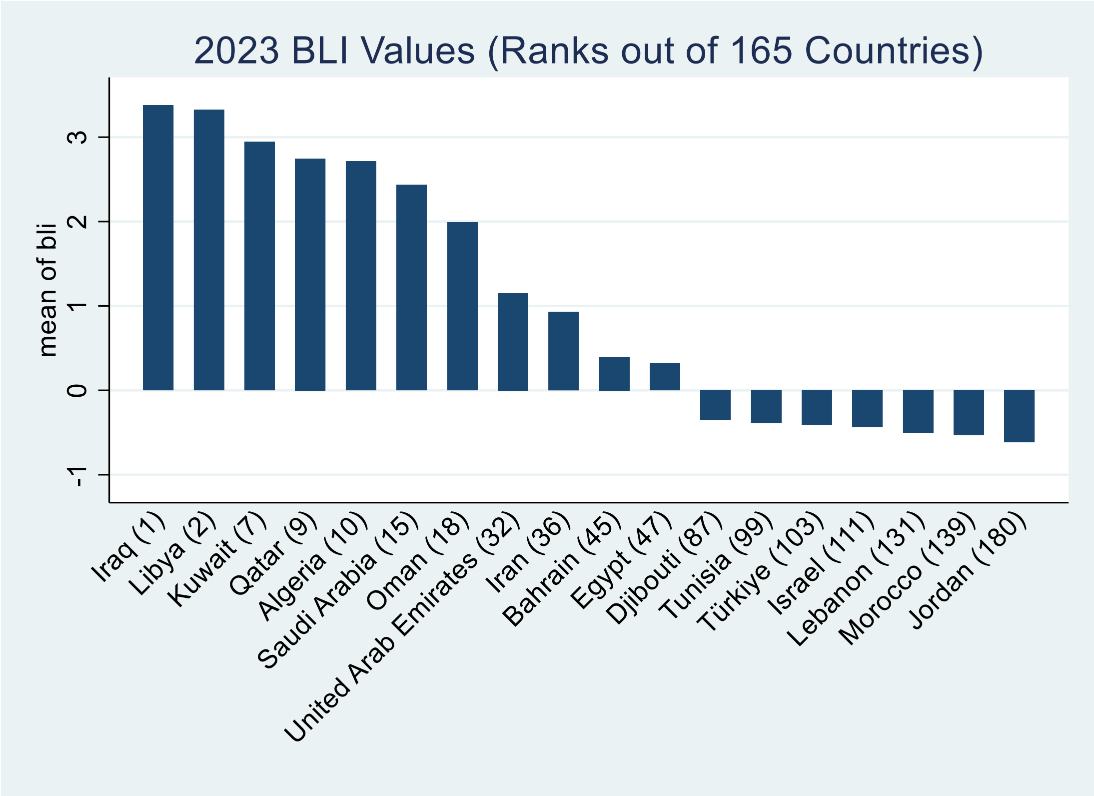
The figure above shows how the average BLI has changed in the MENA region from 1999 to 2023, with separate lines for the regional average, oil exporters, and oil importers. The BLI captures how much a country's exports remain tied to products that are both carbon-intensive and low in technological complexity, signaling limited diversification and weak transition capacity.

All three groups display a gradual decline over time. This downward pattern suggests that MENA countries, on average, have slowly moved away from export structures dominated by low-complexity brown goods. Still, the speed of this shift varies across groups. Oil exporters consistently post the highest BLI levels, reflecting their long-standing dependence on carbon-heavy, low-complexity products and the limited structural change seen in these economies. Oil importers start at much lower BLI levels and their decline is more noticeable, pointing to a more steady move toward somewhat more diversified and higher-complexity exports.

Although all series trend downward, the gap between oil exporters and oil importers remains wide. This highlights enduring structural differences within the region and suggests that achieving a broad and lasting green transition will continue to be a significant challenge for MENA countries.

We also compare countries' most recent BLI levels to highlight how the MENA economies differ in their current exposure to brown lock-in. Figure 2 shows the BLI levels of MENA countries in 2023, ranked from the highest to the lowest.

Figure 2: BLI values, 2023



The figure above displays the 2023 BLI levels for MENA countries, ordered from highest to lowest. Countries at the top of the chart, such as Iraq, Libya, Kuwait, Qatar, and Algeria, show the strongest brown lock-in, indicating that their exports remain heavily concentrated in carbon-intensive and low-complexity products. This points to limited progress in moving toward more diverse or more sophisticated sectors. At the lower end of the distribution, countries like Tunisia, Türkiye, Israel, Lebanon, Morocco, and Jordan record much lower BLI scores. This suggests weaker brown lock-in and more diversified export profiles, which provide a better basis for long-term transition. Taken together, the ranking highlights the significant differences within the region: while some economies remain strongly tied to brown, low-complex production, others have shifted further away from this pattern.

Next, we present the panel regression results for the MENA sample.

Table 2: Panel Regression Results: MENA Countries

VARIABLES	MENA Total	Oil Exporters	Non-Oil Exporters
Financial globalization (financial_glob)	-0.010***	-0.011***	-0.001
	(0.003)	(0.003)	(0.004)
Trade globalization (trade_glob)	0.006***	0.007***	0.003*
	(0.001)	(0.001)	(0.002)
Gross capital formation (gcf)	0.002	0.005**	0.003
	(0.001)	(0.002)	(0.001)

Government expenditure (gov)	0.006***	0.007**	0.005
	(0.002)	(0.003)	(0.004)
GDP per capita (gdppc)	0.041	-0.134	-0.114
	(0.149)	(0.2)	(0.073)
Population density (pop_density)	0.000	0.000	0.001**
	(0.000)	(0.000)	(0.000)
Observations	398	228	170
Number of countries	18	10	8
F-stat. (Overall)	6.53	5.85	1.90
	[0.000]	[0.000]	[0.008]
F-stat. (Country FE)	1388.06	157.87	211.63
	[0.000]	[0.000]	[0.000]
R^2	0.3418	0.4629	0.2845

Notes:

1. All independent variables are included with a two-period lag (L2).
2. Driscoll–Kraay standard errors with lag(3) are reported in parentheses.
3. *** p<0.01, ** p<0.05, * p<0.10.

The regression results reveal a clear pattern for the MENA region. The most notable finding is that financial globalization has a negative and significant effect on the BLI in both the full MENA sample and the oil-exporting group. This result indicates that greater financial openness is associated with a lower degree of brown lock-in. In other words, as these economies become more financially integrated, their export structures gradually shift away from carbon-intensive and low-complexity products. For many oil-exporting countries, increased financial openness may help channel resources toward more diverse activities, support technology adoption, or ease access to foreign capital that can promote upgrading. Even though these economies remain heavily dependent on hydrocarbons, financial integration appears to create some room for gradual structural adjustment, which reduces the intensity of brown specialization. For non-oil exporters, the coefficient is not statistically significant. These countries are more diversified and less tied to large resource-based inflows, so changes in financial openness may not translate directly into shifts in their export structures. As a result, financial globalization neither increases their brown lock-in nor provides a strong push toward further diversification.

In contrast, trade globalization has a positive and significant effect across all three groups. This implies that greater trade openness is linked to higher brown lock-in, meaning that countries become more concentrated in carbon-intensive, low-complexity products as they integrate more deeply into global trade. Stronger trade integration can reinforce existing export patterns, especially when economies are already specialized in resource-based or low-complexity goods. In such cases, openness may simply expand the scale of existing brown exports rather than encouraging firms to upgrade products or shift toward higher-complexity activities. The effect is slightly stronger for oil-exporting countries. Because their export baskets are already highly concentrated in hydrocarbons, additional trade openness tends to amplify these patterns, making increases in brown lock-in more visible. Even small shifts in trade flows can therefore translate into noticeable rises in their BLI levels.

Other controls behave as expected. Gross capital formation shows a positive effect for oil exporters. This result suggests that higher gross capital formation increases brown lock-in among oil exporters, indicating that new investments continue to flow into carbon-intensive, low-complexity activities. Government expenditure is also positive for both the full sample and oil exporters, suggesting that public spending in these economies tends to reinforce existing brown, low-complexity production patterns rather than supporting structural change. Population density has a small but positive effect for non-oil exporters, indicating that more densely populated economies show slightly higher brown lock-in, although the magnitude of the coefficient is limited.

These findings suggest several policy directions for the MENA region. First, financial openness appears to reduce brown lock-in, especially in oil-exporting countries. This means that deeper financial integration can support gradual structural change but only if capital is directed to productive sectors. Policies that encourage long-term investment, improve financial regulation, and channel foreign capital toward technology, manufacturing, and complex services can help these countries move away from simple, carbon-intensive exports. Second, the positive link between trade globalization and brown lock-in implies that trade integration alone does not help countries move toward more complex or greener export structures. In many cases, it may simply expand existing brown, resource-based activities. Because of this, trade policies should be designed more carefully. Reducing tariffs or increasing participation in global markets should go hand in hand with measures that support upgrading, such as encouraging export diversification, improving firm capabilities, and strengthening quality standards. Finally, lasting diversification requires public investment in skills, technology, and productive capabilities. While some MENA countries are already slowly shifting away from low-complexity brown products, progress is uneven. More targeted industrial policies—especially those supporting SMEs, manufacturing, and technology-intensive activities—can help the region build a stronger foundation for long-term transition and reduce its dependence on brown, low-complexity exports.

III.ii. Firm-Level Analysis (Turkiye)

In the second part of the study, we calculate a firm-level BLI index for Turkiye and analyze its main determinants. While the original BLI was developed by Andres et al, 2023 at the country level, our contribution is to adapt and extend this measure to the firm level by using detailed Turkish firm-level data. The determinants of firm-level BLI are also estimated through a Heckman two-step procedure.

III.ii.1 Firm-level Data

For the firm-level analysis, we use confidential firm-level data obtained from TÜİK (TurkStat). The dataset reports exports at the product level using HS codes. Since the Product Complexity Index is available in the HS 1992 classification, we first convert all product codes in the TurkStat data to HS 1992[2]. The HS system has gone through several revisions (2012, 2017, and 2022), so for each update we map the original TurkStat codes to HS 1992 using the official UN

[2] The results and interpretations in this paper are solely the author's responsibility and do not represent the views of TurkStat

conversion tables[3]. Once the product codes are harmonized, we compute the BLI using TurkStat's foreign trade statistics.

Our sample covers all firms, including both exporters and non-exporters, which is essential for the empirical strategy. In the Heckman selection framework, the first stage uses the full firm population to estimate the probability of exporting at least one brown product. The second stage is then run only for firms that do export brown products, in order to explain the variation in their firm-level BLI. To construct the independent variables, we combine three different TurkStat sources: foreign trade statistics, sector balance-sheet data, and the annual industry and services statistics. Bringing these datasets together allows us to match firms' export structures with their financial characteristics and sectoral information.

The firm-level model relies on the following independent variables, which are described as follows: **Leverage** represents the firm's financial structure and measures the extent to which activities are financed through debt. It is calculated as total debt (the sum of short-term and long-term financial liabilities) divided by total assets. **ROA_dummy** captures low profitability relative to firms operating in the same industry. It takes the value of 1 if a firm's return on assets is below the 10th percentile of the ROA distribution within its four-digit sector, and 0 otherwise. **Capital intensity** reflects the amount of physical capital used per worker and is constructed as the ratio of capital stock to the number of employees, where capital stock corresponds to fixed tangible assets reported in TurkStat's sector balance-sheet statistics. **Labour productivity (lp)** measures how efficiently firms use labour in production and is computed as net sales per employee, using information from the annual industry and services statistics. **Firm_size** is measured as the logarithm of total employment, while **firm_age** is defined as the logarithm of the number of years since establishment. Finally, a **year trend** is included to capture common macroeconomic changes and regulatory shifts affecting all firms over time. For the manufacturing sector, we use **total factor productivity (TFP)** instead of labour productivity, since manufacturing performance depends on both capital and labour inputs. TFP reflects the part of output that cannot be explained by these observable inputs. We follow the standard Cobb–Douglas framework, using firm-level capital stock and labour as production inputs. All output and input variables are deflated with the appropriate price indices to obtain real measures. This TFP indicator provides a more accurate picture of firm efficiency and technological capability than simple labour productivity, making it a more suitable metric for manufacturing activities.

In addition to the full-sample estimation, we also run the Heckman model separately by firm size. For firm-size differences, we consider three groups: small firms (fewer than 50 employees), medium-sized firms (50–249 employees), and large firms (250 employees or more). This helps us see whether the factors driving brown lock-in vary across firms with different resource capacities and organisational structures.

The Heckman model is also estimated separately across broad sector groups: manufacturing, other industry (mining, energy, water, and construction), trade and services (wholesale–retail trade, transportation, accommodation, and information–communication), professional and real estate activities. To do so, we identify industry-specific patterns that may influence both the likelihood of exporting brown products and the level of firm-level BLI.

[3] https://unstats.un.org/unsd/classifications/Econ

III.ii.2 Firm-Level Empirical Strategy

In this part of the paper, we follow the general approach introduced by Andres et al. (2023) and adapt it to the firm level. The country-level index in Andres et al. combines the export share of each brown product with its complexity score. In our firm-level setting, we apply the same structure to each firm's export basket. This allows us to measure how dependent a firm is on brown and low-complexity activities. Formally, the firm-level BLI index is defined as:

$$BLI_c = \sum_b \left(\frac{exports_{cb}}{\sum_p export\, s_{cp}} \right) \times (1 - \widetilde{PCI}_b).$$

Here, the first term represents the share of brown product $b$in the total exports of firm c. The second term, $1 - \widetilde{PCI}_b$, uses the normalized complexity score of each product. Since higher complexity values indicate more sophisticated goods, taking $(1 - \widetilde{PCI}_b)$gives greater weight to brown products that are technologically simple and therefore harder to move away from during the green transition. By multiplying export shares with $(1 - \widetilde{PCI})$, the index captures both the importance of brown goods in a firm's export basket and the difficulty of upgrading away from these activities. Firms that export a large amount of low-complexity brown products receive higher BLI values, indicating a stronger lock-in.

To analyze the determinants of firm-level brown lock-in, we estimate a Heckman two-step selection model**.** This method is appropriate because the Brown Lock-in Index (BLI) can only be computed for firms that export at least one brown product. Estimating the outcome equation on this restricted sample would create selection bias. The Heckman procedure addresses this by modelling the export decision in the first stage and the BLI level in the second stage. Therefore, in the first stage, all firms, i.e. exporters and non-exporters, are included in the sample**,** while the second stage is estimated only for firms that export brown products.

The first step models the probability that a firm exports at least one brown product. Let

$$brown\_dummy_{it} = \begin{cases} 1 & \text{if firm } i \text{ exports any brown product in year } t \\ 0 & \text{otherwise.} \end{cases}$$

The first stage (Brown Export Decision) is specified as:

$$\begin{aligned} brown\_dummy^*_{it} &= \gamma_0 + \gamma_1 L.\,leverage_{it} + \gamma_2 L.\,roa\_dummy_{it} + \gamma_3 L.\,capital\_intensity_{it} \\ &\quad + \gamma_4 L.\,lp_{it} + \gamma_5 L.\ln(firm\_age_{it}) + \gamma_6 L.\ln(firm\_size_{it}) + \gamma_7 year\_trend_t \\ &\quad + u_{it}, \end{aligned}$$

where the latent variable $brown_dummy^*_{it}$is estimated using a probit model. The lag operator L**.**denotes one-year lags of all covariates. This step produces the inverse Mills ratio, which is included in the second stage.

The second stage explains the firm's Brown Lock-in Index (BLI), conditional on being a brown exporter:

$$BLI_{it} = \beta_0 + \beta_1 L.leverage_{it} + \beta_2 L.roa\_dummy_{it} + \beta_3 L.capital\_intensity_{it} + \beta_4 L.lp_{it} + \beta_5 L.\ln(firm\_age_{it}) + \beta_6 L.\ln(firm\_size_{it}) + \beta_7 year\_trend_t + \rho\lambda_{it} + \varepsilon_{it},$$

where λ_{it} is the inverse Mills ratio. A statistically significant ρindicates that selection bias is present and that the Heckman correction is necessary.

III.ii.3 Empirical Findings for Firms in Turkiye

Table below presents the descriptive statistics for the firm-level variables used in the analysis.

Table 3: Descriptive Statistics for Firm-Level Variables in Turkish Firms

Variables	Mean	p50	SD	p25	p75	Min	Max	N
bli_firm	0.01	0.00	0.05	0.00	0.00	0.00	0.87	710537
leverage	0.83	0.77	0.83	0.46	0.95	0.00	12.49	6859007
roa_dummy	0.10	0.00	0.30	0.00	0.00	0.00	1.00	6859007
capital_intensity	1743888	286492	34600000	104653	817971	0	26700000000	6859007
labor_productivity (lp)	1683185	206925	39000000	59555	710641	0	61600000000	6859007
firm_age	13.68	12.00	8.94	6.00	20.00	0.00	233.00	6835539
firm_size	17.01	4.00	169.05	1.00	10.00	1.00	78708.00	6859007
tfp	0.70	0.82	1.14	0.48	1.10	-11.39	12.31	1264102

Overall, the data show that firms are quite different from each other, especially in terms of size, age, productivity and financial structure. As expected, the average BLI is close to zero, since most firms do not export brown products. Variables like leverage, capital intensity and labour productivity are very spread out, which suggests that firms differ much in their technological and financial situations. These patterns suggest that, in the analysis, it is useful to look at both export participation and the level of brown lock-in separately.

Table 4 below presents the number of firms each year, the number and share of exporters, and the number of firms with BLI > 0 together with their share among exporters for the period 2013–2023

Table 4: Number of Firms, Exporters, and Firms with BLI > 0, 2013–2023

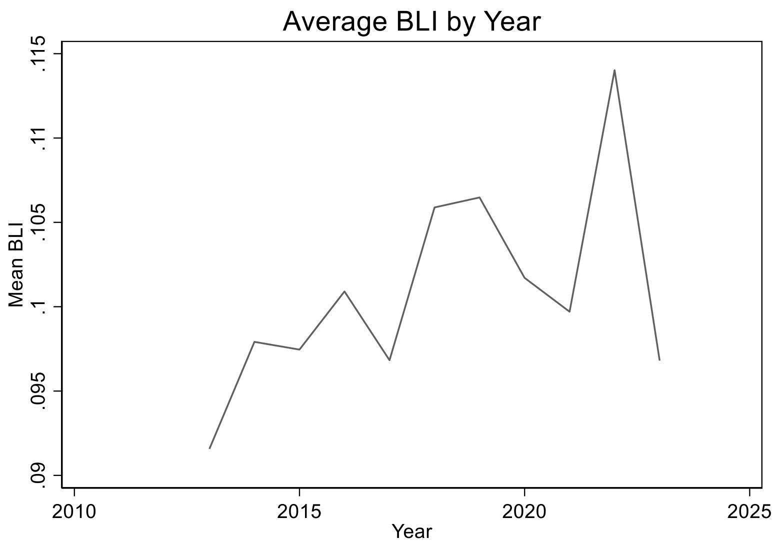
Years	Number of total firms	Number of exporters	Share of exporters (%)	Number of BLI>0 firms	Share of BLI>0 among exporters (%)
2013	486,554	49,473	10.2	3,983	8.1
2014	501,824	52,110	10.4	4,123	7.9
2015	525,254	53,602	10.2	4,098	7.6
2016	546,650	55,485	10.2	4,097	7.4
2017	577,240	59,001	10.2	4,357	7.4

2018	610,877	64,024	10.5	4,759	7.4
2019	637,475	70,230	11.0	5,402	7.7
2020	660,548	70,459	10.7	5,204	7.4
2021	726,648	80,082	11.0	5,636	7.0
2022	788,209	84,395	10.7	6,420	7.6
2023	799,214	71,725	9.0	5,209	7.3

According to the table above, the share of exporters within the overall firm population stays fairly stable during this period, stays around 9–11 percent. Among exporters, the proportion of firms with brown lock-in remains consistently close to 7–8 percent, showing only minor year-to-year changes. Taken together, the figures indicate that the share of exporting firms involved in brown activities is quite steady, even though both the total number of firms and the number of exporters increase over the decade

Figure-3 shows the average BLI over time for firms exposed to brown lock-in (BLI > 0).

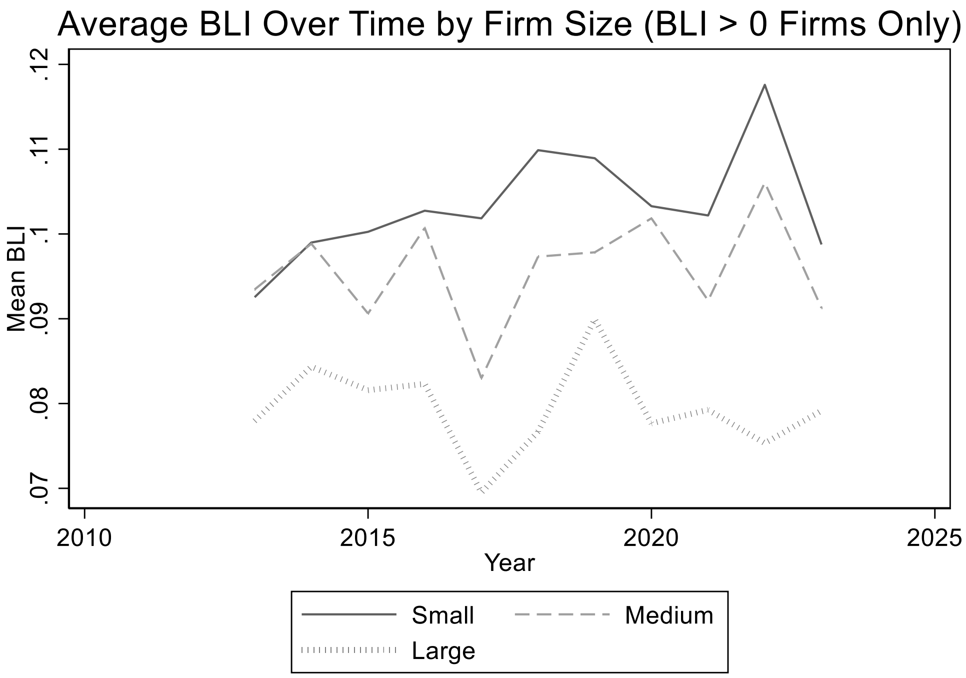
Figure 3: Average BLI by Year, 2013-2023



According to the figure, the mean BLI for these firms changes gradually over the period, with some clear fluctuations across years. The average level rises in the earlier part of the series, increases again around 2019, and reaches a marked peak in 2021. After this peak, the mean BLI falls sharply in the next year. While the pattern is not entirely steady, the overall trend suggests that the intensity of brown lock-in among affected firms varies from year to year, with periods of moderate increases and occasional short-term jumps.

Figure 4 shows the average BLI over time by firm size for firms exposed to brown lock-in. The figure shows that the mean BLI differs across firm sizes, although all groups display some year-to-year variation. Small firms generally have the highest average BLI throughout the period, followed by medium-sized firms, while large firms consistently record the lowest values. All three groups show mild fluctuations over time, with small firms experiencing a clearer peak around 2021. Despite these movements, the relative ranking between size groups remains stable, suggesting that smaller firms tend to exhibit a higher intensity of brown lock-in compared with medium and large firms.

Figure 4: Average BLI Over Time by Firm Size (BLI > 0 Firms Only), 2013-2023



III.ii.3 Empirical Findings for Firms in Türkiye

This section presents the empirical results for firms in Türkiye, focusing on how brown lock-in relates to exporting behavior and firm characteristics.

Table 5 presents the Heckman two-step estimation results, reporting both the selection equation (First Stage: Brown Export Decision) and the outcome equation (Second Stage: Firm-Level BLI)

Table 5: Heckman Two-Step Estimation Results (All Firms)

	(1) First Stage: Brown Export Decision	**2) Second Stage: Firm-Level BLI**
brown_dumy	2.449***	
	(165.41)	
Leverage	-0.069***	0.025***
	(-8.12)	(3.76)
Roa_dummy	-0.074***	0.017
	(-4.30)	(1.43)
Capital_intensity	0.000	0.000
	(1.07)	(-1.18)
Labor_productity	0.000***	0.000
	(6.84)	(1.33)
Firm_age	0.010	-0.017***
	(1.71)	(-3.89)
Firm_size	0.079***	-0.005**

	(31.14)	(-2.71)
Mills Lambda	-0.078***	
	(-30.18)	
Number of obs.	5419747	
Number of firms with BLI>0 (second stage)		8683

The table above reports the Heckman two-step estimation results for all firms in the sample. The first stage (the ‘brown export decision’) reflects the probability that a firm exports at least one brown product. Because this stage mainly serves to address selection bias, we note only briefly that several firm characteristics, such as leverage, profitability, and size, are significant predictors of brown exporting.

Since our main interest is the intensity of brown lock-in among exporting firms, the focus is on the second-stage estimates. Column (2) shows the determinants of the firm-level Brown Lock-in Index (BLI). The main finding is that **leverage** enters with a positive and strongly significant coefficient. This indicates that firms with higher debt levels tend to have higher BLI scores, meaning they are more dependent on brown, low-complexity export products. One possible explanation is that highly leveraged firms may prioritise short-term financial stability and continue exporting familiar brown products rather than shifting toward greener or more complex activities that involve higher risks or upfront investment. **Profitability (roa_dummy)**, **capital intensity**, and **labour productivity** do not have statistically significant effects in the BLI equation. This indicates that, once other factors are taken into account, these variables do not systematically explain brown lock-in for the average firm in the sample. In contrast, both **firm age** and **firm size** are negative and significant, meaning that older and larger firms tend to have lower BLI levels. This pattern implies that more established and bigger firms are somewhat less tied to brown and low-complexity products, possibly because they have built stronger capabilities, have better access to information and finance, or maintain a broader product range that includes more complex goods. In short, brown lock-in seems to be more pronounced among younger and smaller firms than among older and larger ones

From a policy perspective, the positive link between leverage and brown lock-in suggests that a firm’s overall debt burden can influence its ability to move toward greener and more complex activities. If highly leveraged firms are more likely to remain in brown and low-complexity exports, easing their financial constraints through more accessible and stable long-term financing, rather than relying mainly on short-term borrowing, could help reduce this lock-in. In addition, the negative coefficients for firm age and firm size indicate that younger and smaller firms are more exposed to brown lock-in. This highlights the need for targeted support, such as export promotion, innovation funding or green credit programmes, to help less established firms upgrade their products and enter more complex and greener export markets. Overall, the results suggest that financial and industrial policies should work together if the aim is to gradually shift firms away from brown export structures.

Table 6 presents the Heckman two-step estimation results separately for small, medium, and large firms.

Table 6: Heckman Two-Step Estimation Results (by Firm Size)

	Small		**Medium**		**Large**	
	(1) First Stage: Brown Export Decision	**2) Second Stage: Firm-Level BLI**	**(1) First Stage: Brown Export Decision**	**2) Second Stage: Firm-Level BLI**	**(1) First Stage: Brown Export Decision**	**2) Second Stage: Firm-Level BLI**
brown_dumy	2.499***		2.200***		1.773***	
	(0.016)		-0.046		(0.083)	
Leverage	-0.065***	0.018**	-0.038	0.097***	-0.027	0.106**
	(0.009)	(0.007)	-0.039	(0.029)	(0.073)	(0.052)
Roa_dummy	-0.094***	0.016	0.038	-0.045	0.151	0.004
	(0.018)	(0.013)	-0.076	(0.045)	(0.117)	(0.066)
Capital_intensity	0	0.000	0.000*	0.000	0.000***	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Labor_productivity	0.000***	0.000	0.000***	0.000	0.000***	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm_age	-0.012**	-0.021***	0.228***	-0.001	0.336***	0.004
	(0.006)	(0.005)	(0.027)	(0.015)	(0.051)	(0.029)
Firm_size		-0.004*	0.047	0.012	0.036	-0.016
		(0.002)	(0.03)	(0.017)	(0.03)	(0.018)
Mills Lambda	-0.072***		-0.111***		-0.161***	
	(0.003)		(0.009)		-0.021	
Number of obs.	4690856		820333		40683	
Number of firms with BLI>0 (second stage)		6815		889		304

The table above highlights how the determinants of brown lock-in differ by firm size. For small firms, leverage has a positive effect on BLI, but its size is relatively modest. Other firm characteristics also matter: older and slightly larger small firms show lower BLI values, suggesting that experience and some degree of scale help them move away from brown and low-complexity products. Among medium-sized firms, leverage becomes the main driver of brown lock-in. More indebted medium firms are much more likely to remain locked into brown exports, while variables such as age, size, productivity, and capital intensity have almost no effect in the second stage. This indicates that medium firms are especially sensitive to financial constraints. For large firms, the pattern is similar but even stronger. Leverage again raises BLI, and the estimated effect is the largest among all size groups. Once large firms are active in export markets, their age, size, or productivity does not reduce their lock-in, implying that established firms tend to stay in traditional brown sectors unless they have sufficient financial room to adjust. Overall, the results show that financial constraints play a growing role as firm size increases, and that brown lock-in becomes more persistent for medium and large firms with high leverage.

These findings have several policy implications. Since leverage is the main factor increasing brown lock-in across small, medium, and large firms, policies that ease financial pressures, such as low-cost green credit lines, investment guarantees, or targeted tax incentives, could help firms shift toward more complex and greener export products. For small firms, experience and modest capability gains, reflected in variables like age and size, seem to have a stronger effect on reducing brown lock-in than leverage does. This suggests that training programmes, technology adoption support, and digitalisation efforts could help smaller firms move away from brown exports. Large and older firms appear less likely to change their product mix without direct incentives, which highlights the need for stronger green-industrial policies, such as support tied to decarbonisation goals or gradual phase-out plans for brown sectors. Overall, the results show the importance of designing size-specific policies: capability-based support for small firms, better financial access for medium firms, and targeted transition tools for large and highly leveraged firms.

Table 7 presents the Heckman two-step estimation results by sector

Table 7: Heckman Two-Step Estimation Results (by Sector)

	Manufacturing		Other Industry		Trade and Services		Professional and Real Estate Activities	
	(1) First Stage: Brown Export Decision	2) Second Stage: Firm-Level BLI	(1) First Stage: Brown Export Decision	2) Second Stage: Firm-Level BLI	(1) First Stage: Brown Export Decision	2) Second Stage: Firm-Level BLI	(1) First Stage: Brown Export Decision	2) Second Stage: Firm-Level BLI
brown_dumy	2.197***		2.365***		2.444***		2.618***	
	(0.031)		(0.06)		(0.018)		(0.085)	
Leverage	-0.054**	0.039***	-0.108***	0.006	-0.077***	0.024***	-0.004	-0.016
	(0.021)	(0.013)	(0.04)	(0.034)	(0.011)	(0.008)	(0.027)	(0.026)
total_factor_productivity (tfp)	-0.048***	-0.047***						
	(0.008)	(0.005)						
Roa_dummy	-0.078**	0.007	0.018	0.011	-0.098***	0.014	-0.219**	0.053
	(0.034)	(0.022)	(0.059)	(0.048)	(0.022)	(0.015)	(0.098)	(0.08)
Capital_intensity	0.000	0.000	0.000	0.000	0.000***	0.000	0.000**	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Labor_productity			0.000	0.000	0.000***	0.000	0.000***	0.000
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm_age	0.009	-0.001	0.054**	-0.002	-0.029***	-0.019***	0.007	-0.071***
	(0.012)	(0.008)	(0.023)	(0.019)	(0.008)	(0.005)	(0.03)	(0.023)
Firm_size	0.099***	-0.026***	0.096***	-0.022***	0.084***	0.008***	0.041***	0.018**
	(0.005)	(0.003)	(0.01)	(0.007)	(0.004)	(0.002)	(0.012)	(0.009)
Mills Lambda	-0.086***		-0.084***		-0.077***		-0.041***	
	(0.006)		(0.014)		(0.003)		(0.014)	
Number of obs.	987267		820333		2618584		673058	
Number of firms with BLI>0 (second stage)		2162		472		5613		349

The table above shows that the drivers of firm-level brown lock-in differ across sectors. **Leverage** plays a key role in manufacturing and in trade and services, where higher debt levels are associated with significantly higher BLI values. The effect is strongest in manufacturing, suggesting that financial pressure makes it harder for firms to upgrade away from brown and low-complexity products. In trade and services, leverage also matters, but the effect is more moderate. By contrast, leverage is not significant in other industry or in professional and real estate activities, indicating that financial conditions do not meaningfully shape brown lock-in in these sectors. **Total factor productivity (TFP)** also plays an important role in manufacturing. TFP is negative and significant, indicating that more productive manufacturing firms have lower BLI levels. This suggests that firms with stronger capabilities and better production efficiency are more likely to upgrade toward more complex and greener products. **Firm age** reduces BLI in trade & services and in professional & real estate activities, suggesting that in these sectors more experienced firms are better able to diversify and gradually move away from brown products. **Firm size** shows mixed patterns: it lowers BLI in manufacturing and other industry, but raises it in trade & services, and professional & real estate activities. One possible interpretation is that scale works differently across sectors. In manufacturing and other industry, larger firms may have stronger capabilities, broader product portfolios, and better access to technology, which helps them move away from brown and low-complexity products. In contrast, in service-based or low-technology sectors, larger firms may continue to rely on established brown activities, so size alone does not support upgrading.

These results suggest that policies to reduce brown lock-in need to be both sector-specific and financially focused. First, improving access to finance, especially long-term finance, can help firms shift toward greener and more complex export products. This matters because moving away from brown activities often requires investments that take longer to generate returns. Second, policies supporting productivity growth in manufacturing, such as technology upgrading, R&D support, and skills development, can indirectly reduce brown lock-in by helping firms upgrade their product mix. Third, younger firms in trade and services and in professional activities face a higher risk of brown lock-in, so support schemes for firm development, such as training, business advisory services, and early-stage export assistance, should especially target these firms. Fourth, sector-specific strategies matter. In manufacturing, scale and better financial conditions help firms upgrade. But in services and professional activities, policies should focus more on developing capabilities rather than simply encouraging firms to grow in size. Finally, export-oriented industrial policies should encourage firms that remain heavily specialised in brown products to diversify. Targeted incentives, preferential credit, and knowledge-transfer programmes can help these firms move toward greener and more complex exports. Overall, reducing brown lock-in at the firm level requires a coordinated policy mix that combines financial support, capability upgrading, and sector-specific transition pathways.

IV. Conclusion

This paper examines brown lock-in from two complementary perspectives: country-level patterns in the MENA region and firm-level dynamics in Türkiye. Brown lock-in refers to a persistent dependence on brown, low-complexity products that makes it difficult for economies and firms to shift toward greener and more sophisticated activities. Understanding both the level and the evolution of this lock-in, as well as the factors that drive it, is essential for designing effective policies that support structural transformation.

Our results for the MENA region show that financial globalization reduces brown lock-in, indicating that greater access to global financial markets can help countries move away from simple, resource-based export structures. In contrast, trade globalization increases brown lock-in across all country groups, suggesting that current trade patterns reinforce existing specialisation in low-complexity products rather than encouraging diversification. The MENA results also differ between oil exporters and oil importers, reflecting the distinct structural constraints and export profiles of these two groups. These findings highlight the need for policies that deepen financial integration while restructuring trade incentives. Expanding access to stable, long-term international finance may support upgrading, whereas trade policies should focus on capability building and the development of higher-value export sectors.

The firm-level analysis for Turkiye shows that financial conditions are central to understanding brown lock-in. Leverage consistently increases firms' BLI scores, indicating that more indebted firms remain more dependent on brown and low-complexity export products. By contrast, firm age and firm size reduce brown lock-in, suggesting that experience and a modest degree of scaling help firms gradually diversify their product mix. In manufacturing, total factor productivity also has a negative and significant effect, showing that more productive firms are better able to upgrade and move away from brown activities. Our results also differ across sectors and firm sizes, indicating that brown lock-in is not uniform but shaped by firms' structural and operational characteristics

These results imply that financial and industrial policies should work together to ease the transition toward greener and more complex exports. Improving firms' access to finance, strengthening capability-building programmes, and supporting technology upgrading in manufacturing are especially important. Because the determinants of brown lock-in vary by both firm size and sector, policy interventions need to be tailored accordingly, as discussed in the previous section.

All in all, these findings highlight the importance of coordinated and forward-looking strategies to support a gradual shift away from brown dependence. Future work could further explore the mechanisms behind this transition and assess how different policy tools shape firms' and countries' ability to upgrade.

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