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A SYSTEM DYNAMICS SIMULATION OF ENERGY CONSUMPTION AND CO_2 EMISSIONS IN PAKISTAN UNDER ENERGY-INTENSITY REDUCTION SCENARIOS

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Abstract

This study investigates long-run association among economic growth, energy consumption, and CO_2 emissions, by employing a system dynamics model, via use of energy-intensity reduction policies under different scenarios. The study focused on an energy-deficient developing country, with its energy system characterized by a heavy dependence on fossil fuels, ever rising energy demand, and persistent inefficiencies, and subsequent high greenhouse gas emissions. The model is estimated for a period of 1995 to 2025 and runs through to forecast emissions up to 2040, by using the economic growth rate (i.e. annual figures for GDP), total energy consumption and CO_2 emissions. It is worth mentioning that the system dynamics approach explicitly incorporates feedback processes, stock–flow structures, and time delays, which are either missing or insufficiently represented in traditional econometric methods. Furthermore, we find a strong correspondence between simulated and observed trends for energy consumption and emissions. Moreover, we undertake scenario based analysis to evaluate effects of different pathways for reducing energy intensity. We further find that CO_2 emissions are experiencing a rapid growth and can potentially reach a level of 278 million tons by 2040. Conversely, we observed that sustained improvements in energy intensity offer considerable mitigation and co-benefits. Our findings show, an estimated 5 percent annual improvement in energy intensity can drastically reduce emissions, with projected reduction of around 22.6 and percent 53. 7 percent by 2030 and 2040, respectively, in comparison to the baseline emissions, We also forecast with more ambitious targets, i.e. 10 percent improvement, can reduce emissions by 41.0 percent and almost 79.4 percent, respectively. We can safely assume that energy efficiency enhancements have the potential to substantially decouple the economic growth from carbon emissions. Our study presents energy-intensity reduction as a key policy instrument for delivering long-run environmental sustainability, without compromising economic growth, and it offers a dynamic analytical framework for assessing prospective energy and climate policies in developing countries.

INTRODUCTION

Energy is one of the most widely studied topics in economics and is now increasingly regarded as key to development. Energy, capital, labor and raw materials are essential inputs in the production of most goods and services. Energy consumption and efficiency affect all economic and industrial activities, while energy productivity and improved energy utilization are central themes influencing the growth performance of any country. The energy infrastructure of developing countries is largely dependent on fossil fuels (coal, oil and natural gas), which are the major contributors of CO_2 emissions. It has been thoroughly established that CO_2 emissions have been a major factor in climate change ever since the industrial revolution, threatening fundamental aspects of human well-being through reduced access to water, food security, health outcomes and land productivity (Stern, 2008). Consequently, reducing fossil fuel dependence has become an essential objective of climate mitigation strategies. While environmental degradation is a global problem, its impact is especially severe in countries facing rapid increase in energy demand. The fulfillment of global CO_2 reduction targets relies on the obligation of the emitting countries. This is especially difficult to achieve in countries where energy production is closely linked to economic growth and poverty alleviation. Policies aimed at reducing CO_2 output have sometimes been met with resistance on the ground that they would impede industrial production and economic growth, at least for the short term. Nevertheless, the environmental sustainability and production efficiency are considered as two sides of a coin instead of two conflicting goals which constraints the competitiveness of the firm and the instrument choices of policy makers (Wu et al., 2014). Governments are thus turning to policies that can promote both economic growth and environmental quality.

Financial development and energy policy reform may serve as instruments for achieving this dual goal. Several studies present evidence for a long-run relationship between economic growth, energy consumption and CO_2 emissions (Hettige et al., 1992; Ang, 2007; Ozturk and Acaravci, 2010). Other studies also find bidirectional causality between income growth and emissions, stressing the feedback process connecting production and pollution (Al-Mulali, 2011; Chandran and Tang, 2013). Financial development can increase energy demand and emissions by means of greater industrial production and investments in capital. On the other hand, if financial development leads to the technological upgrading and efficiency enhancement, it can bring about the reduction of energy consumption and pollutant emissions. As with previous studies, financial development can be approximated through indicators such as domestic credit to the private sector as a percentage of GDP, which reflects the importance of financial intermediaries in the allocation of funds to productive uses (Boutabba, 2014). Although income levels have risen in the last few decades, Pakistan has witnessed increasing environmental stress as a result of its energy regime. Air pollution, urban smog, and greenhouse gas emissions have become worse and the concern of many politicians and citizens. Climate change has become a material risk to financial stability through the induced floods, droughts, and extreme temperatures, which could seriously disrupt agriculture and industry unless action is taken (Stern, 2001). To successfully address these risks, it may be necessary to employ carbon pricing instruments, energy taxes, and regulatory reforms.

Carbon exchange mechanisms are derived from emissions trading schemes, which were first conceptualized and developed in the 1970s, and subsequently generalized into cap-and-trade systems (Wu and Olson, 2015). Effective mitigation of these risks will likely require carbon pricing instruments, energy taxation and regulatory reforms. Carbon emission exchange mechanisms originate from emissions trading concepts developed in the 1970s and later implemented in cap-and-trade systems (Wu, Zheng and Olson, 2015). Both a carbon tax and cap-and-trade arrangements can generate government revenues through taxes or auctioned permits. Explicit carbon taxation and fossil-energy taxation are often considered as two powerful policy instruments to abate CO_2 emissions, and taxation is sometimes claimed to be among the most direct instruments to control emissions (Duan et al., 2019). Carbon pricing increases the cost of carbon-intensive energy products faced by firms, shaping energy price risk and creating incentives for energy-saving investments. Reducing energy use simultaneously lowers energy costs and exposure to price volatility. Carbon pricing also affects the price of energy products intensive in carbon, influencing energy price risk and contributing to energy-saving investment incentives. Less energy use means reduced energy costs and less vulnerability to price shocks.

Emerging economies have now become the center of global energy demand growth, with South Asia playing an increasingly significant role in this growing energy demand (International Energy Agency, 2013). Pakistan is among the most energy-constrained countries in the region, facing chronic power shortages and high import dependence for oil and liquefied natural gas. Over the years, population growth along with industrial and transport sector expansion were the major contributors for increased energy consumption in Pakistan. Meanwhile, the country has been heavily dependent on fossil fuels for electricity, with coal and natural gas making up a large portion of the energy used.

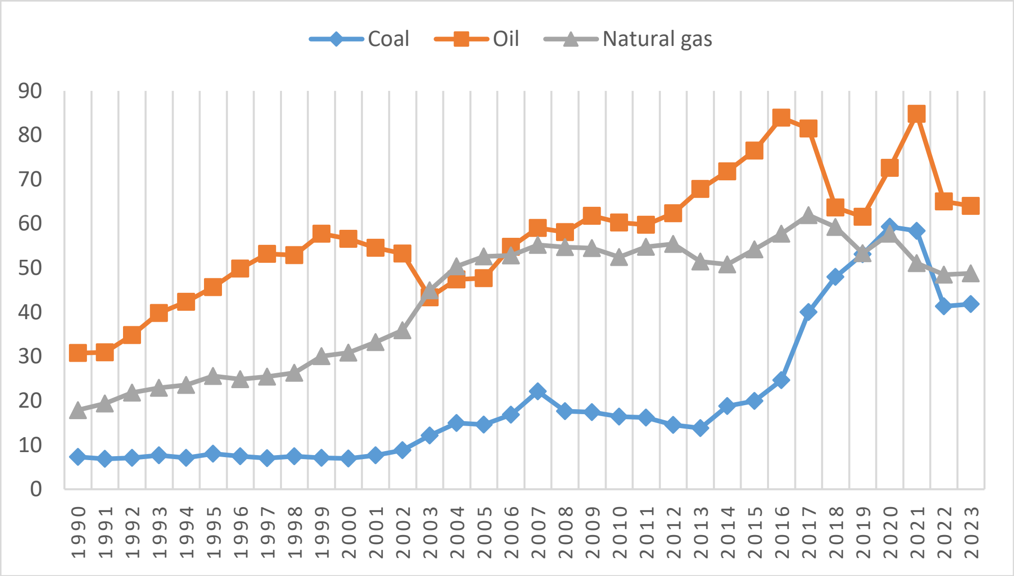

Figure 1: Energy Consumption of Pakistan(MTOE)

Source: IEA, 2025

Energy subsidies, inefficient pricing and weak energy management have contributed to persistent inefficiencies in energy use, limiting incentives for conservation and slowing the diffusion of modern energy technologies.

Pakistan's energy intensity remains relatively high indicating the use of older technologies and the less frequent use of energy-efficient machinery and devices. This trend already has generated increasing CO_2 emissions especially in power and transport sectors. Evidence from international energy outlook assessments indicates that the level and composition of energy use, including indirect emissions associated with electricity production are key drivers of emissions trajectories (International Energy Agency, 2008). These forces highlight the need for a unified analytical framework to examine the relationship between GDP, energy consumption and environmental quality. This research aims to analyze the causality among energy consumption, economic growth and CO_2 emissions for Pakistan in order to project future paths considering different policy options using a system dynamics model that captures the feedback loops among major variables. System dynamics has an explicit focus on causal processes and feedback mechanisms underlying system behaviours over time and has been broadly applied to socio-economic and energy-environment systems to investigate complexities, lags, and feedback architectures (Sterman, 2002; Radsicki and Taylor, 1997). Evidence from international energy outlook assessments indicates that the level and composition of energy use including indirect emissions associated with electricity production are key drivers of emissions trajectories (International Energy Agency, 2008).

The remainder of the study is organized as follows. Section 2 presents a brief review of the relevant literature. Section 3 describes the modeling framework and methodology. Section 4 discusses the simulation results and model validation. Section 5 concludes with policy implications.

1. Literature Review

In recent decades, the growing effects of climate change has led to enhanced focus on the mitigation of carbon dioxide (CO_2) emissions by global and national entities (Zhou et al., 2013). The nexus of energy consumption, economic growth and environmental degradation has been thoroughly investigated in empirical studies (Soytas et al., 2007; Lean and Smith, 20010; Apergis and Payne, 2010(a), 2010(b); Bartleet and Gounder, 2010; Menyah and Rufael, 2010; Ozturk and Acaravci, 2010; Niu et al., 2011; Arouri et al., 2012). These studies have widely corroborated that economic growth results in enhanced energy consumption and CO_2 emissions although the size and direction of causality among these variables are time and country sensitive. Several lines of research have addressed the challenge of characterizing the dynamic interrelationships among these variables with the use of time-series and panel data methods. Luo and Wu (2016) studied the time-varying correlations between carbon allowance prices and crude oil markets as well as stock index through an orthogonal GARCH framework, bringing attention to financial and energy dependence in emissions. A few researchers emphasize the importance of the income effect and structural transformation, claiming that earlier stages of development experience rapidly increasing emissions growth whilst in the later stages some decoupling may occur as a result of gains in productivity and other technological development (Ang, 2007). There are also recent papers that consider the influence of data analytics, and decision-support systems on energy efficiency. The applications of data analytics (Zhou, Fu and Yang, 2016) in energy data analytics enable new insights of energy consumptions of households and industries and hence may lead to more targeted energy efficiency policies.

On the other hand, energy management and risk analysis has been receiving attention among decision-support methods, particularly in commercial and industrial (Wu et al., 2014).These methodologies emphasize the scope to combine behavioral, economic, and technological data within cohesive analytical architectures. Modeling energy systems, therefore, has become increasingly important to studying the interactions between economic growth, technological change, and environmental consequences. Multiple agents, feedback and time lags also render standard static or reduced-form models inadequate for long-run analysis. System dynamics modeling is a powerful approach that can be used to study such complexities based on the visibility of stocks, flows and feedback loops (Sterman, 2002). This method has been extensively applied in socio-economic systems (Radsicki and Taylor, 1997), for the analysis of technological hazards (Wu et al., 2014), and in the investigation of energy demand and supply (Ansari and Seifi, 2012; Chi et al., 2022; Dong et. al., 2012).

System dynamics models have been used in energy and emissions to predict energy demand in the future and to assess mitigation policies. Liu et. al., (2018) used a comparable methodology to predict China's natural gas consumption. In the transportation sector, the system dynamics model was developed to examine CO2 reduction potentials of inter-city passenger transportation by Han and Hayashi (2008). Feng et al. (2013) and Fong et al. (2009) researched the urban surround energy and emissions employing system dynamics approaches, revealing the feasibility of this approach for policy analysis for alternative scenario trajectories. System dynamics models have been used to analyze industrial processes, e.g., the relationship between manufacturing, energy, and CO2 emissions. Anand et al. (2006) devised a model for the Indian cement industry to assess emission mitigation policies relating to population stabilization, energy conservation and process technology progress. Nevertheless, their model does not explicitly incorporate energy prices or capacity growth endogenously and output growth is assumed to be exogenously determined. Some more research attempted to enhance these models by incorporating economic feedbacks, price effects and policy variables (Ilyas, et al, 2022; Ansari and Seifi, 2012; Kiani and Pourfakhrisei, 2010).

For the economies in transition, the use of system dynamics modeling enables an analysis that effectively captures the interaction between economic development goals and environmental constraints. Rapidly growing populations, energy subsidies and slow technology diffusion in many of these countries results in increasing energy intensity and emissions. The literature indicates that the effect of instruments for promoting energy-efficiency and for transforming energy-system on long-term emissions trajectory can be considerable (Duan et al., 2019). Nonetheless, empirical evidence is scarce for South Asian countries, especially for Pakistan as the country faces unique challenges in terms of energy system inefficiencies and supply shortages. Although the international literature has been growing, integrated system dynamics studies on the energy–economy–environment nexus are relatively scarce at the country-level. Most of the existing literature on Pakistan has employed econometric techniques to examine the causal relationships between energy use, GDP, and CO_2 emissions without explicitly accounting for feedback structures or policy scenarios. This reduces the potential of such studies to assess long-term adjustment trajectories associated with alternative energy intensity or mitigation policies. This study makes a contribution to the literature by using a system dynamics model to project Pakistan's energy use and CO_2 emissions in alternative policy scenarios, thus broadening previous applications of this approach in context to South Asia.

2. Methodology

In the paper, we develop a dynamic modelling framework that captures energy consumption and CO_2 emissions evolution in Pakistan in the long run. The model is constructed following the principles of system dynamics, which emphasize feedback mechanisms, stock–flow relationships and time delays in complex systems (Sterman, 2000). System dynamics modeling has also been extensively used in socio-economic and energy systems since it can represent nonlinear interactions among major variables and assess policy measures by conducting scenario analysis (Radsicki and Taylor, 1997; Wu et al., 2014; Feng et al., 2013). Unlike static or purely econometric methods, this framework permits simulating future paths of variables under alternative assumptions about economic growth, energy intensity, and mitigation policies.

Problem statement

The purpose of this study is to examine the time varying nature of the linkages between energy consumption, economic growth and CO2 emissions in Pakistan and to analyze the potential impacts of energy-intensity reduction policies. Energy deficiency, reliance on fossil fuels and escalating environmental prices are endemic in Pakistan. Therefore, to formulate sustainable energy policies, it is important to quantify the impact of energy efficiency and activity on emissions. The key variables in the model include the gross domestic product (GDP), total energy use, energy intensity and CO2 emissions. The simulation period is 2000 – 2040, providing a basis for historical validation and future scenario assessments.

3.2 Key variables and causal relationships

For analyzing temporal variations of CO2 emissions, it is essential to know what direct or indirect factors that may affect the emission. These driving forces are hierarchically expressed by a causal loop reflecting the interactions with economic activities, energy demand and environmental results. In the model, economic growth causes production and consumption to rise, and thus energy demand increases. More energy use is associated with more CO_2 emissions, especially in fossil fuel based systems. However, the costs to the environment and society of increased emissions may in turn affect policy responses and investments in energy efficiency.

The feedback structure is a mixture of reinforcing and balancing feedback loops. Reinforcing loop is on economic growth: higher GDP leads to higher energy demand which supports industrial production and the expansion of economy. Improvements in energy intensity introduce a balancing loop: as reductions in energy intensity decrease energy use per unit of output, they reduce the rate of emissions growth. Energy prices and policy measures are considered to impact energy consumption behavior by modifying the preferred energy use level per unit of output. These relationships are the conceptual basis for the system dynamics model and guide the development of the simulation equations.

3.3. Model specification

The model is based on the identity that total CO_2 emissions are determined by the level of energy consumption and the emission factor associated with the energy mix. Energy consumption is expressed as a function of economic activity and energy intensity. Accordingly, the system is represented by the following relationships:

$$E_t = GDP_t \times EI_t$$
$$CO_2 = E_t \times EF_t$$

where Et denotes total energy consumption in year t, GDPt represents real gross domestic product, EIt is energy intensity (energy use per unit of GDP), and EFt denotes the emission factor reflecting the carbon content of the energy mix. GDP evolves dynamically according to an exogenous growth rate, while energy intensity is allowed to change over time in response to policy scenarios. The emission factor is assumed to remain constant in the baseline case, reflecting the prevailing structure of Pakistan's energy mix dominated by fossil fuels.

Energy production is assumed to respond to past energy demand with a one-period delay, reflecting adjustment lags in capacity expansion and fuel supply. This assumption is consistent with prior system dynamics applications in energy modeling (Kiani and Pourfakhraei, 2010; Li et al., 2011). Environmental costs are linked to CO_2 emissions and are treated as an outcome variable rather than an explicit feedback determinant in the present model.

3.4. Data

Annual data on GDP, total primary energy consumption and CO_2 emissions are used to calibrate the model. GDP data are obtained from national accounts, while energy consumption figures are taken from Energy year book. CO_2 emissions are derived from fuel consumption using standard emission coefficients consistent with international guidelines (International Energy Agency, 2008). Energy intensity is computed as the ratio of total energy consumption to GDP. The model is calibrated over the historical period 1995–2025 to ensure that simulated values are consistent with observed trends.

Model validation is conducted by comparing simulated outputs for energy consumption and CO_2 emissions with historical data over the calibration period. The parameters are adjusted iteratively to minimize discrepancies between simulated and observed values. This approach follows established practices in system dynamics modeling, where emphasis is placed on reproducing general trends rather than exact point estimates (Sterman, 2000).

3.5. Scenario design

To assess the effect of policy measures, alternative scenarios are developed with varying energy intensity reductions. Two policy scenarios are considered: (i) an energy intensity reduction scenario in which energy intensity decreases by 5 % from the baseline path, which can be considered a mild scenario, and (ii) a 10 % decrease energy intensity reduction scenario is also provided as a severe energy policy scenario. These correspond to realistic efficiency enhancements associated with technological upgrading, energy conservation and regulatory reform. Analogous scenario-based methodologies have been applied in earlier analyses to evaluate mitigation potentials under varying policy assumptions (Duan et al., 2013; Feng et al., 2013). For each scenario energy use and CO2 emissions over the projection period are modeled. The results are then compared to the baseline to determine how much emission reduction is due to efficiency improvement. This approach allows to evaluate the effect when different energy policies are implemented on the environmental quality in the long run, considering the dynamics of economic growth.

3. Simulation Results and Policy Scenarios

This section reports the simulation results of the system dynamics model for Pakistan and evaluates its performance by comparing simulated and observed values of key variables. The analysis focuses on three components of the system: energy production (proxied by total energy supply), energy consumption, and CO_2 emissions.

4.1. Energy Production

Figure 1 illustrates the trajectory of total energy production in Pakistan for the period of study. Energy production follows an ever-increasing pattern, due to development of generation capacity and increasing primary energy supply along with economic growth. The model captures the long run unbalanced growth of energy supply in the data, suggesting increasing demand triggers an endogenous adjustment of supply with a delay structure that can be interpreted consistent with system dynamics assumptions. Over the period the total energy production is rising wholesale, which means that average growth in total energy production is positive in the sample period from 1995 to 2024.

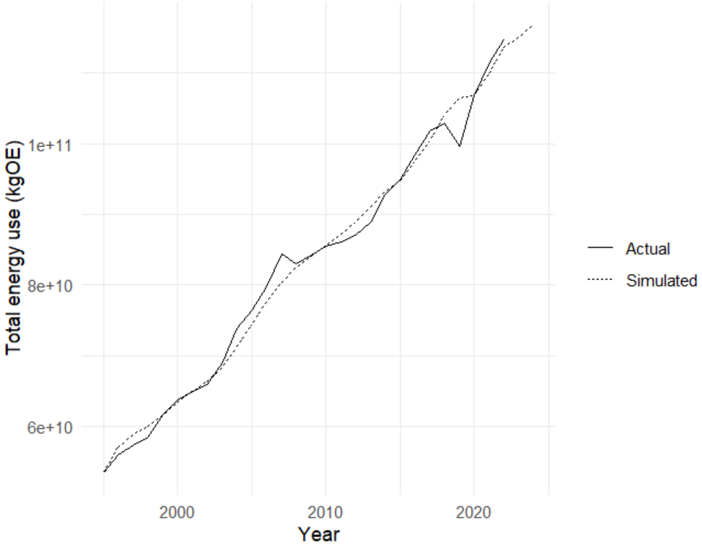

Figure 1: Actual and simulated total energy consumption in Pakistan, 1995–2024.

This trend is a result of the rapid growth in the fossil fuel based generation in Pakistan, especially the use of natural gas and coal, and a slow increase of hydropower and renewable capacity. The implication of this is that the tight fit between simulated and actual production suggests that the supply-side adjustment mechanism that defines the model generates a reasonably good approximation to the dynamics of the Pakistan's energy system.

4.2. Energy consumption

Figure 2 presents the comparison between the observed and simulated total energy consumption. Both series exhibit a pronounced increasing trend, largely reflecting population growth, income growth, and industrial development. The predicted series has a good fit with observed throughout the estimation period. The energy use module exhibits good in-sample results quantitatively. The small value of Theil's U statistic (0.011) further confirms that the difference between the predicted and observed energy use is not significant.

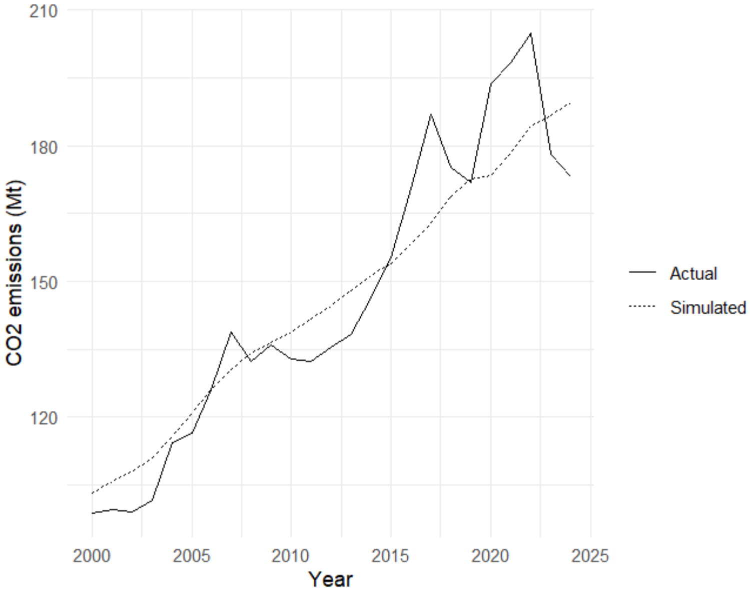

Figure 2. Actual and simulated CO_2 emissions in Pakistan, 2000–2024.

These findings imply that, the estimated dynamic specification for the economic activity, oil prices and lagged energy consumption successfully characterizes the long-run energy demand behavior in Pakistan. Strong fit also indicates that energy consumption history of Pakistan can be elegantly modeled through a concise feedback based model structure.

The strong correspondence between simulated and observed energy consumption is consistent with earlier empirical studies documenting stable long-run relationships between income, energy prices, and energy demand in developing economies (Narayan and Smyth, 2008; Apergis and Payne, 2010). For Pakistan in particular, Shahbaz et al. (2018) and Ahmed et al. (2017) report similar dynamics, with economic growth identified as the main driver of rising energy use.

4.3. CO_2 emissions

Figure 3 illustrates a comparison of observed and simulated CO2 emissions. Both series exhibit a gradually rising pattern, with emissions increasing as energy use and fossil fuel use increase. The emissions module results in a 5.63% MAPE and a R^2 of 0.884, meaning that the model is able to explain about 88% of the variation in the observed CO2 emissions. While the fit for emissions is less good than for energy consumption, this is to be expected as the model uses an average emission factor and does not explicitly capture short-term fluctuations in the fuel mix or technology mix of generation. However, the overall trend and scale of emissions are generated with fairly good precision. The results demonstrate that the developed system dynamics model can reproduce Pakistan's historical trends of energy production, energy consumption, and CO2 emissions with reasonable accuracy. Thus, the model serves as an adequate platform for scenario-based policy analysis.

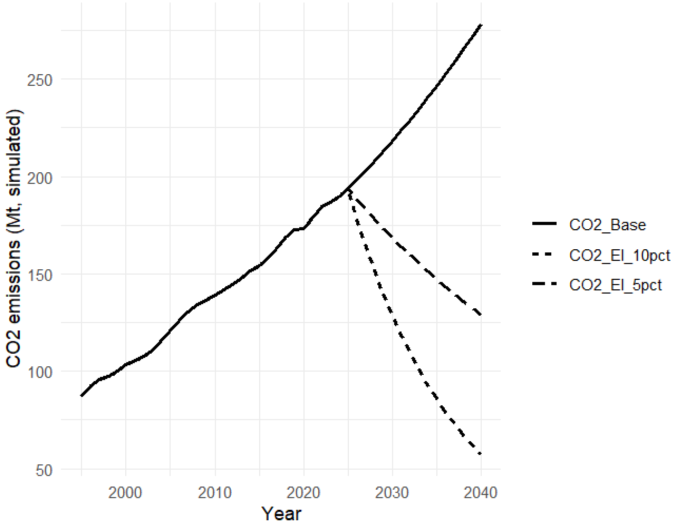

Figure 3. Baseline and policy scenario projections of CO_2 emissions in Pakistan, 1995–2040.

The strong correspondence between simulated and observed energy consumption is consistent with earlier empirical studies documenting stable long-run relationships between income, energy prices, and energy demand in developing economies (Narayan and Smyth, 2008; Apergis and Payne, 2010).

5. Policy Scenarios

This section examines the effects of alternative energy-intensity reduction policies on future energy consumption and CO_2 emissions in Pakistan. The baseline scenario assumes that historical relationships between energy use, economic growth, and prices continue without additional efficiency-oriented intervention. Two alternative scenarios are then constructed by imposing sustained reductions in energy intensity.

5.1. Energy intensity and energy consumption

Under the baseline, energy use rises with economic growth as energy-intensive patterns of production and consumption persist. By contrast, the policy scenarios impose annual declines in energy intensity relative to the baseline trajectory. The first case considers a 5% reduction of energy intensity per year from 2025. A second, rather more aggressive, cut of 10% is applied during the same period. The simulation results show that the two situations significantly change the long-run path of energy consumption. Under the 5% scenario, total energy use grows much more slowly than in the baseline, and eventually levels off, while under the 10% scenario it falls steeply over time. These results stress the key importance of demand-side efficiency improvements for future energy use. Even modest, consistent reductions in energy intensity lead to large cumulative effects in total consumption in the long run.

5.2. Energy intensity and CO_2 emissions

Figure 4 shows estimated CO2 emissions for the baseline and two energy-intensity reduction scenarios. Without efficiency gains, emissions take off, approaching 218 million tons in 2030 and 278 million tons in 2040. Under the 5% energy-intensity reduction path, emissions decrease to roughly 169 million tons in 2030, representing a cut of about 22.6% compared to the baseline. Emissions continue to decline slightly further to about 129 million tons in 2040, which corresponds to a cut of about 53.7% relative to the baseline path. The effects are much more pronounced under the 10% case. CO_2 emissions drop to about 129 million tons in 2030 in this scenario, which translates into a decrease of around 41.0% in relation to the baseline. It will be a surprise for most people, but global emissions plummet to an estimated 57 million tons by 2040 which is a reduction of almost 79.4% relative to (and probably well below) the baseline projection. These results indicate that persistent improvements in energy intensity have the potential to significantly decouple economic growth from carbon emissions in Pakistan. The baseline scenario is a projection that assumes no change in the rate of growth of emissions associated with increased energy use, while the two policy scenarios represent a substantial reduction in the emissions path. The 5% scenario is a sensible path reflecting modest efficiency gains; while the 10% scenario represents the scale of mitigation that could be achieved under an even more aggressive and concerted efficiency approach. The level of emissions reductions that result under the energy-intensity scenarios is comparable to scenario-based analyses for other middle-income nations, which show that continuous efficiency gains can result in a 40–60% long-term emissions reduction compared to reference trajectories (Wang et al., 2019). These findings reinforce the pivotal importance of energy efficiency as a cornerstone of climate mitigation efforts, as highlighted in global reports (Ang, 2006; IEA, 2022).

6. Conclusion and Policy Implications

In this paper, a system dynamics model is formulated to study the long-term energy consumption and CO_2 emissions in Pakistan and the impact of various energy-intensity diminution policies. The model was tested against historical data and good evidence was found both in the prediction of energy consumption as well as of CO2 emissions. Results of simulations reveal that under the baseline, Pakistan's CO_2 emissions will follow a strong increasing trend and reach around 218 Mt by 2030 and 278 Mt by 2040. This path is consistent with projections in earlier studies and reports from the international community, which emphasize the dominant position of fossil fuels in Pakistan's energy system and a close energy–growth nexus (Shahbaz et al., 2014; Rauf et al., 2018; IEA, 2023). Policy simulations imply that the trajectory can be quite dramatically changed by sustained energy intensity improvements. A 5% per year improvement in energy intensity reduces emissions by 22.6% in 2030 and by 53.7% in 2040 relative to the baseline and a 10% reduction causes even larger decrease, by 41.0% in 2030 and by an impressive 79.4% in 2040. These findings are consistent with the general literature identifying gains in energy efficiency as a key tool for disentangling growth from total energy related carbon emissions (Ang, 2006; Apergis and Payne, 2010).

REFERENCES:

Ahmed, K., Rehman, M. U., & Ozturk, I. (2017). What drives carbon dioxide emissions in the long-run? Evidence from selected South Asian Countries. *Renewable and Sustainable Energy Reviews*, 70, 1142-1153.

Al-Mulali, U. (2011). Oil consumption, CO2 emission and economic growth in MENA countries. *Energy*, *36*(10), 6165-6171.

Anand, S., Vrat, P., & Dahiya, R. P. (2006). Application of a system dynamics approach for assessment and mitigation of CO2 emissions from the cement industry. *Journal of environmental management*, *79*(4), 383-398.

Ang, B. W. (2006). Monitoring changes in economy-wide energy efficiency: from energy–GDP ratio to composite efficiency index. *Energy policy*, *34*(5), 574-582.

Ang, J. B. (2007). CO2 emissions, energy consumption, and output in France. *Energy policy*, *35*(10), 4772-4778.

Ansari, N., & Seifi, A. (2012). A system dynamics analysis of energy consumption and corrective policies in Iranian iron and steel industry. *Energy*, *43*(1), 334-343.

Apergis, N., & Payne, J. E. (2010). Energy consumption and growth in South America: Evidence from a panel error correction model. *Energy economics*, *32*(6), 1421-1426.

Apergis, N., & Payne, J. E. (2010). Renewable energy consumption and growth in Eurasia. *Energy economics*, *32*(6), 1392-1397.

Apergis, N., Christou, C., & Gupta, R. (2017). Are there environmental Kuznets curves for US state-level CO2 emissions?. *Renewable and Sustainable Energy Reviews*, *69*, 551-558.

Arouri, M. E. H., Youssef, A. B., M'henni, H., & Rault, C. (2012). Energy consumption, economic growth and CO2 emissions in Middle East and North African countries. *Energy policy*, *45*, 342-349.

Bartleet, M., & Gounder, R. (2010). Energy consumption and economic growth in New Zealand: Results of trivariate and multivariate models. *Energy Policy*, *38*(7), 3508-3517.

Boutabba, M. A. (2014). The impact of financial development, income, energy and trade on carbon emissions: evidence from the Indian economy. *Economic modelling*, *40*, 33-41.

Chandran, V. G. R., & Tang, C. F. (2013). The impacts of transport energy consumption, foreign direct investment and income on CO2 emissions in ASEAN-5 economies. *Renewable and Sustainable Energy Reviews*, *24*, 445-453.

Chi, Y. Y., Zhao, H., Hu, Y., Yuan, Y. K., & Pang, Y. X. (2022). The impact of allocation methods on carbon emission trading under electricity marketization reform in China: A system dynamics analysis. *Energy*, *259*, 125034.

Dong, H., Fujita, T., Geng, Y., Dong, L., Ohnishi, S., Sun, L., ... & Fujii, M. (2016). A review on eco-city evaluation methods and highlights for integration. *Ecological Indicators*, 60, 1184-1191.

Duan, H., Zhang, G., Wang, S., & Fan, Y. (2019). Robust climate change research: a review on multi-model analysis. *Environmental Research Letters*, *14*(3), 033001.

Feng, Y. Y., Chen, S. Q., & Zhang, L. X. (2013). System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China. *Ecological Modelling*, *252*, 44-52.

Fong, W. K., Matsumoto, H., & Lun, Y. F. (2009). Application of System Dynamics model as decision making tool in urban planning process toward stabilizing carbon dioxide emissions from cities. *Building and environment*, *44*(7), 1528-1537.

Han, J., & Hayashi, Y. (2008). A system dynamics model of CO2 mitigation in China's inter-city passenger transport. *Transportation Research Part D: Transport and Environment*, *13*(5), 298-305.

Hettige, H., Lucas, R. E., & Wheeler, D. (1992). The toxic intensity of industrial production: global patterns, trends, and trade policy. *The American Economic Review*, 478-481.

International Energy Agency (IEA). (2008). *Energy technology perspectives*. OECD Publishing. https://www.iea.org/reports/energy-technology-perspectives-2008

International Energy Agency (IEA). (2013). *World energy outlook*. OECD Publishing. https://www.iea.org/reports/world-energy-outlook-2013

International Energy Agency (IEA). (2022). *World energy outlook*. OECD Publishing. https://www.iea.org/reports/world-energy-outlook-2022

International Energy Agency (IEA). (2023). *World energy outlook*. OECD Publishing. https://www.iea.org/reports/world-energy-outlook-2023

Khan, M. Z., Azfar, R. W., Khan, M. I., & Hamza, M. Determinants of Technology Acceptance of Solar Photovoltaic in Private Buildings in Pakistan. *Available at SSRN 5034437*.

Kiani, B., & Pourfakhraei, M. A. (2010). A system dynamic model for production and consumption policy in Iran oil and gas sector. *Energy Policy*, *38*(12), 7764-7774.

Lean, H. H., & Smyth, R. (2010). CO2 emissions, electricity consumption and output in ASEAN. *Applied energy*, *87*(6), 1858-1864..

Liu, C. H., Lin, S. J., & Lewis, C. (2012). Environmental impacts of electricity sector in Taiwan by using input-output life cycle assessment: The role of carbon dioxide emissions. *Aerosol and Air Quality Research*, *12*(5), 733-744.

Liu, G., Dong, X., Jiang, Q., Dong, C., & Li, J. (2018). Natural gas consumption of urban households in China and corresponding influencing factors. *Energy Policy*, *122*, 17-26.

Menyah, K., & Wolde-Rufael, Y. (2010). Energy consumption, pollutant emissions and economic growth in South Africa. *Energy economics*, *32*(6), 1374-1382.

Narayan, P. K., & Smyth, R. (2008). Energy consumption and real GDP in G7 countries: new evidence from panel cointegration with structural breaks. *Energy economics*, *30*(5), 2331-2341.

Niu, S., Ding, Y., Niu, Y., Li, Y., & Luo, G. (2011). Economic growth, energy conservation and emissions reduction: A comparative analysis based on panel data for 8 Asian-Pacific countries. *Energy policy*, *39*(4), 2121-2131.

Okereke, C., Wittneben, B., & Bowen, F. (2012). Climate change: Challenging business, transforming politics. *Business & Society*, *51*(1), 7-30.

Omri, A., & Saidi, K. (2022). Factors influencing CO2 emissions in the MENA countries: the roles of renewable and non-renewable energy. *Environmental Science and Pollution Research*, *29*(37), 55890-55901.

Ozturk, I., & Acaravci, A. (2010). CO2 emissions, energy consumption and economic growth in Turkey. *Renewable and Sustainable Energy Reviews*, *14*(9), 3220-3225.

Radsicki, M. J., & Taylor, R. A. (1997). Introduction to System Dynamics. *US Department of Energy*.

Rauf, A., Liu, X., Amin, W., Ozturk, I., Rehman, O. U., & Sarwar, S. (2018). Energy and ecological sustainability: challenges and panoramas in belt and road initiative countries. *Sustainability*, *10*(8), 2743.

Ilyas, R., Khan, H. U., & Rauf, A. (2022). Welfare impacts of policy reforms: a case of electricity subsidies in Pakistan. International Journal of Energy Economics and Policy, 12(3), 41-49.

Shahbaz, M., Zakaria, M., Shahzad, S. J. H., & Mahalik, M. K. (2018). The energy consumption and economic growth nexus in top ten energy-consuming countries: Fresh evidence from using the quantile-on-quantile approach. *Energy Economics*, *71*, 282-301.

Soytas, U., Sari, R., & Ewing, B. T. (2007). Energy consumption, income, and carbon emissions in the United States. *Ecological economics*, *62*(3-4), 482-489.

Sterman, J. (2002). System Dynamics: systems thinking and modeling for a complex world.

Stern, D. I. (2001). The environmental Kuznets curve: a review. *The economics of nature and the nature of economics*, 193.

Stern, N. (2008). The economics of climate change. *American economic review*, *98*(2), 1-37.

Wang, J., Wang, S., Li, S., & Feng, K. (2019). Coupling analysis of urbanization and energy-environment efficiency: Evidence from Guangdong province. *Applied Energy*, *254*, 113650.

Wu, D. D., Zheng, L., & Olson, D. L. (2014). A decision support approach for online stock forum sentiment analysis. *IEEE transactions on systems, man, and cybernetics: systems*, *44*(8), 1077-1087.

Wu, X., Xu, Y., Lou, Y., & Chen, Y. (2018). Low carbon transition in a distributed

energy system regulated by localized energy markets. *Energy Policy*, *122*, 474-485.
Zhou, K., Fu, C., & Yang, S. (2016). Big data driven smart energy management: From big data to big insights. *Renewable and sustainable energy reviews*, *56*, 215-225.
Zhou, X., Zhang, J., & Li, J. (2013). Industrial structural transformation and carbon dioxide emissions in China. *Energy policy*, *57*, 43-51.