ASSESSMENT OF CO2 EMISSIONS USING AN ENERGY-ECONOMY SIMULATION MODEL FOR TANZANIA UNDER DIFFERENT SCENARIOS

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RESUMEN
El análisis de las relaciones entre economía, energía y medio ambiente plantea un reto complejo, sobre todo en las naciones en desarrollo que experimentan un rápido crecimiento económico y demográfico. Este estudio introduce un modelo de dinámica de sistemas diseñado específicamente para investigar la intrincada relación entre actividades económicas, producción de electricidad y emisiones de CO2. Centrándose en Tanzania, el modelo evalúa varios escenarios y políticas de expansión de la capacidad instalada y sus implicaciones para las emisiones de gases de efecto invernadero, teniendo en cuenta las limitaciones de la energía en el crecimiento económico, que a su vez repercuten en la demanda energética. Al representar la economía de forma endógena, el modelo ofrece una comprensión matizada de cómo las opciones energéticas afectan tanto al rendimiento económico como a los resultados climáticos. El análisis compara escenarios que exploran las transiciones energéticas con el telón de fondo de la expansión de los combustibles fósiles. Los resultados preliminares sugieren que los ajustes de los marcos políticos pueden promover una combinación energética más sostenible, lo que se traduce en reducciones significativas de las emisiones de CO2. En última instancia, este enfoque mejora la resistencia climática al tiempo que fomenta el crecimiento económico sostenible.

Palabras clave: Modelo Energía-Economía, Dinámica de Sistemas, Emisiones de GEI, Cambio Climático.

ABSTRACT
Analyzing the relationship between the economy, energy and the environment poses a complex challenge, particularly in developing nations experiencing rapid economic and population growth. This study introduces a System Dynamics model specifically designed to investigate the intricate relationship between economic activities, electricity production, and CO2 emissions. Focusing on Tanzania, the model evaluates various scenarios and installed capacity expansion policies and their implications for greenhouse gas emissions, considering the limitations of energy on economic growth, which in turn impact energy demand. By representing the economy endogenously, the model offers a nuanced understanding of how energy choices affect both economic performance and climate outcomes. The analysis compares scenarios that explore

energy transitions against the backdrop of fossil fuel expansion. Preliminary results suggest that adjustments to policy frameworks can promote a more sustainable energy mix, leading to significant reductions in CO2 emissions. Ultimately, this approach enhances climate resilience while fostering economic sustainable growth.

Key words: Energy-Economy Model, System Dynamics, GHG Emissions, Climate Change.

1. INTRODUCTION

As energy demand rises rapidly in regions like Africa, driven by industrial and demographic growth, countries face significant challenges in energy supply. Renewable energies remain underdeveloped in Africa, contributing less than 20% to the energy mix (IEA, 2022; IRENA, 2020). The impacts of climate change are particularly severe on the continent, undermining natural resources and economic stability, with GDP per capita declining by an estimated 13.6% due to human-induced climate change (IPCC, 2022). Tanzania, for instance, saw a reduction of over 10% in GDP per capita between 1991 and 2010 due to these impacts. Although Africa has the lowest per capita CO_2 emissions globally (IEA, 2022), its growing economies and reliance on fossil fuels indicate that, without a shift towards renewables, the continent could become a significant contributor to global GHG emissions in the future (Sikder et al., 2022).

In Tanzania, with a 5.9% average GDP growth rate between 2010 and 2020, energy demand is projected to increase substantially (World Bank, 2024a). Projections estimate Tanzania's GDP between $714 billion and $1,173 billion by 2050, with a population between 101 and 121 million (IIASA, 2024). This growth highlights the need for expanded energy resources. Currently, only 46 % of Tanzania's population has access to electricity, and improving access is essential for enhancing productivity, reducing household energy costs, and fostering sustainable economic growth (NBS, 2022).

This study examines the connection between electricity and economic systems in Tanzania, providing a model to support the WEF (Water, Energy, Food) Nexus as part of the ONEPLanET project under Europe Horizon. The model is innovative in its focus on the Energy-Economy link, which is often treated exogenously in traditional WEF models. Unlike conventional approaches, this model captures dynamic interactions and feedback between energy supply and economic growth.

The relationship between electricity and the economy is deeply interconnected, as energy is a crucial input for production, transport, and consumption, while economic growth drives energy demand. System dynamics is a suitable methodology for modelling this complexity, as it allows for capturing the feedback loops between economic growth and energy consumption.

2. METHODOLOGY

The methodological process consists of the following stages: first, a conceptual approach on how the model works, based on a causal diagram. This is followed by a literature review to parameterize the model variables and the collection of historical data to enable model calibration and validation. The next step involves implementing the equations governing the model in simulation software VENSIM DSS (2024). Finally, the model is validated, scenarios are approached, and results are obtained.

2.1. Brief description of the model

A system dynamics model has been developed to examine the interconnection between energy and the economy. In this model, economic growth directly impacts energy demand, while the rate of energy infrastructure expansion determines the availability of energy for productive activities and households. If energy supplies are constrained, this may lead to a deceleration of economic growth. The model also considers the effect of these interactions on CO_2 emissions, which are intensifying climate change. This model's dynamic is shown in the causal diagram in Figure 1.

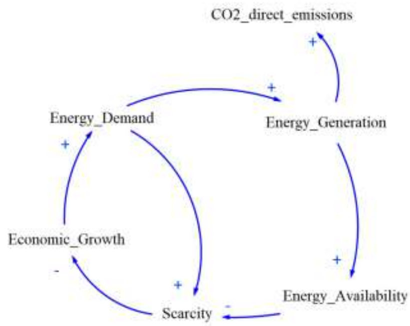

Fig. 1: General causal diagram of Energy-Economy model. Source: Own elaboration.

Regarding the energy module, it estimates final energy demand by energy type across different productive sectors and households, using Gross Domestic Product (GDP) and sectoral energy intensity as key variables. Given that this case study focuses on the electricity production sector in Tanzania, particular emphasis is placed on electricity demand, which is addressed through the installation of power generation capacity whose main dynamics are presented in Figure 2.

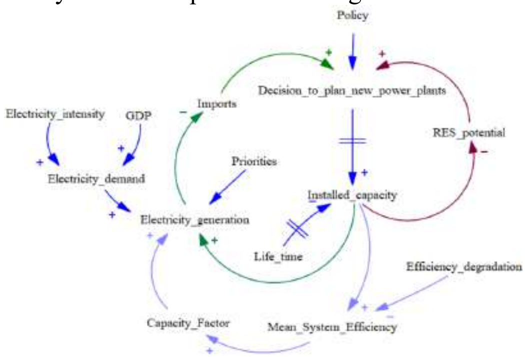

Fig. 2: Causal diagram of capacity installation dynamics. Source: Own elaboration.

Once the electricity demand is estimated, it is compared with the local supply in the energy balance and the import needs are then considered to cover the shortfall.
The local supply is determined according to the energy policy to be evaluated by imposing restrictions on the potential of renewables, considering the planning and construction times of each technology. Thus, renewable and fossil fuel technologies generate different dynamic loops with different speeds depending on their technical parameters.
The model allows to assess how long it will take to achieve energy sovereignty, minimizing imports, which incentivizes the installation of capacity to cover the shortfall. Subsequently, primary energy consumption, along with associated CO2 emissions are calculated. Finally, the technical feasibility of the energy policy is assessed by calculating several indicators on energy security.
Regarding the economic module, the first central aspect is the macroeconomic dynamics, where variables such as the GDP, consumption, especially of households, workers' compensation and the operating surplus are modelled endogenously. In Figure 3, the dynamics that define the economic module can be seen.

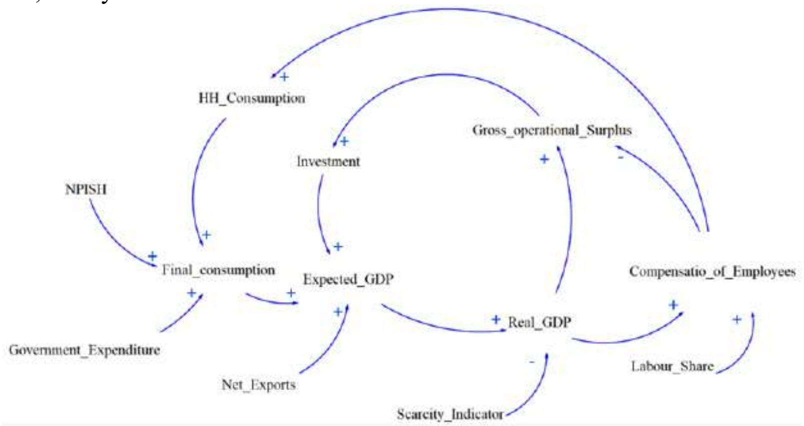

Fig. 3: Causal diagram of economy module. Non-profit Institutions Serving Households (NPISH), Household Consumptions (HH_Consumption). Source: Own elaboration.

This approach makes it possible to capture the interdependencies and feedbacks between the components of the economy in detail, making it possible to simulate complex scenarios of economic growth, income redistribution and consumption patterns.
By modelling these variables endogenously, the model captures the dynamic feedback between the most important macroeconomic variables. For example, an increase in investment can expand the capital stock, which in turn raises productive capacity and GDP, potentially increasing workers' compensation and consumption. However, changes in the distribution between workers' compensation and operating surplus can also influence aggregate demand differently, depending on how sensitive consumption is to labour income. This set of feedbacks is essential for understanding important aspects of demand.

The second key issue of the model is the use of an energy scarcity indicator, which assesses the relationship between energy supply and demand in different productive sectors. This indicator makes it possible to analyse the economy's capacity to meet its energy needs, a critical element for the sustainability of economic growth, especially in contexts of energy transition and climate change.
The relationships between variables in the model have been estimated using historical data and embedded equations, providing a foundation for accurately capturing past trends and future dynamics.

2.2. Scenarios and policies

The study explores three economic scenarios to assess their potential impact on energy demand and economic growth in Tanzania. The BAU without Scarcity scenario assumes that the economy continues along its current trajectory without significant changes in policies or socio-economic context. It adheres to historical patterns and linear projections of key variables, serving as a reference to understand how the economy is expected to evolve without additional interventions and assumes no resource limitation affecting the economy.
In contrast, the BAU with Scarcity scenario incorporates the limitations imposed by resource scarcity while still following similar historical patterns. This scenario analyses how these constraints could affect economic performance, revealing the potential for energy shortages and their repercussions on growth.
The third scenario, Fast Growth with Scarcity, assumes that certain exogenous variables remain following BAU's projections, The critical distinction in this scenario is the assumption of a higher marginal propensity to invest if compared with BAU's projections.
In the simulation, the average GDP growth rate differs between the scenarios: in both BAU scenarios, the economy is projected to grow at an average rate of 8%, while in the Fast Growth scenario, the average GDP growth rate rises to 11%. Electricity demand grows faster under the second scenario, whereas energy intensities have been kept in line with historical trends in both scenarios.
In addition, the scenarios can be combined with three energy policies of capacity expansion process.

- Fossil expansion according to PSMP 2020: this policy forecasts 20 GW of installed capacity in 2050, 40% of which is renewable. This policy is characterized by a high share of coal power plants (26%) compared to the base period and a lower share of hydroelectric power plants compared to the same period.
- Renewable Expansion: this policy forecasts 20 GW of installed capacity by 2050, with renewables comprising 51%. Notably, photovoltaic and wind power play a significant role in the capacity mix, each accounting for approximately 10%, replacing half of the installed capacity of coal-fired plants in Policy 1.
- BAU Power Plan Expansion policy follows historical capacity installation trends from 2000 to 2023, according to IRENASTAT statistics (IRENA, 2024). This policy indicates a moderate installation of

diesel and gas power plants, while the number of hydroelectric facilities remains constant throughout the period.

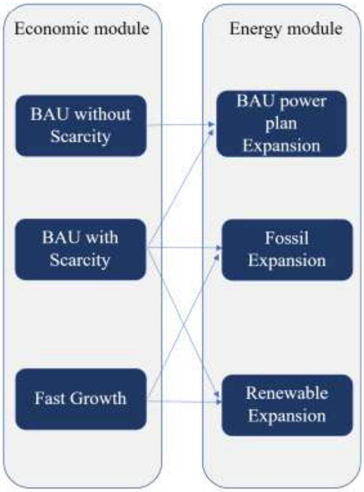

Fig. 4: Scenarios and policies combinations. Source: Own elaboration.

In terms of policy application, as shown in Figure 4, the BAU without Scarcity scenario was simulated using the BAU Power Plan Expansion. The BAU with Scarcity scenario incorporated all three energy policies. Lastly, the Fast Growth with Scarcity scenario utilized both the Fossil Expansion and Renewable Expansion.
The combination of the three economic scenarios with the corresponding energy policies has yielded six distinct policy scenarios.

3. RESULTS AND DISCUSSION

According to the applied methodology, the model estimates that in the BAU scenario (e.g. 8% growth), assuming the continuation of the current installation rate, Tanzania will face a high level of energy dependence (i.e., reliance on imports) that could reach 40% of its electricity demand by 2050, as illustrated in Figure 6. This outcome arises because the rate of power infrastructure installation lags significantly behind the growth in electricity demand. If historical trends in demand growth and energy infrastructure development continue, Tanzania is likely to experience energy shortages, which may limit economic growth. Based on assumptions about the constraints that energy availability places on economic development, this economic slowdown is quantified in Figure 5, where in the BAU scenario with resource scarcity, GDP growth remains low and nearly flat throughout the simulation period. This pattern reflects the limitations imposed by restricted resources, which constrain economic expansion and inhibit substantial GDP growth. The red line stays low compared to the other scenarios, indicating that the economy struggles to expand under these conditions.

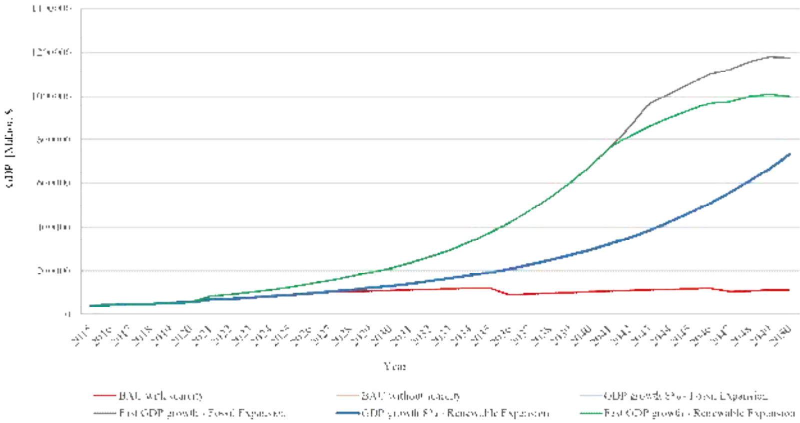

Fig. 5: Evolution of Tanzania's GDP by 2050 under different scenarios. Source: Own elaboration.

The results for BAU without scarcity, the 8% growth scenario with fossil expansion, and the 8% growth scenario with renewable expansion exhibit a similar growth dynamic over time[1]. In all three cases, the economy experiences significant GDP growth and installations of new energy capacity are sufficient to meet demand needs, providing a foundation for stable growth in the early years.

In both Fast Growth scenarios—one with fossil expansion and the other with renewable expansion—the economy initially experiences robust GDP growth supported by significant investments in energy capacity. However, starting around 2040, demand begins to outpace the generation capacity, highlighting a potential turning point where resource scarcity could become a limiting factor.

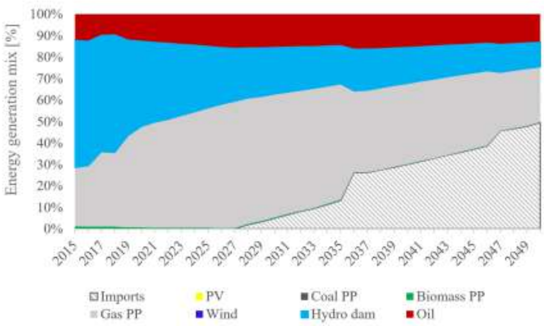

Fig. 6: Tanzania's electricity mix by 2050 in BAU scenario. Source: Own elaboration.

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[1] The economic growth for these three policy scenarios presents the same trajectory, shown in the blue line on Fig 5

This emerging gap suggests that, despite the rapid growth seen in the earlier years, the lack of sufficient generation capacity could constrain economic expansion in the long term. The strain on resources visible after 2040 underscores the vulnerability of both scenarios to scarcity, as the inability to meet rising energy demands may start to hinder economic performance and slow the growth trajectory.
In terms of sustainability, Figure 8 shows the evolution of cumulative CO2 through the different scenarios. The BAU with scarcity and BAU without scarcity scenarios follow the same energy generation policy, which results in both lines showing an identical trajectory. In the BAU with scarcity scenario, the economy consistently uses the full energy generation capacity, constrained by limited resources, which restricts economic growth and keeps emissions stable. In the BAU without scarcity scenario, while the same generation capacity is utilized, the absence of scarcity allows for economic growth without these constraints. This explains why the two scenarios display the same emissions dynamics, as both are based on the same energy policy and capacity utilization, but with differing economic implications due to resource availability.

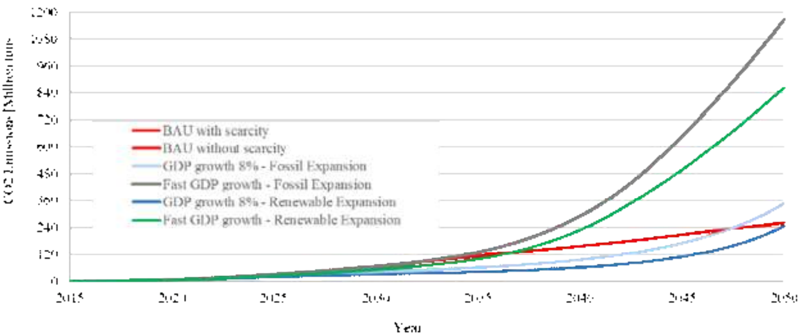

Fig. 7: Evolution of Tanzania's cumulative direct emissions from the electricity sector projected by 2050. Source: Own elaboration.

In both the 8% and 11% growth scenarios, emissions differ significantly depending on the energy expansion strategy. The fossil expansion scenarios lead to a steep rise in emissions, as fossil fuels are heavily utilized to sustain rapid economic growth. In contrast, the renewable expansion scenarios result in much lower emissions, despite supporting high growth rates. This underscores that, irrespective of the growth rate, renewable expansion consistently yields lower emissions than fossil expansion, making it a more sustainable choice environmentally. However, although renewable energy results in lower emissions than fossil fuels, under the 11% growth scenario, the increase in emissions is still significant, which raises concerns.

3. CONCLUSIONS

This study assesses the impact of different policy scenarios on Tanzania's long-term GHG emissions from the electricity sector and economy growth. It has been made with an energy-economy model developed using a System Dynamics approach.

From an economic perspective and considering the ecological economics viewpoint where resources can limit economic growth, the BAU with Scarcity scenario, combined with the BAU Power Plan policy, identifies a significant limitation on the economy due to the scarcity of energy resources. This constraint highlights the critical importance of ensuring adequate energy supply to support economic activities.

The findings further illustrate that, regardless of the percentage of economic growth, the Fossil Expansion policy leads to significantly higher accumulated CO_2 emissions by 2050 compared to the Renewable Expansion policy. In the 11% growth scenario, emissions for both policies are considerably larger than in the BAU scenario, highlighting the substantial environmental impact associated with accelerated economic growth. This underscores the importance of policy shifts that prioritize renewable energy development, not only to reduce emissions but also to ensure adequate electricity supply for growing demand. The data highlights that meeting this demand through renewable sources is the most effective path to minimizing emissions. While Africa currently has the lowest per capita CO_2 emissions worldwide, its expanding economies and dependence on fossil fuels mean that, without a pivot toward renewables, the continent could become a significant contributor to global greenhouse gas emissions in the future.

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