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Human Capital, Natural Resource Rents and Iran's Load Capacity Factor: An ARDL–ECM Approach

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Highlights

- **Assessment of Iran's load capacity factor (LCF) using annual data from 1990–2020.**
- **Application of the ARDL–ECM model to explore short- and long-run dynamics.**
- **GDP and natural resource rents reduce LCF, while human capital and energy efficiency improve it.**
- **Highlights policy directions for promoting green growth and environmental sustainability.**

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Abstract

Understanding the dynamics between economic growth and environmental sustainability—especially in natural-resource-dependent economies—is fundamental for achieving sustainable development. This study examines the determinants of environmental sustainability in Iran by analyzing the effects of GDP, human capital, energy efficiency, and natural resource rents on the load capacity factor (LCF—the ratio of biocapacity to ecological footprint) over 1990–2020 using an ARDL framework. Long-run results reveal statistically significant relationships consistent with theoretical expectations: GDP has a negative and sizable effect on LCF, indicating that the current energy- and extraction-intensive growth pattern exacerbates environmental pressure. Human capital exerts a positive and significant effect on LCF, highlighting the role of education and skills in improving productivity and sustainable resource management. Energy-efficiency indicators also show a strong positive impact, suggesting that higher output per unit of energy consumption enhances ecological sustainability. Conversely, natural resource rents negatively and significantly affect LCF, implying that reliance on extractive revenue undermines biocapacity via mechanisms such as economic dependence on extraction and reduced incentives for innovation. The error-correction term (−0.634) is negative and significant, implying an annual adjustment of roughly 63% of short-run deviations back to the long-run equilibrium. Policy implications recommend prioritizing energy-efficiency improvements, investment in specialized education and green technologies, economic diversification to reduce rent dependence, and adoption of environmental pricing tools (e.g., carbon taxes or emissions trading) to align economic growth with ecological sustainability.

1. Introduction

The rapid pace of economic growth in many developing and resource-rich economies has heightened concerns about long-term environmental sustainability.

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While higher income typically improves living standards, it can also intensify pressure on natural capital through greater energy consumption, resource extraction, and pollution (IPCC, 2021). Conventional single-dimensional indicators such as CO_2 emissions or the ecological footprint alone only capture part of the environmental problem.

The Load Capacity Factor (LCF)—defined as the ratio of biocapacity to ecological footprint—provides a comprehensive measure of environmental sustainability by simultaneously capturing ecological supply and demand (Siche et al., 2010). An LCF below unity indicates that human demand exceeds nature's regenerative capacity, signalling an unsustainable trajectory. Understanding the channels through which key macroeconomic variables affect this ratio is therefore essential for designing effective sustainability policies, particularly in resource-dependent developing economies.

Four primary channels are expected to shape LCF dynamics:

First, economic growth typically increases demand-side pressure on ecosystems. Rising output, especially when driven by energy-intensive industrial and urban activities, expands the ecological footprint through higher energy consumption, resource extraction, and waste generation (Balsalobre-Lorente et al., 2018; Wang, 2019). In the absence of technological or structural offsets, GDP growth is therefore likely to reduce LCF by widening the gap between demand and available biocapacity.

Second, energy intensity (or its inverse, energy efficiency) directly influences the ecological footprint component of LCF. Higher energy use per unit of GDP amplifies fossil-fuel-related land requirements for carbon sequestration and increases overall environmental pressure (Danish et al., 2020). Conversely, improvements in energy efficiency—through cleaner technologies or structural shifts toward less energy-intensive sectors—lower the footprint per unit of output, thereby raising LCF (Amuakwa-Mensah & Adom, 2017; Kang & Kang, 2022).

Third, natural resource rents can affect LCF through multiple pathways. On the one hand, rents may finance environmental investments and technology transfer (the "resource blessing" hypothesis). On the other, heavy reliance on extractive revenues often crowds out innovation, weakens institutions, and encourages excessive depletion, ultimately eroding biocapacity and reducing LCF (Huang et al., 2020; Tiba, 2019; Hassan et al., 2019). The net effect remains an empirical question, with evidence suggesting dominance of the resource-curse mechanism in many contexts (Zafar et al., 2019).

Fourth, human capital operates primarily on the supply side and through behavioural channels. A more educated and skilled workforce facilitates the adoption of cleaner technologies, improves natural resource governance, and shifts consumption patterns toward sustainability, thereby enhancing both biocapacity management and efficiency of resource use (Ganda, 2019; World Bank, 2012). These effects are expected to exert a positive influence on LCF.

Iran offers a critical case for examining these channels. As a major fossil-fuel producer with persistently high energy intensity and substantial natural resource

rents, the country has experienced a sharp and continuous decline in LCF over recent decades (Global Footprint Network, 2018). Figure 1 illustrates the widening gap between Iran's per-capita ecological footprint and biocapacity since the late 1970s, confirming a deepening ecological deficit.
Despite growing research on Iran's environmental pressures, few studies employ the LCF as the central indicator, and none—to our knowledge—systematically investigate the simultaneous roles of GDP, energy efficiency, natural resource rents, and human capital within this framework.

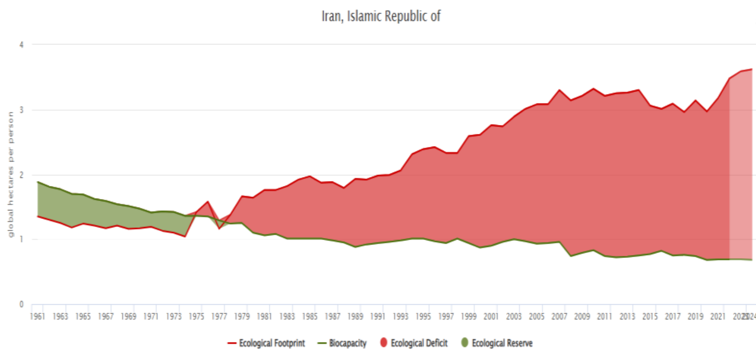

Figure 1. Ecological Footprint Index and Bio Capacity in Iran
Source: *Global Footprint Network (2018)*

This study fills that gap by estimating the short- and long-run effects of these four variables on Iran's LCF over 1990–2020 using the ARDL bounds-testing approach with error-correction modelling. The paper makes three contributions: (i) adopting LCF as a comprehensive indicator that jointly accounts for ecological supply and demand; (ii) being the first Iranian study to explicitly incorporate human capital in an LCF framework; and (iii) offering tailored policy recommendations for a resource-dependent economy.

The rest of the paper is structured as follows. Section 2 reviews the theoretical background and summarizes the empirical literature on LCF and related indicators. Section 3 describes the data sources, variable construction, and econometric methodology. Section 4 presents the empirical results, robustness checks, and diagnostics. Section 5 concludes with policy implications, limitations, and suggestions for future research.

2. Theoretical Framework and Literature Review

2.1. Theoretical Background

Air, water, and soil pollution, together with the spread of diverse contaminants, impose multidimensional harms on human health, ecosystems, and economic welfare. Pollutants such as particulate matter, sulfurous gases, and nitrogen oxides increase respiratory and cardiovascular disease burdens and reduce quality of life. Environmental impacts extend beyond human morbidity to include glacier retreat, rising atmospheric and ocean temperatures, sea-level rise, declining agricultural yields, biodiversity loss, and altered precipitation patterns— threats that undermine economic continuity and food security. These realities call for indicators that go beyond single-dimension metrics and capture both supply- and demand-side aspects of ecological systems. (Shahbaz et al., 2019)

Human activities—agriculture, industry, fishing, and international trade—have progressively intensified pressure on terrestrial and marine systems. Principal global threats to biodiversity include habitat loss and degradation, overfishing, and climate change. Researchers have therefore employed a range of indicators—air and water pollution metrics, deforestation measures, CO_2 emissions, biodiversity loss indices, and the ecological footprint—to quantify environmental degradation (Shahbaz et al., 2019).

The ecological footprint (EF) is widely used to measure human demand on nature across scales—from products and firms to cities and nations (Solarin et al., 2019). EF compares resource consumption and waste assimilation requirements against the biosphere's regenerative capacity; operationally, it is expressed as the biologically productive area required under current technologies and management regimes (Monfreda et al., 2004). In practice, EF captures the demand-side pressure on ecological assets, while biocapacity represents the supply-side capacity. EF can be read both as the ecological cost of provisioning consumed goods and services and as a route to carrying-capacity concepts that limit sustainable population and consumption patterns (Rees, 2006).

In recent decades human demand has exceeded planetary carrying capacity: most countries now run ecological deficits, compelling them to import resources, draw down natural capital (e.g. through overfishing or deforestation), or rely on global sinks for carbon emissions. Biocapacity, reported in global hectares (gha), quantifies an ecosystem's ability to regenerate biological materials and assimilate wastes given prevailing land uses and technologies; the gha unit standardizes productivity differences across land types and time (GNF, 2018).

To better assess environmental quality, current ecological assets must be explicitly considered. Siche et al. (2010) propose the Load Capacity Factor (LCF = biocapacity / ecological footprint) as a composite metric: LCF < 1 denotes ecological unsustainability (a deficit), while LCF > 1 indicates relative sustainability (Siche et al., 2010).

On the demand side, EF aggregates all biologically productive areas required by a population—food, fiber, timber, infrastructure land, and the carbon-sequestration area needed to offset fossil-fuel emissions. On the supply side, biocapacity reflects available productive areas (cropland, grazing land, forests, fishing grounds, built land) and their capacity to supply resources and sequester wastes. Comparing EF to local or global biocapacity reveals whether a region relies on imports or on depletion of natural capital.

Rising economic output, extraction, and EF are tightly linked: without sustainable practices, resource depletion accelerates and regeneration lags. Industrial production often depends on fossil fuels, increasing energy demand and the ecological footprint (Balsalobre-Lorente et al., 2018). Economic growth typically raises urbanization, transport, and industrial activity—factors that boost energy use (Wang, 2019).

Given Iran's status as a major fossil-fuel producer and consumer, its LCF is well below unity, reflecting resource-dependence and deteriorating environmental quality. Energy intensity—energy use per unit of GDP—directly affects LCF by shifting demand pressures on natural resources: increases in intensity raise consumption-related impacts and can worsen sustainability outcomes.

Energy is essential for development, but fossil-fuel dependence means higher energy intensity often exacerbates pollution. Energy intensity, a conventional proxy for national energy efficiency, has generally declined globally in recent decades; nevertheless, improving energy efficiency remains a key sustainable-development objective (Danish et al., 2020). Policymakers therefore emphasise technology adoption and structural transformation toward less energy-intensive activities to lower energy intensity and related emissions.

Empirical literature typically treats energy consumption as a key driver of pollution (Baloch et al., 2019; Dehghan Shabani & Shahnazi, 2019; Hou et al., 2019; Isik et al., 2019). While evidence on energy efficiency's environmental role is still growing, several studies support its importance in reducing environmental pressure (Amuakwa-Mensah & Adom, 2017; Shahbaz et al., 2016). It is important, however, to interpret energy-intensity measures with care: as a value-added ratio, intensity can fall with rising GDP even if absolute energy use remains high—so lower intensity does not automatically equal superior environmental performance (Kang & Kang, 2022).

Resource endowments and extraction patterns also shape development and environmental outcomes. Intensive exploitation tends to increase energy use, CO_2 emissions, and environmental degradation—especially where extraction is energy-intensive and damages habitats or water resources. Natural-resource rents—the surplus revenues from resource extraction—are thus central to understanding environmental impacts (Huang et al., 2020).

The literature proposes two contrasting hypotheses. The "resource blessing" view argues that resource rents can finance growth, technology transfer, and investments in green infrastructure (Lashitew & Werker, 2020). The "resource The literature proposes two contrasting hypotheses. The "resource blessing" view argues that resource rents can finance growth, technology transfer, and investments in green infrastructure (Lashitew & Werker, 2020). The "resource curse" thesis, however, contends that resource wealth can undermine institutions, concentrate economies in extractive sectors, and worsen environmental performance (Tiba, 2019). Empirical findings are mixed: some studies find that rents harm environmental quality (Hassan et al., 2019; Bekun et al., 2019; Khan et al., 2020), while others report neutral or mitigating effects under particular rent types or institutional settings (Zafar et al., 2019; Balsalobre-Lorente et al., 2018). Heterogeneity in rent composition, transmission channels, and governance helps explain these divergent results.

Human capital is a further key determinant. By promoting R&D, technology adoption, managerial capacity, and environmental awareness, human capital can reduce energy intensity and the ecological burden, and can shift economies toward less energy-intensive, higher-value production. From a welfare perspective, investing in human capital supports a just transition to a green economy, but success requires complementary social policies to avoid adverse side effects such as unemployment or increased inequality (Ganda, 2019; World Bank, 2012).

Empirical studies support the positive environmental role of human capital (Zafar et al., 2019), showing that skills and education facilitate technology transfer and efficiency gains. Accordingly, in this study human capital is expected to reinforce environmental sustainability—by improving biocapacity management and reducing consumption pressure—especially when combined with incentives for clean technologies and market-based instruments.

2.2. Literature Review

Domestic studies have examined various aspects of the energy–environment nexus in Iran. Galdavi et al. (2025) calculated ecological footprint and biocapacity in Khorasan Razavi and found a severe ecological deficit, recommending policies including consumption reduction, clean technologies, and land-use management. Zabihi et al. (2024) analyzed the role of energy consumption structure and per-capita GDP in changes in carbon emissions, finding that greater diversity in energy consumption contributes to reduced environmental pressures. Esfahani et al. (2022) showed that non-renewable energy consumption, urbanization and fertility rates have a positive effect on the ecological footprint, whereas renewable energy use and human capital exert an opposite (reducing) effect on this indicator. Safarzadeh & Shad Ostanjin (2021), using Iranian data, found that hydropower consumption reduces the carbon footprint and CO_2 emissions. Parsasharif et al. (2021) reported a positive impact of energy consumption and financial development and a negative effect of trade openness on the ecological footprint across selected Asian and European countries. Hemati & Khoshkalam Khosroshahi (2020) investigated the interaction between economic freedom and governance and their effects on the ecological footprint in developing countries, showing that economic freedom tends to increase the footprint while better governance reduces it. Tarazkar et al. (2020) confirmed an N-shaped relationship between economic growth and the ecological footprint in Middle Eastern countries, implying increased environmental degradation at higher growth levels. Mohammadi & Zarif (2018) found that energy intensity, chemical fertilizer use, and industrial value added worsen the Environmental Performance Index in OPEC and OECD countries. Molaei and Basharat (2015) documented a positive relationship between per-capita GDP and per-capita ecological footprint in Iran.

Among international studies, Wang & Xu (2025) analyzed E7 panel data and found that globalization and industrial output exacerbate environmental degradation, while natural resources and environmental technologies significantly mitigate it. Karim et al. (2025) applied the STIRPAT model and CS-ARDL on G7 countries and concluded that green innovation reduces environmental pressure in the long run, the service sector has a positive short-term but negative long-term effect, and population and structural changes show mixed impacts. Georgescu & Kinnunen (2024) used ARDL on Finland's data and found that GDP and FDI reduce the ecological footprint, energy use increases it, and a U-shaped Environmental Kuznets Curve is observed. Sun et al. (2024) reported that environmental technologies, urbanization and higher shares of renewable energy use improve environmental sustainability across APEC countries. Pata and Samour (2023) examined OECD countries and found a positive association between renewable energy consumption and the load capacity factor, while the insurance market exhibited a negative effect. Sasen et al. (2022) investigated disaggregated resource rents in BRICS economies and revealed mixed outcomes: total resource rents were in some cases associated with lower CO_2 emissions, whereas mineral, forestry and oil rents significantly increased CO_2 emissions. Kang & Kang (2022), analyzing 104 countries by income groups, showed that higher-income countries exhibit greater energy-intensity efficiency and that simultaneous improvements in income and environmental regulation deliver the largest gains in energy efficiency. Ganda (2022) found that human capital has a positive and significant effect on both environmental quality and environmental sustainability in BRICS countries in the short and long run, and that there is bidirectional causality between human capital and sustainability. Kongbuamai et al. (2021) confirmed that economic growth and non-renewable energy consumption increase the ecological footprint. Ben-Salha et al. (2021), using PMG estimation for resource-rich countries, reported evidence consistent with a Among international studies, Wang & Xu (2025) analyzed E7 panel data and found that globalization and industrial output exacerbate environmental degradation, while natural resources and environmental technologies significantly mitigate it. Karim et al. (2025) applied the STIRPAT model and CS-ARDL on G7 countries and concluded that green innovation reduces environmental pressure in the long run, the service sector has a positive short-term but negative long-term effect, and population and structural changes show mixed impacts. Georgescu & Kinnunen (2024) used ARDL on Finland's data and found that GDP and FDI reduce the ecological footprint, energy use increases it, and a U-shaped Environmental Kuznets Curve is observed. Sun et al. (2024) reported that environmental technologies, urbanization and higher shares of renewable energy use improve environmental sustainability across APEC countries. Pata and Samour (2023) examined OECD countries and found a positive association between renewable energy consumption and the load capacity factor, while the insurance market exhibited a negative effect. Sasen et al. (2022) investigated disaggregated resource rents in BRICS economies and revealed mixed outcomes: total resource rents were in some cases associated with lower CO_2 emissions, whereas mineral, forestry and oil rents significantly increased CO_2 emissions. Kang & Kang (2022), analyzing 104 countries by income groups, showed that higher-income countries exhibit greater energy-intensity efficiency and that simultaneous improvements in income and environmental regulation deliver the largest gains in energy efficiency.

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Mariani et al. (2010) used an overlapping-generations framework to show that life expectancy and environmental quality are jointly determined and that a positive association between longevity and environmental quality emerges both along transition paths and in long-run steady states.

Overall, the literature demonstrates extensive research on links among economic factors, energy consumption, resource rents, human capital and environmental outcomes (ecological footprint, CO_2 emissions and broader sustainability indicators). However, most empirical work focuses on developed countries or specific country groups, leaving a relative gap in comprehensive studies tailored to countries with particular economic and environmental characteristics such as Iran. Given Iran's strong reliance on fossil fuels, high energy intensity, resource rents linked to oil, public-health challenges and pressures on natural capital, it faces significant environmental problems. This study aims to fill part of the existing gap by examining the long-run effects of per-capita GDP, energy efficiency (energy per unit of GDP), natural-resource rents and human capital on environmental sustainability in Iran. A key novelty of the present research is the simultaneous consideration of both supply-side and demand-side environmental factors through the comprehensive indicator of the Load Capacity Factor (LCF) as the dependent variable. To the best of our knowledge, this is the first Iranian study to analyze the role of human capital on the LCF. The findings can inform policymakers in designing more effective strategies to mitigate environmental harms, improve resource management, and strengthen human-capital policies. The paper also contributes by investigating how resource rents and the interactive effects of human-related variables influence the LCF.

3. The Model

To examine both short-run and long-run relationships among the study variables, we adopt the Autoregressive Distributed Lag (ARDL) modelling framework. Unlike Johansen cointegration methods, the ARDL approach does not require that all regressors be integrated of the same order; it can be applied to a mixture of I(0) and I(1) variables, which makes it particularly attractive for empirical work where variables exhibit different orders of integration. ARDL permits simultaneous estimation of long-run coefficients and short-run dynamics and, when combined with an error-correction representation (ECM), provides a direct estimate of the speed of adjustment to the long-run equilibrium after transitory shocks. Moreover, ARDL performs well in small samples, allows for different lag lengths across variables, and offers greater flexibility in lag selection—features that improve estimation precision and the reliability of inference. Importantly, ARDL mitigates certain endogeneity concerns arising from contemporaneous correlation of the regressors by modelling dynamic lag structures (Pesaran & Shin, 1995).

The distinction between short-run and long-run effects has substantive grounding in economic and environmental dynamics. Short-run responses of income, human capital or energy intensity may be limited or even counter-intuitive because of implementation lags (e.g. investment gestation, behavioural adaptation). For instance, an immediate inflow of resource rents may initially stimulate extraction without a concomitant environmental response, whereas long-run effects materialise through channels such as increased environmental awareness, productivity improvements, structural change away from energy-intensive activities, and broader adoption of clean technologies. The ARDL/ECM framework explicitly captures these dynamics by estimating short-run differenced effects (associated with lagged differences) and long-run level relationships (the cointegrating vector).

This study uses annual time-series data for Iran covering 1990–2020 to analyse the environmental impacts of GDP per capita, human capital, energy efficiency and natural-resource rents. The empirical specification is:

$$\ln(LCF_t)=\alpha+\beta_1\ln(GDP_t)+\beta_2\ln(HC_t)+\beta_3\ln(EEI_t)+\beta_4\ln(RENT_t)+\varepsilon_t \quad (1)$$

where LCF denotes the load-capacity factor measured in global hectares, GDP is GDP per capita (a proxy for economic development), HC is the human-capital index, EI is an energy-efficiency indicator defined as GDP per unit of energy use (i.e. the inverse of conventional energy intensity), and RENT denotes natural-resource rents (share of GDP). Because the model is specified in logarithms, each coefficient may be interpreted as an elasticity: βj expresses the percentage change in LCF associated with a 1% change in the corresponding explanatory variable.

Guided by theoretical reasoning and existing empirical evidence, the expected signs of the coefficients are as follows. An increase in per-capita GDP can, through scale effects, raise demand pressures and thus degrade biocapacity; hence β1 is expected to be negative. Human capital facilitates the diffusion of clean technologies, raises environmental awareness and improves resource management, so β2 is expected to be positive. Since the model employs an energy-efficiency measure (GDP per unit energy)—the inverse of conventional energy intensity—higher values indicate improved efficiency (lower intensity), and thus β3 is expected to be positive. Finally, natural-resource rents typically exert adverse effects on ecological supply through intensive extraction and habitat degradation, implying β4 is likely to be negative.

Table 1. Research Variables and Indicators

Variable (in logarithmic form)	Definition	Source
lnLCF	Load Capacity Factor	Global Footprint Network
lnGDP	Gross Domestic Product	World bank
lnHC	Human Capital (Knowledge and Skills of Labor Force)	World bank
lnEEI	Energy Efficiency Index (GDP per Unit of Energy Use)	World bank
lnRENT	Natural Resource Rent (% of GDP)	World bank

Source: *Authors' computations*

Prior to estimating the ARDL model, and to ensure the absence of endogeneity, multicollinearity and contemporaneous causality among regressors, a set of diagnostic tests was performed. These comprised the Pearson correlation matrix, the variance inflation factor (VIF) and Granger-causality tests. All diagnostic results indicated a satisfactory specification: no severe multicollinearity, no systematic endogeneity, and no pronounced temporal causality among the variables. Accordingly, the necessary conditions for applying the ARDL framework and for interpreting its short- and long-run estimates were satisfied.

4. Empirical Results

4.1. Unit-root tests

Before estimation, it is essential to test the time-series properties of all variables to avoid spurious regression. A series is considered stationary if a shock to it is transitory and the series returns to its long-run equilibrium. We employ the augmented Dickey–Fuller (ADF) test, which is commonly used for testing stationarity in time-series data. The ADF test outcomes are reported in Table 2. According to these results, the energy-efficiency indicator (EI) is stationary at level (I(0)), whereas the load capacity factor (LCF), GDP per capita (GDP), human capital index (HC) and natural-resource rents (RENT) attain stationarity after first differencing (I(1)). These integration properties validate the use of the ARDL bounds testing approach, since the variables are a mixture of I(0) and I(1) and none are integrated of order two.

Table 2. Unit Root Test Results

Variable	Probability	t-Statistic	Order of Integration
lnLCF	0.000	-5.93	I(1)
lnGDP	0/007	-2/78	I(1)
lnHC	0.049	-3/58	I(1)
lnEEI	0/012	-4/22	I(0)
lnRENT	0/003	-3/63	I(1)

Source: *Authors' computations*

4.2. Tests of classical assumptions and model specification

To ensure the reliability of the estimated coefficients, classical diagnostic checks were carried out. Table 3 reports the results of the normality test for the residuals (Jarque–Bera), serial-correlation test (Breusch–Godfrey LM) and heteroskedasticity test (Breusch–Pagan–Godfrey). In addition, the Ramsey RESET test was used to assess potential specification error.

Table 3. Diagnostic Test Results for the ARDL Model

Test	Reported statistic	P-value	Null hypothesis
Test of normality (Jarque–Bera)	3/63	0/162	Residuals are normally distributed
Breusch–Godfrey serial-correlation LM test	1/07	0/390	No serial correlation in residuals
Heteroskedasticity test (Breusch–Pagan-Godfrey)	0/93	0/570	Homoskedasticity (no heteroskedasticity)
Ramsey RESET test (functional-form)	1/38	0/204	Correct functional form (no omitted variables)

Source: *Authors' computations*

According to Table 3, the Jarque–Bera test yields a p-value of 0.162, which is above the conventional 5% threshold; therefore the null hypothesis of normally distributed residuals cannot be rejected. The Breusch–Godfrey LM test for serial correlation produces an F-statistic p-value of 0.390 ($p > 0.05$), implying no evidence of serial correlation in the residuals. The Breusch–Pagan–Godfrey heteroskedasticity test returns an F-statistic p-value of 0.570 ($p > 0.05$), indicating homoskedastic residuals. Finally, the Ramsey RESET test yields a p-value greater than 0.05, consistent with correct functional form and no omitted-variable bias in the estimated specification. Collectively, these diagnostics support the validity of the model and the use of the estimated coefficients for inference.

4.3. Bounds test and long-run estimation

To examine the existence of a long-run relationship among the variables, we apply the bounds testing procedure developed by Pesaran et al. (2001). Under the ARDL bounds framework, the joint significance of the levels of the variables in an unrestricted error-correction representation is tested using an F statistic. At the 95% confidence level, the critical lower and upper bounds are 2.26 and 3.48, respectively

(Table 4). The computed F statistic of 4.00 exceeds the upper bound critical value; hence the null hypothesis of no long-run relationship can be rejected. This provides evidence of cointegration among the load-capacity factor and the explanatory variables.

Table 4. Bounds Test at the 95% Level

Test Statistic	Value	Sig.level	I(0)	I(1)
F-statistic	8/26	10%	1/9	3/01
F-statistic	4	5%	2/26	3/48

Source: *Authors' computations*

Given the confirmed long-run linkage, the long-run coefficients were estimated and are reported in Table 5.

Table 5. Estimation of the long-run Form

Variable (log)	**Coefficient*[1]**	**t-Statistic**	**Prob**
lnGDP	-0/23	-8/22	0/000
lnHC	1/32	3/35	0/008
lnEEI	1/88	25/06	0/000
lnRENT	-0/38	-3/37	0/008

Source: *Authors' computations*

According to the estimates reported in Table 5, all long-run coefficients are statistically significant. GDP per capita has a negative and significant effect on the Load Capacity Factor: a 1% increase in GDP is associated with an approximately 0.23% decline in LCF, implying that economic growth over the sample period—given its current energy- and resource-intensive structure—has tended to increase pressure on natural capital and weaken environmental sustainability. This finding suggests that growth in the absence of adequate environmental safeguards and policy interventions may accelerate extraction, expand energy-intensive industrial activities, and, overall, reduce the ratio of biocapacity to ecological demand.

Conversely, human capital has a positive and economically meaningful long-run effect on LCF: a 1% rise in the human-capital index is associated with roughly a 1.32% increase in LCF. This result underscores the central role of education, skills and institutional capacity in promoting cleaner technologies, improving production efficiency and strengthening social and institutional responsiveness to environmental issues.

In this study, the energy-efficiency indicator (EI) is defined as GDP per unit of energy use (i.e. the inverse of conventional energy intensity). Under this definition, the estimated positive coefficient—approximately +1.88—appropriately

1. The model is estimated using the logarithmic form of the variables, allowing the coefficients to be interpreted as elasticities. Variations in coefficient magnitudes reflect the inherent nature of the relationships between variables or the degree of their influence. Coefficients with absolute values less than one indicate that the dependent variable is relatively inelastic to changes in the independent variable, while those exceeding one imply that changes in the independent variable have a disproportionately stronger effect.

reflects that improvements in energy efficiency are associated with higher environmental sustainability. More precisely, a 1% increase in output per unit of energy (interpreted as a 1% improvement in energy efficiency) is associated on average with about a 1.88% increase in LCF. Because EI here is the inverse of the usual energy-intensity measure, the sign of the coefficient should be read accordingly: using the standard Energy/GDP indicator would produce an equivalent coefficient with opposite sign (i.e. an increase in conventional energy intensity would reduce LCF).

Finally, natural-resource rents exert a negative and significant influence on LCF: a 1% increase in resource rents (as a share of GDP) is associated on average with about a 0.38% reduction in LCF. This outcome is consistent with the resource-rent channel through which dependence on extractive revenues can undermine environmental policy and investment in sustainable activities.

Overall, the pattern of results highlights a policy trade-off: strengthening human capital and expanding renewable-oriented efficiency can substantially improve environmental outcomes, whereas unchecked growth and excessive reliance on resource rents—absent appropriate environmental governance—are likely to produce adverse ecological consequences.

4.4. Error-correction model estimation

Beyond establishing long-run relationships, it is necessary to examine how short-run disequilibria are corrected. The error-correction formulation indicates the portion of the previous period's deviation from the long-run equilibrium that is eliminated in the current period. As shown in Table 6, the estimated error-correction coefficient (CointEq(−1)) is negative and statistically significant. This implies that deviations of LCF from its long-run equilibrium are corrected over time: if a shock to any explanatory variable displaces LCF from its long-run path, the deviation is transitory and is substantially adjusted back toward equilibrium. The estimated coefficient magnitude (≈ −0.634) indicates that about 63% of the prior period's disequilibrium is corrected within one year.

Table 6. Error Correction Model (ECM)

Variable	Coefficient	t-Statistic	Prob
D(LCF(-1))	0/225	2/308	0/046
D(GDP)	-0/076	-2/540	0/031
D(GDP(-1))	-0/012	-0/320	0/769
D(GDP(-2))	0/286	8/628	0/000
D(EEI)	0/725	9/422	0/000
D(EEI(-1))	-0/772	-4/300	0/002
D(EEI(-2))	-0/404	-3/097	0/012
D(EEI(-3))	-0/358	-3/430	0/007
D(RENT)	-0/182	-9/879	0/000
D(RENT(-1))	0/083	4/057	0/002
D(RENT(-2))	0/090	5/829	0/000
CointEq(-1)	-0/634	-7/725	0/000

Source: *Authors' computations*

4.5. Structural stability tests

Parameter stability was evaluated using the cumulative sum (CUSUM) and the cumulative sum of squares (CUSUMQ) tests at the 5% significance level. In Figures 2 and 3, the 95% confidence bounds are plotted as the pair of dashed red lines. If the test statistic (the blue line) stays within these bounds throughout the sample period, the null hypothesis of parameter stability cannot be rejected, indicating correct model specification and stable coefficients. In our application the test statistics remain inside the confidence bands, so the null hypothesis of structural stability is supported at the 5% level.

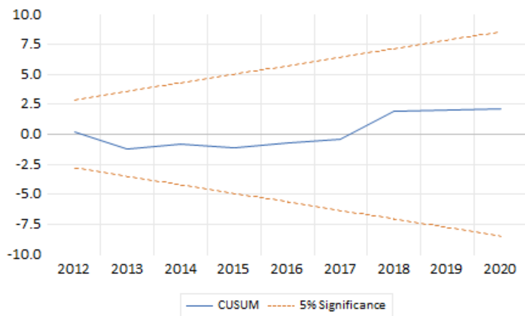

Figure 2. Stability Test of Coefficients CUSUM

Source: *Authors' computations*

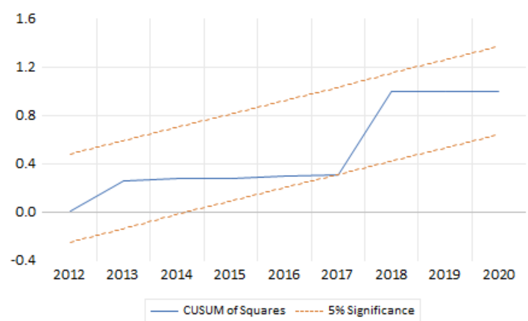

Figure 3. Stability Test of Coefficients CUSUMQ

Source: *Authors' computations*

5. Discussion and Conclusion

This study examined the determinants of Iran's Load Capacity Factor (LCF) over the period 1990–2020 using the ARDL–ECM framework. The analysis focused on GDP, human capital, energy efficiency (measured as GDP per unit of energy use), and natural resource rents. Pre-estimation diagnostics confirmed the suitability of the ARDL approach: variables are I(0) or I(1), classical assumptions are satisfied (no serial correlation, homoskedasticity, normality, and correct functional form), the bounds test establishes a long-run cointegrating relationship

(F-statistic = 4.00 > upper critical bound at 5%), and CUSUM and CUSUMSQ tests confirm parameter stability.

5.1. Comparison of Findings with Existing Literature

The long-run results are highly consistent with both domestic and international evidence:

- The negative effect of GDP on LCF (−0.23%) aligns with Molaei & Basharat (2015) and Tarazkar et al. (2020) for Iran and the Middle East, who documented growth-driven ecological pressure, and with Georgescu & Kinnunen (2024) and Kongbuamai et al. (2021) internationally.

- The strong positive impact of human capital (+1.32%) corroborates Ganda (2022) and Kim and Go (2020) on the sustainability-enhancing role of education and skills, and extends Esfahani et al. (2022) by being the first Iranian study to explicitly link human capital to the comprehensive LCF indicator.

- Energy efficiency emerges as the most powerful driver (+1.88%), reinforcing Zabihi et al. (2024) for Iran, Danish et al. (2020) globally, and Kang & Kang (2022) across income groups.

- The adverse effect of natural resource rents (−0.38%) supports the resource-curse hypothesis, consistent with Ben-Salha et al. (2021), Sasen et al. (2022), and Hemati & Khoshkalam Khosroshahi (2020).

Taken together, the findings confirm that while resource-intensive growth and rent dependence erode environmental carrying capacity, human capital and energy efficiency are significantly stronger countervailing forces. The error-correction term (−0.634) implies a relatively rapid annual adjustment of 63% toward long-run equilibrium.

5.2. Policy Implications

The empirical evidence points to clear, actionable policy priorities for improving Iran's LCF:

1. Accelerate Energy Efficiency Gains: Enforce mandatory efficiency standards in industry and buildings, expand fiscal incentives for retrofitting, and fully implement SATBA's renewable energy targets.
2. Invest Strategically in Green Human Capital: Integrate environmental and clean-technology modules into technical-vocational training and higher education curricula, and strengthen applied research in sustainable resource management.
3. Internalize Environmental Costs of Growth: Introduce market-based instruments (e.g., carbon pricing or emissions trading) to align private incentives with ecological limits.
4. Break Resource-Rent Dependence: Channel a larger share of oil revenues into sovereign wealth funds and non-extractive, knowledge-based sectors to reduce Dutch-disease effects and environmental degradation.
5. Institutionalize LCF Monitoring: Adopt LCF as a core national sustainability indicator, publish regular provincial assessments, and integrate it into five-year development plans.

5.3. Practical Recommendations

- Launch pilot "Green Skills" programs in collaboration with the Technical and Vocational Training Organization, targeting oil-dependent provinces (e.g., Khuzestan, Bushehr).
- Build on Iran's ongoing efforts to develop a knowledge-based and technology-driven economy to expand high-value service and technology exports.
- Partner with the Global Footprint Network to develop localized, open-access LCF calculation tools for Iranian policymakers and researchers.

5.4. Limitations and Directions for Future Research

This study is subject to three main limitations: (i) reliance on annual national data (31 observations) limits short-run granularity; (ii) omission of potentially relevant variables such as urbanization rate, renewable energy share, or trade openness; and (iii) aggregation at the national level masks significant provincial heterogeneity.

Future studies could exploit quarterly data when available, conduct sub-national analyses, or extend the sample beyond 2020 to capture recent sanction and energy-price dynamics. In addition, examining the effects of institutional and climatic variables—conditional on the availability of stable and long-term annual data for Iran—could represent a valuable direction for future research.

5.5. Concluding Remarks

Iran's persistent ecological deficit is not inevitable. While current growth patterns and resource-rent dependence continue to erode the country's load capacity, the results offer a clear and optimistic roadmap: decisive investment in human capital and energy efficiency can more than offset these pressures. By shifting from a resource-dependent to a knowledge-driven, low-carbon development model, Iran has a realistic pathway to reconcile economic progress with long-term environmental sustainability.

Author Contributions

Conceptualization, all authors; methodology, all authors; validation, all authors; formal analysis, all authors; resources, all authors; writing original draft preparation, all authors; writing review and editing, all authors; all authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

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