

(Grodno, Belarus); Vasil STRUK (struk@grsu.by), Doctor of Technical Sciences, Professor, Professor of the Department of Materials Science and Resource-Saving Technologies, Yanka Kupala State University of Grodno (Grodno, Belarus); Ludmila NEKHOROSHEVA (kepp@bseu.by), Doctor of Economic Sciences, Professor, Head of the Department of Industrial Enterprise Economics, Belarusian State Economic University (Minsk, Belarus); Aliaksandr ANTONAU (antonov\_as@grsu.by), Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Materials Science and Resource-Saving Technologies, Yanka Kupala State University of Grodno (Grodno, Belarus).

**Abstract.** The article considers the directions of realization of the concept of sustainable socio-economic development of Belarus. It is shown that in order to reduce the material intensity of products it is necessary to have a special technological impact on residual products (waste) of the production process and recycling of depreciated products in order to return full-fledged material and energy resources to the sphere of industry. The functional connection of the closed cycle elements has been developed, which allows to realize the concept of sustainable socio-economic development. It is proposed to create cluster structures of scientific, educational and production organizations and institutions in order to activate targeted research activities.

**Keywords:** sustainable socio-economic development; closed technological cycle; special technological impact; algorithm of closed cycle realization; cluster structures.

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**YANG NING, WANG XIANPENG**

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**THE ECONOMIC BENEFITS OF LOW-CARBON  
INNOVATION IN THE PATH TOWARDS SUSTAINABLE  
NATIONAL GROWTH**

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**Abstract.** Energy demand plays a pivotal role in propelling economic growth, and ensuring the availability of affordable, dependable energy remains a primary goal for sustainable development. In the past, the escalating energy needs of nations have been met primarily through fossil fuels; however, as the world advances, there is an increasing necessity to focus on energy alternatives with smaller carbon footprints, and ultimately, those that are carbon-neutral. The pace at which decarbonization occurs will vary between countries, influenced by unique local conditions and circumstances. This paper

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*Yang NING (yangningphd@imb.by), Postgraduate studies 1st year, International Institute of Management and Business (Minsk, Belarus);*

*Wang XIANPENG (wxp-phd@bntu.by), Doctor of Engineering, Ph.D, Economics, International Institute of Management and Business (Minsk, Belarus).*

explores how the transition to low-carbon energy impacts economic growth and national development, especially in lower-income nations. It offers empirical insights into the relationship between energy use, emissions, and economic growth, while also highlighting strategies to expedite decarbonization efforts. Through an examination of both theoretical and applied literature, the paper evaluates the economic compromises and co-benefits associated with reducing carbon emissions in energy systems. Additionally, it explores avenues for creating a cleaner, more resilient, and sustainable growth model, presenting potential pathways for developing nations to shift towards an economy with a lower carbon footprint.

**Keywords:** Economic Benefits; Low-Carbon; Sustainable National Growth.

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**Introduction.** For more than two hundred years, energy derived from fossil fuels has served as a foundational element for economic progress and expansion. The centrality of fossil fuels in shaping the economic landscape is extensively documented in both historical and contemporary analyses of growth catalysts. In line with the United Nations' Sustainable Development Goals, the significance of modern energy systems—characterized by the availability of affordable, dependable, and sustainable energy—is acknowledged as critical for driving development. Yet, the future energy framework must undergo transformation, as reliance on fossil fuels must be reduced to tackle climate change. In order to maintain global temperature increases within safe boundaries—specifically, well below 2°C, with an aspiration for a 1.5°C rise—substantial reductions in carbon emissions are essential, as outlined by the Paris Agreement, which entered into force in 2016. [1]

Realizing these climate objectives demands a fundamental shift, especially in developing nations, which have historically contributed a minimal proportion of global emissions. However, this dynamic is shifting, as six of the top ten emitters of greenhouse gases are now emerging economies, accounting for about 60% of global emissions. Moving forward, these countries will be the principal sources of future emissions growth. As such, addressing the energy requirements of developing nations must account for the intensifying urgency of carbon limitations. To meet global climate targets, developing countries cannot replicate the high-carbon development paths followed by more industrialized nations. [2]

Decoupling economic expansion from carbon emissions presents a significant challenge. Realizing this objective necessitates a sharp reduction in the carbon intensity of economic output—quantified as the amount of carbon emissions per unit of GDP. Fortunately, this shift is feasible, as renewable energy technologies are becoming more cost-effective and accessible, propelled by economies of scale and technological advancements. Over time, the price of clean, renewable energy sources has decreased significantly, enabling them to compete more effectively with fossil fuels. Moreover, the growing efficiency of energy technologies and equipment offers further avenues for reducing emissions while supporting economic development. [3]

Nevertheless, the transition to low-carbon energy is fraught with obstacles. The immediate costs associated with this transition—particularly regarding the restructuring of energy infrastructure—can be substantial. Developing countries, in particular, face intricate political and economic choices as they make considerable investments in energy infrastructure to accommodate a growing population. The long lifespan of energy assets means that investments made today will determine future emission trajectories for decades, creating the risk of stranded assets. To achieve the 2°C climate goal, energy investments must be carefully aligned with long-term carbon constraints. [4]

This paper investigates the economic ramifications of shifting to low-carbon energy in developing nations, focusing on both the obstacles and prospects involved. It assesses the potential immediate costs while also emphasizing the long-term advantages of adopting a cleaner, more vibrant, and sustainable growth model. The paper concludes by reflecting on the long-term advantages of low-carbon innovations for promoting sustainable development.[5]

### Carbon Emissions, Energy Consumption, and Economic Development

To understand the potential for low-carbon innovation, it is essential to examine the relationship between economic growth (GDP), energy consumption, and greenhouse gas emissions. These links provide valuable insights into the feasibility of decarbonizing the energy sector while sustaining economic development. In the context of pursuing sustainable growth, countries must reduce either the energy intensity of their economies, the carbon intensity of energy, or both. [6-7]

When combining energy and carbon intensity data, the global average carbon intensity of GDP stood at 347 kg CO<sub>2</sub> per \$1000 GDP. The isoquant analysis reveals that countries with higher energy and carbon intensities are positioned in the top-right quadrant, emitting more carbon per unit of economic output. Conversely, countries with lower intensities are situated in the bottom-left quadrant, emitting less carbon. Notably, although many developing countries fall below the global average for carbon intensity of GDP, a significant number still perform worse than the global benchmark (Figure 1).

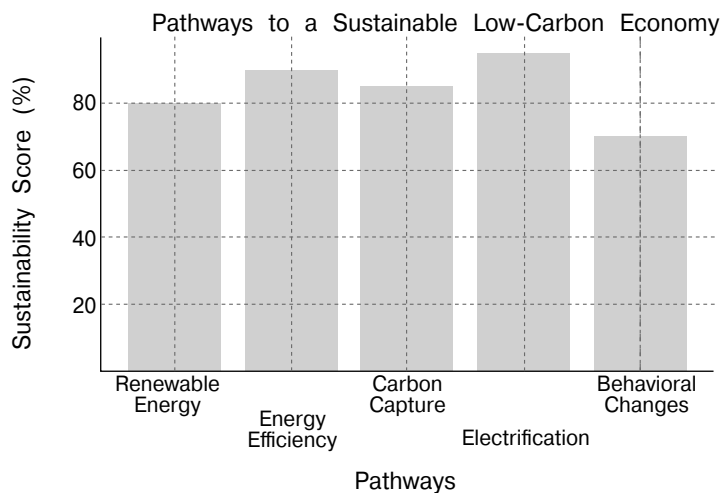


Figure 1. Pathways to a Sustainable Low-Carbon Economy

The economic frameworks of high-income countries have traditionally demonstrated greater efficiency in energy consumption. These nations exhibited a reduction in energy intensity of approximately 20%, alongside a 17% drop in carbon intensity per unit of energy, compared to low- and middle-income countries. These trends suggest a general correlation between higher income levels and lower carbon emissions per unit of GDP, although this pattern is shaped by factors such as industrial composition, resource availability, and policy choices.

Monitoring energy and carbon intensities over time further highlights progress in decarbonization efforts. The data reveals consistent improvements in energy intensity across both developed and developing nations, with many countries achieving annual reductions of up to 4% between 2001 and 2011. However, some low- and middle-income nations saw increases in energy intensity, primarily

due to the economic transitions they were undergoing. These trends emphasize the critical role of advancing low-carbon innovations, which could expedite the decoupling of economic growth from carbon emissions, thereby creating pathways for sustainable and equitable economic development.

### Carbon Intensity of Energy Supply and Low-Carbon Transformation

While these countries are advancing in energy efficiency through structural transformations and technological improvements, they are inadvertently increasing the carbon footprint of their energy supply. [8] The case of large developing economies such as Indonesia and Vietnam, where coal use surged significantly, exemplifies this phenomenon. Between 2001 and 2011 (Figure 2).

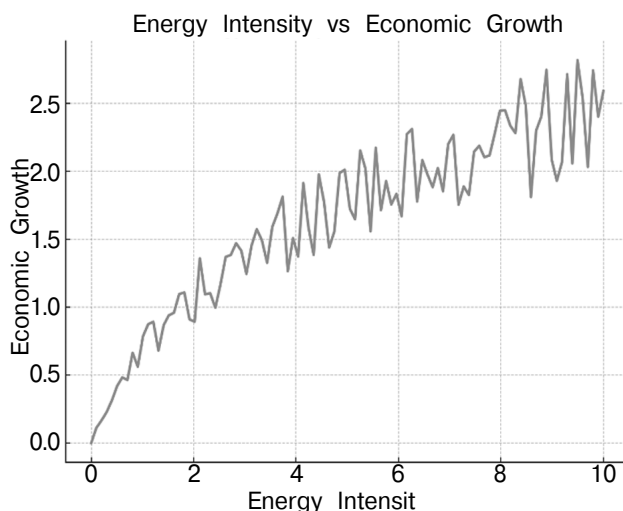


Figure 2. Energy Intensity vs Economic Growth

In contrast, wealthier nations have made notable progress in lowering both energy and carbon intensity. Between 1990 and 2011, these countries decreased their energy intensity by 24%, while also reducing the carbon intensity of their energy supply by 6%. In comparison, low- and middle-income countries achieved a 55% reduction in energy intensity during the same period, bringing their energy usage per unit of GDP in line with that of high-income nations when adjusted for purchasing power parity. However, this improvement in efficiency was counterbalanced by a 10% rise in the carbon intensity of their energy sources. Upper-middle-income countries experienced similar patterns, but starting from higher levels of both energy and carbon intensity.

The global picture of carbon emissions per unit of GDP has improved at an average annual rate of just under 1%, predominantly through reductions in energy intensity. This improvement highlights the growing potential for low-carbon innovation to drive economic growth without the same environmental trade-offs that characterized past industrialization. More recently, substantial progress has been made in reducing global carbon emissions. In 2014, 2015, and 2016, global carbon dioxide emissions remained stable, despite GDP growth of approximately 3% per year. This decoupling of economic growth from carbon emissions resulted in a 3% annual reduction in global carbon intensity of GDP. This trend is expected to continue, with projections anticipating a 2.6% annual decrease in carbon intensity of GDP by 2035, driven by both a 0.5% reduction in carbon intensity and a 2.1% improvement in energy efficiency.[9; 10]

These developments underscore the importance of low-carbon innovation in achieving sustainable economic growth. As the world moves towards cleaner, more efficient energy systems, the potential economic benefits of low-carbon technologies will continue to grow, offering opportunities for both developed and developing countries to innovate while addressing the climate crisis.

### **Pathways to a Low-Carbon Energy Sector for Sustainable Growth**

In this section, we explore how transitioning to a low-carbon energy framework can facilitate long-term economic growth while aligning with global climate goals. Achieving the targets set forth in the Paris Agreement requires significant commitment and a well-defined strategy for reducing carbon emissions. To limit the global temperature increase to well below 2°C, cumulative carbon emissions over the course of this century must be restricted to between 600 and 1100 GtCO<sub>2</sub>. However, current global emissions hover around 40 GtCO<sub>2</sub> annually, with the majority stemming from the use of fossil fuels. The remaining carbon budget is considerably smaller than the carbon content of existing fossil fuel reserves, highlighting the urgent need for a swift transformation in the energy sector.

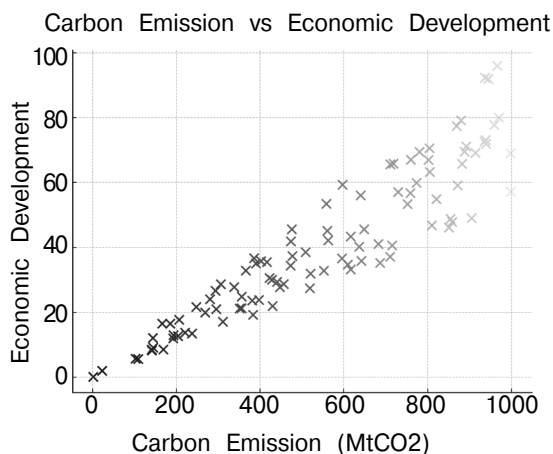
The most cost-effective path to reaching these targets involves global emissions peaking within the next decade, followed by a sustained decline. This will require a marked acceleration in reducing carbon emissions per unit of GDP. For example, the International Energy Agency (IEA) has projected a scenario where the carbon intensity of global GDP decreases by 5.3% annually from 2014 to 2040. This reduction would be driven by a combination of enhanced energy efficiency (3.0% per year) and a decline in the carbon intensity of energy (2.4% per year). Achieving such rapid reductions is vital for creating an economic landscape where both growth and decarbonization can coexist, enabling economies to transition to a low-carbon model without hindering development.

To achieve the long-term goal of ‘net zero’ emissions—where anthropogenic emissions are balanced by removal through natural sinks—countries must implement swift and substantial energy transitions. This will require balancing short-term economic growth with long-term sustainability goals, leveraging low-carbon technologies that can stimulate innovation while reducing emissions. Numerous energy-economy models have been developed to simulate various emissions reduction pathways, helping to shape the direction of national policies and global climate strategies.

However, most of these models are highly aggregated and do not provide detailed insights into how individual countries can decarbonize. For the major greenhouse gas emitters, more granular data can be derived from national-level simulations. The UN Deep Decarbonization Pathways Project (DDPP) offers valuable insights through country-specific, bottom-up models. These simulations indicate that very rapid reductions in both energy and carbon intensity are theoretically possible, with some countries achieving near-total decarbonization of their energy sectors by mid-century (Figure 3).

Although the DDPP scenarios set forth exceptionally ambitious goals, they underscore the possibility for swift innovation and technological progress within the energy domain. Every nation will encounter distinct obstacles, shaped by its energy composition and economic framework. For example, countries like Brazil, with a predominantly carbon-neutral electricity grid reliant on hydropower, will pursue a different trajectory than nations like India or China, where coal remains a dominant source of energy. Likewise, the decarbonization priorities for high- and middle-income countries will center on modernizing power generation infrastructure, enhancing energy efficiency in sectors like industry and transport,

and rethinking electricity distribution networks. On the other hand, low-income nations will need to concentrate on the transition to clean electricity, sustainable biomass utilization, and extending access to essential energy services such as lighting, heating, and water supply.



*Figure 3.* Carbon Emissions vs Economic Development

Despite these differences, several common trends are emerging. The growing integration of low-carbon innovation in energy systems presents clear economic benefits, such as new opportunities for job creation in clean energy industries, reduced energy costs over the long term, and greater energy security. These shifts are not only vital for environmental sustainability but are also key drivers of economic growth, particularly in nations committed to fostering a green economy. As we discuss in the following sections, these low-carbon innovations offer tremendous potential for countries to accelerate growth while achieving their climate targets.[11]

### **Reducing the Carbon Intensity of Energy to Foster Sustainable Growth**

A key strategy for achieving a low-carbon economy is the rapid transformation of the energy sector, particularly through the decarbonization of electricity. This shift is essential not only for reducing global emissions but also for spurring sustainable economic growth. The energy sector is responsible for approximately two-thirds of global greenhouse gas emissions, with the electricity sector being a major contributor. However, by decarbonizing electricity, we can significantly reduce emissions across other sectors, including transport, residential energy use, and some industrial activities. This process aligns with the increasing electrification of economies, where expanding electricity demand is balanced by a reduction in emissions, provided that the carbon intensity of power generation is kept low.[12]

The carbon impact of energy generation is primarily influenced by the energy mix—especially the ratio of fossil fuels to renewable or nuclear sources. Fossil fuels still account for approximately 80% of global energy supply, with coal, oil, and natural gas being the predominant sources. However, a shift toward cleaner energy options, such as solar and wind, is gaining momentum, despite these technologies still emerging from relatively small-scale adoption. The pace and scale of this transition will differ across nations, depending on factors such as resource availability, economic conditions, and levels of urbanization.

One of the most efficient ways to reduce emissions from the energy sector is to transition from high-carbon fuels like coal to cleaner alternatives such as natural gas, and ultimately to zero-emission energy sources. This shift

is already occurring in several countries, where coal-based power generation is rapidly declining. For example, the construction of new coal-fired power plants is becoming increasingly unfeasible, with the added challenge of retrofitting them with costly carbon capture technologies. In the long run, there is no viable role for unabated coal in a low-carbon energy system.

While natural gas offers a lower carbon alternative to coal, it too will eventually need to be paired with carbon capture technologies to meet stringent decarbonization targets. This transition will require careful management, especially in countries with slower emission reduction trajectories or where economic structures are deeply tied to fossil fuel industries.

In low-income countries, distributed energy systems, such as mini-grids powered by renewable energy, are emerging as a cost-effective alternative to traditional grid extensions. These systems can be especially beneficial in rural areas, where extending the grid may be economically unfeasible. As energy storage costs continue to fall, off-grid solutions powered by solar and backed by storage systems are becoming an increasingly viable option for countries in regions such as sub-Saharan Africa and South Asia.

In conclusion, reducing the carbon intensity of energy production is not only a necessary step towards achieving global climate goals but also a major driver of sustainable economic growth. The expansion of low-carbon energy systems will create new economic opportunities, improve energy security, and provide innovative solutions for nations striving to reduce their carbon footprint while promoting inclusive, sustainable development.

### Reducing the Energy Intensity of GDP for Sustainable Economic Growth

In developing countries, energy consumption, particularly electricity use, is expected to grow significantly due to increasing demand and a shift towards electricity-powered activities that were traditionally fueled by fossil fuels. While the expansion of energy demand is inevitable, decarbonization scenarios emphasize the need for a more efficient approach to meet this growing demand. As economies transition towards low-carbon models, they must ensure that energy use becomes more efficient, aligning with sustainable economic growth (Figure 5).

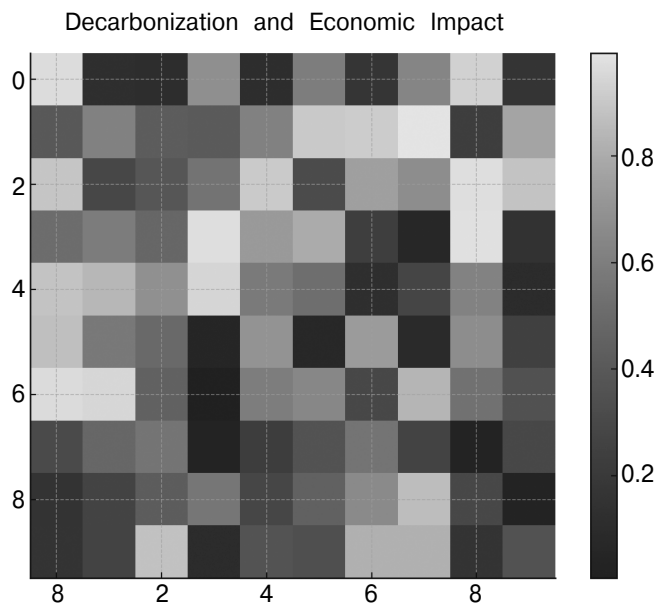


Figure 5. Decarbonization and Economic impact

The energy intensity of a nation's economy — the amount of energy used per unit of GDP — is primarily influenced by its economic structure and the adoption of energy-efficient technologies. As economies develop, they tend to shift towards less energy-intensive sectors, which reduces the overall energy required to generate economic output. This structural shift often includes a movement from energy-heavy industries, like mining, metals, and cement production, to more energy-efficient sectors such as services and light manufacturing. This transition not only reduces energy consumption but also creates economic opportunities in emerging industries, thus fostering sustainable growth.

Technological advancements in energy efficiency also play a crucial role in reducing energy intensity. Innovations in energy-efficient machinery, smarter industrial processes, and renewable energy solutions help reduce energy use while maintaining or improving output. As countries invest in low-carbon innovations, efficiency improvements become a driving force for both economic growth and environmental sustainability. For example, industries can replace outdated, energy-inefficient processes with more modern, energy-saving technologies, leading to lower operational costs and a smaller carbon footprint.[13]

The debate surrounding the “energy efficiency gap” — the difference between the observed energy efficiency levels and the potential for energy savings — has long been a topic of academic discussion. While some economists argue that the gap is overstated, engineering studies consistently show that significant energy savings are achievable, particularly in industries like mining, steel production, and chemicals. For example, studies for South Africa have highlighted substantial energy savings potential across its industrial sectors, which could lead to considerable cost reductions and environmental benefits. These savings, in turn, could reinvest into the economy, driving further innovation and sustainable growth.

The potential for energy efficiency improvements is not confined to high-income households but extends to lower-income communities as well. In these areas, improvements in the thermal efficiency of buildings and the adoption of low-cost energy-saving solutions can help reduce energy expenditures, improving living standards and creating economic opportunities. These energy savings can have a multiplier effect, improving the overall economic health of the nation by lowering household energy costs, enhancing productivity, and fostering innovation in energy-efficient technologies.

In conclusion, reducing the energy intensity of GDP is not only a key component of decarbonization but also a catalyst for sustainable economic growth. By integrating low-carbon innovations and promoting energy efficiency, countries can meet their growing energy demands while driving job creation, technological advancement, and long-term economic prosperity. This approach not only ensures a sustainable future but also strengthens national economies by making them more competitive in the global market.

### **The Role of Low-Carbon Innovation in Sustainable Economic Growth**

This section examines how the transition to low-carbon technologies influences economic growth and development. Shifting towards a low-carbon economy has the potential to significantly transform national economies, particularly those with high carbon emissions. As countries embark on a low-carbon path, entire sectors are likely to shrink, especially those reliant on fossil fuels, such as coal mining, oil extraction, and gas production. In contrast, industries involved in the creation of energy-efficient products, renewable energy generation, and the manufacturing of low-carbon technologies will see substantial growth.

These transformations not only disrupt traditional industries but also create new market opportunities, fostering innovation and necessitating large-scale

infrastructure investments. The resulting structural changes often involve the reallocation of labor and capital, which can generate short-term costs. However, the long-term economic benefits of a low-carbon transition – such as job creation in green sectors and the development of sustainable infrastructure – are significant.

In this context, the economic benefits of low-carbon innovation extend beyond national borders. International collaboration is crucial to accelerating climate change mitigation, as such efforts often require large investments and shared resources. Economies of scale in the development and deployment of low-carbon technologies play a vital role in driving down costs and increasing accessibility. For example, government policies promoting solar photovoltaic (PV) technology in certain countries have led to lower production costs, making solar energy increasingly competitive with fossil fuel-based electricity.

Additionally, the flow of financial resources is a key factor in driving low-carbon innovation, though access to such funding varies across regions, particularly between developed and developing countries. The potential economic gains from transitioning to a low-carbon economy are diverse, but the impact is complex and influenced by multiple factors. While theoretical models suggest various influences, empirical studies, despite their limitations, offer insights into the economic effects of decarbonization. However, accurately measuring the macroeconomic impact of decarbonization remains challenging due to the influence of many other variables on national growth trajectories. Comparative studies across countries are also limited, as few have undergone a full decarbonization of their energy systems.[14]

### **Changes in Market Efficiency and Economic Resilience in a Low-Carbon Transition**

One of the primary distortions stems from government policies. As nations move toward cleaner energy solutions, these policies often interact with existing taxation, subsidies, and regulations. If the push for low-carbon energy aligns with, or complements, existing distorting policies, it could enhance overall market efficiency. However, if clean energy policies contradict or counteract such distortions, efficiency gains may be limited. A clear example of this dynamic is the implementation of a carbon tax in regions that subsidize fossil fuels. Fossil fuel subsidies promote inefficient energy consumption, and eliminating these subsidies through carbon taxation could improve market efficiency. This approach enhances economic productivity, reducing inefficiencies linked to excessive fossil fuel use, up to the point where the carbon tax counteracts the subsidy's effect.

Further, policies designed to support low-carbon transitions, such as carbon taxes and emissions trading schemes, can generate fiscal revenue for governments. This revenue can be reinvested into the economy by reducing existing taxes, which in turn could stimulate economic activity and foster a “double dividend” of environmental and economic benefits. On the flip side, the imposition of a carbon tax over existing taxes can create economic distortions, particularly through changes in relative prices, including those affecting labor. Despite this, some studies have shown that “environmental tax reform” can lead to greater economic efficiency, particularly when taxes are designed to promote greener technologies and cleaner energy consumption.

Air pollution represents a critical environmental and health issue, especially in developing and industrializing nations. In some regions, such as Northern China, air pollution has been found to reduce life expectancy by as much as five years. Reducing air pollution through the adoption of low-carbon energy technologies can lead to substantial economic benefits by enhancing labor productivity and reducing healthcare costs. As such, these environmental

co-benefits often serve as strong motivators for implementing policies aimed at reducing carbon emissions. For instance, China's approach to clean energy has been heavily influenced by the co-benefits of improved public health, energy security, and the potential for economic diversification.

The low-carbon transition also strengthens economic resilience. As noted by Bowen and Fankhauser, a low-carbon energy shift offers countries the opportunity to mitigate the risks associated with natural resource constraints and excessive price volatility. Moreover, as highlighted by Hallegatte et al., transitioning to low-carbon energy increases resilience to environmental shocks, such as those caused by climate change.

The resilience benefits of a low-carbon transition are particularly critical for low-income countries, which are more vulnerable to the impacts of climate change. These nations are already experiencing the economic consequences of climate shocks, which can trap communities in poverty through disruptions to health systems, education, and capital accumulation. By reducing the frequency and severity of these climate-related disruptions, low-carbon energy solutions offer a pathway to more stable and sustainable growth for these vulnerable economies.

Additionally, low-carbon energy systems improve energy security, both in terms of physical infrastructure and economic resilience. Low-carbon technologies, which often rely on domestic or locally sourced renewable energy, reduce dependence on long-distance energy transportation and international energy markets. This decentralization of energy production helps reduce vulnerability to global price fluctuations in fossil fuel markets, ensuring more stable and affordable energy access. In this way, a shift to low-carbon energy systems not only supports environmental sustainability but also enhances national economic security and resilience.[15]

## Conclusion

Climate change increasingly restricts the use of fossil fuels, giving rise to the concept of “green growth”—an economic model that is resource-efficient, environmentally sustainable, and resilient to climate extremes. While fossil fuels have historically driven economic growth, it remains essential to question whether green growth truly benefits all sectors of society. The literature reviewed suggests that developing countries should begin decarbonizing their energy systems early. Although the speed of decarbonization will vary, early action can prevent the risks associated with “stranded assets” and enable leapfrogging to new, more productive technologies, much like the mobile telecommunications revolution. With declining renewable energy costs and advancing storage technology, decarbonization of the electricity sector is not only technically but also economically feasible. A clean energy transition offers additional benefits for growth, innovation, market efficiency, and reduced local air pollution. However, early decarbonization faces challenges. The structural changes needed, such as enhancing energy efficiency and transitioning away from heavy industries, can be politically difficult and entail short-term economic costs. Achieving global climate mitigation goals will require rapid improvements in emissions intensities, energy efficiency, and a shift toward low-carbon electricity use, which, though challenging, is technically feasible.

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**ЯН НИН, ВАН СЯНЬПЭН**

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**ЭКОНОМИЧЕСКИЕ ВЫГОДЫ  
ОТ НИЗКОУГЛЕРОДНЫХ ИННОВАЦИЙ НА ПУТИ  
К УСТОЙЧИВОМУ НАЦИОНАЛЬНОМУ РОСТУ**

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**Сведения об авторах.** Ян НИН (yangningphd@imb.by), Аспирантура, 1 курс, Международный институт управления и предпринимательства (г. Минск, Беларусь); Ван СЯНЬПЭН (wxp-phd@bntu.by), Доктор технических наук,

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*Кандидат экономических наук, Международный институт управления и предпринимательства (г. Минск, Беларусь).*

Спрос на энергоносители играет ключевую роль в стимулировании экономического роста, и обеспечение доступности недорогих и надежных источников энергии остается главной целью устойчивого развития. В прошлом растущие энергетические потребности стран удовлетворялись в основном за счет использования ископаемого топлива; однако по мере развития мира растет потребность в альтернативных источниках энергии с меньшим выбросом углекислого газа и в конечном счете в тех, которые являются углеродно-нейтральными. Темпы декарбонизации в разных странах различаются в зависимости от местных условий. В данной статье рассматривается влияние перехода на низкоуглеродную энергетику на экономический рост и национальное развитие, особенно в странах с низким уровнем дохода. В нем дается эмпирическое представление о взаимосвязи между потреблением энергии, выбросами и экономическим ростом, а также освещаются стратегии ускорения усилий по декарбонизации. На основе изучения как теоретической, так и прикладной литературы в статье дается оценка

**Ключевые слова:** экономические выгоды; низкоуглеродный климат; устойчивый национальный рост.

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