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HYBRID SIMULATION MODEL TO ASSESS THE IMPACT OF GREEN ENERGY ON CO_2 EMISSIONS OF NATIONAL POWER GRID OF UZBEKISTAN

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ABSTRACT

In this paper, a hybrid model was developed to assess the impact of green energy on CO_2 emissions produced by National Electricity Grid of Uzbekistan. Input data for the simulation - electricity supply and consumption patterns of each region in different months were represented by different probability distribution types consistent with the nature of the observed data. The developed hybrid simulation model enabled an analysis of possible development options for the national electricity grid considering several national energy projects, such as the introduction of additional hydroelectric, photovoltaic, and nuclear power plants, as well as increased industrial and electric vehicle energy consumption and population growth. The results showed that the addition of green energy reduces CO_2 emissions from conventional power plants, but only if grid energy losses are simultaneously reduced.

Keywords: Electricity grid, digital modeling, hybrid simulation model, green energy, CO_2 emissions, prescriptive analytics.

1. INTRODUCTION

As is well known, managing a business, and ensuring its competitiveness, especially at the international level, is becoming an increasingly complex task. Traditionally characterized as local, then regional, and then national, competition has now become global. Large, medium, and small enterprises are under pressure from global competition. Barriers that once protected companies within their geographic locations through tariffs and transportation costs no longer provide protection. Consequently, the need for data-driven, more effective, and faster decisions is now more important than ever. In these challenging market conditions, prescriptive analytics, i.e., the implementation of modern digital decision-making transformation methodology, promises to provide managers with the information needed to make more effective and faster decisions, thereby improving their competitiveness in the market. Prescriptive analytics is now widely perceived as a savior or assistant for senior executives in the complexities of global business practices.

A separate approach to simulation modeling and the potential for building a hybrid model should also be considered (Jarrah, 2016). Hybrid models can combine agent-based and system dynamics models to simulate "renewable energy generation and storage networks" at the micro level (Bazan et al, 2012). This modeling includes generation and consumption components at the household level and dynamically links schedule information to the grid. This work can be appropriately applied to modeling transmission networks at the macro level, i.e., at the national level. The integration of two different modeling approaches, system dynamics and agent-based models, was fundamental to the construction of the Uzbekistan power grid model.

The problem of developing a hybrid simulation model for large-scale power generation systems was solved by integrating system dynamics and discrete event simulation models (Pruckner & German, 2013). In this work, a system dynamics model is used to represent the continuous energy flow, and a discrete event simulation model represents the decision-making process. This hybrid model represents an operational model that simulates the future annual electricity balance, CO_2 emissions balance, electricity imports and exports, and the wholesale electricity price. The authors concluded that Bavaria (Germany) is likely to experience a shortage of generating capacity if too much emphasis is placed on renewable energy sources and suggested that the construction of new natural gas-fired power plants is essential to cover the potential shortage of generating capacity caused by growing demand in the future. Naturally, they acknowledge that this will lead to increased CO_2 emissions. This example is considered when conducting the experiment using the case of Uzbekistan. A computer simulation model of a smart grid for renewable energy sources can be developed based on the discrete-event simulation methodology (Jarrah, 2016). This study focuses on decision-making in providing the required capacity of the power generation system at the micro level. The developed adaptive power generation system, based on demand data, proved useful in constructing a stochastic energy model.

Several papers have been published describing hybrid simulation models with applications in the energy sector. The operation of solar generators and storage devices can also be simulated by creating a hybrid operating model based on system dynamics and agent-based modeling methods (Mazhari et al, 2019). Individual electricity demand in households was represented by agents and heat demand associated with gas use was not considered. Households do not have regenerative energy systems and are not separated into components. They cannot operate together in a local grid.

A hybrid simulation model based on system dynamics and a discrete-event system is successfully used to analyze a network of residential buildings equipped with various technological alternatives, such as solar modules, micro CHP systems, and electricity storage systems (Bazan et al, 2012). Hybrid simulation models can also integrate agent-based and particle swarm optimization models to create a decision-making tool for future distribution networks with a large number of decentralized electricity generators (Biller & Gunes, 2010). Computer-based tools for decision-making in the energy sector also exist. Specifically, 37 tools for analyzing the integration of renewable energy sources were studied (Connolly et al, 2020). The tools are compared based on their nature (modeling, optimization, etc.), availability (free for download or commercial), geographic region (local, national, and global), and time steps (annual, hourly, and minute).

2. METHODOLOGY

Simulation-based studies of energy systems can help in the transition to a more sustainable energy system of the future by identifying risks and calculation errors.

Further, we consider an example of digital transformation of decision-making at an industrial scale using a hybrid simulation model of the National Electricity Grid of Uzbekistan, which integrates the full cycle of electricity generation, transmission, and consumption with various system development scenarios—implementation of planned new power generation sources, the introduction of green energy, expansion of the solar panel network at farms, growth in the electric vehicle fleet, and the possible use of electric vehicle batteries to power households (Djumanov et al, 2025).

The importance of green energy (GE) has long been a topic of debate. Countries around the world are striving for a carbon-neutral economy, and Uzbekistan is following suit. GE is a key pillar of policies aimed at achieving carbon neutrality. Enormous investments are being made in its implementation, although the return on investment in megawatt-hours (MWh) of electricity generated is naturally low compared to other types of power plants, such as thermal and nuclear, as their use is dependent on weather conditions. Arguably, directing these investments toward more traditional power plants to achieve stable and affordable electricity production may be more socially feasible, as it will improve the quality of daily life for citizens.

To develop a hybrid simulation model of the National Electricity Grid, the necessary input data on electricity supply and demand in Uzbekistan were obtained from the Energy Coordination and Dispatch Center of the Ministry of Energy of the Republic of Uzbekistan. The data was pre-processed using Microsoft Excel and its add-ins, such as @Risk, and the modeling was performed using AnyLogic Professional. The study also included aggregated regional data for fourteen regions of Uzbekistan for the period 2016-2021. Each dataset corresponds to supply, demand, and weather data. Supply-side data includes information on the capacity of various power plants and their actual statistics on the total volume of energy produced and billed for each year. The difference between the generated and billed energy is denoted as loss – EL (Energy Loss). These data are used to model electricity production for each type of power plant. The types of implemented power plants include solar, wind, hydroelectric, and thermal power plants. Data on future planned solar and wind energy projects is collected and integrated to the model as events occurring on a specific date within the simulation.

Demand data contains information on how much energy is consumed daily in each region. They are used to model how much energy each region consumes per hour.

Weather data contains hourly temperature and radiation data for each region. Temperature data is used to simulate extreme weather conditions, where each household in each region consumes more energy than usual if the temperature during the day in the simulated situation reaches a certain threshold. Solar radiation data is used to calculate the energy generated by photovoltaic panels installed in households in each region if energy-saving generators (SG – Smart Grid) are activated in the model.

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For input data modeling purposes, the received data is cleaned and processed to match the same level of data granularity, i.e., hourly data for the hourly simulation time with the corresponding unit of measurement – megawatt-hour. The results of preprocessing the demand and weather data, as well as approximating them with specific types of random number distributions according to predefined data set parameters, are used. The best fit to the random number distribution model was selected based on Akaike's Information Criterion (Heath et al, 2011).

SG should be defined as a technological opportunity within which households in each region can install their own rooftop photovoltaic panels to generate electricity and use it for their own consumption. SG allows for the supply of excess energy to the main grid for consumption by other households. Energy consumed by a household directly from SG is independent of EL from the grid. We also define electric vehicles as vehicles powered by electricity stored in their storage devices, such as batteries. They represent additional demand that consumes energy from the grid.

It should be noted that the total electricity consumption per consumer in MWh is growing faster than the number of consumers, indicating that each consumer is consuming more energy than before. Data on consumption, losses, and weather conditions were preprocessed for input modeling, and corresponding metrics with appropriate units of measurement and random number distribution functions were calculated for each region and by month. It was assumed that in all regions, there is one agent for every 10,000 consumers. For example, in Tashkent, there are 73 agents, and their number is increasing by 1.48% annually. 10.07% of electricity is lost before reaching them. In June, they consume between 3.08 and 3.9 MWh of electricity per hour. Their consumption is increasing by 1.009% annually.

The hybrid simulation model included input data for the main sources of electricity generation: traditional thermal and hydroelectric power plants. The total capacity of existing thermal and hydroelectric power plants (TPPs and HPPs) is 15,046 MWh, which is assumed to provide this electricity generation 24 hours a day, seven days a week. TPPs are assumed to produce 427 kg of CO_2 per megawatt-hour of electricity [11].

The hybrid simulation model also included input data on existing and projected green energy production from solar panels and windmills.

According to the Ministry of Energy, 11 solar power plants with an average capacity of 561 MWh are planned for construction between 2021 and 2024. In addition, six wind turbines with an average capacity of 1,627 MWh are planned for commissioning between 2023 and 2026. It should be noted that the efficient power generation of solar panels and wind turbines is lower than their capacity, as they can only produce energy when there is sun or wind at the installation site.

The project uses an average power capacity of 62 kWh for each electric vehicle, which is equal to the average power of all electric vehicles available worldwide [4].

3. MODELING AND ANALYSIS

A hybrid simulation model of the national electricity grid was developed using AnyLogic 8 application software. The computer-based hybrid simulation model consists of an agent-based model (electricity consumers) and a system dynamics model (electricity generation and transmission network) (Figure 1).

The model includes the following components, as shown in Figure 1:

1) Each power plant type (TPP, HPP, and GE) generates electricity, which is modeled as an input flow. It accumulates in the network as stocks in the system dynamics;

2) Consumption is represented as an output flow from these stocks. Household agents in each of the fourteen regions determine their electricity consumption based on a monthly changing baseline consumption level in MWh and the stochastic behavior of the agents transitioning between states such as active, passive, offline, and extreme weather conditions;

3) Photovoltaic panels installed in each household produce a constant amount of electricity each hour based on the total number of irradiation hours per day, which is modeled as an input flow. The number of irradiation hours per day for each region is calculated based on a stochastic distribution function fitted to historical weather data for each region;

4) The Smart Grid (SG), modeled as a reserve, allows for lossless energy consumption from the energy generated by photovoltaic panels;

5) Electric vehicles are energy consumers and energy storage devices for households, which are modeled as reserves.

The hybrid model has the following inputs:

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1) Each domain includes agents in the agent-based model;

2) Each domain consumes electricity stochastically according to a defined distribution function for each month;

3) The volume of electricity generated from thermal and hydroelectric power plants, green energy, and the Smart Grid;

4) The total megawatt-hour of electricity consumed by the agent from the grid;

5) Electricity lost during transmission;

6) Simulation time (CLOCK).

In this case, input variables 1, 2, and 6 are input parameters of the agent-based model, and input variables 3, 4, and 5 are input parameters of the system dynamics model.

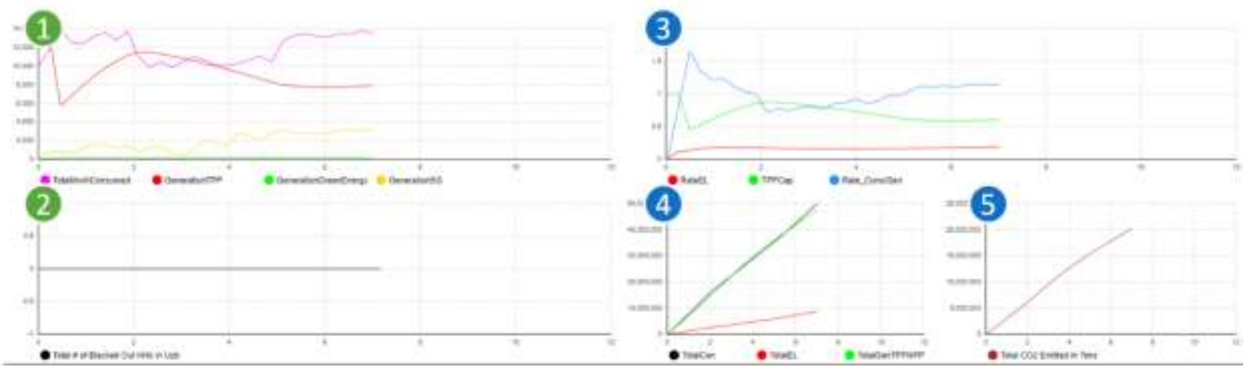


Figure 2. Key Performance Indicators (KPIs) simulated by the model.

All agent states are associated with stochastic transitions simulating different behavior for each agent. An extreme weather state is triggered by an event that monitors the current temperature, generated stochastically based on weather data in each region. A message is sent when the temperature is below or above the 10% and 90% percentiles, respectively. The total MWh consumption for each population in a region is essentially a weighted average of the corresponding number of agents in each state, multiplied by the area's baseline consumption level.

The model tracks the aggregated key performance indicators (KPIs) by country as given in Figure 2:

- weekly MWh consumption and generation,
- hourly number of agents in the black-out state,

3) weekly EL (energy production and consumption ratio), TPP utilization rate,

4) monthly updated aggregate generation and consumption metrics, as well as energy loss,

5) the total amount of CO_2 produced by the thermal power plant over the simulation period.

The following assumptions and logical assumptions were made in the simulation:

1) annual changes in consumption-related parameters,

2) green energy generation,

3) thermal power plant generation and its CO_2 emissions,

4) agent population size,

5) baseline consumption factor,

6) total grid consumption.

First, the population size increases annually at a region-specific compound annual growth rate (CAGR). MWh consumption increases annually at a region-specific CAGR. The EL indicator does not increase annually in each region. The base year for calculating the CAGR is 2021. Projected growth parameters for solar panel power generation are assumed to be from 1.699 to 4.915 MWh, wind turbines from 3.5 to 14.259 MWh, and the percentage of the population owning electric vehicles from 0.05% to 3.3% by 2027, in accordance with project plans.

Second, solar panels and wind turbines are commissioned at predetermined times in accordance with future projects. They generate energy at a constant average hourly rate determined by the project owners. The impact of weather is already included in the average hourly constant rate and is therefore not modeled. All energy-efficient energy sources will be implemented by 2027.

Third, the capacity of thermal and hydroelectric power plants is fixed at any point in the simulation. The thermal power plant's generation rate is updated hourly based on grid energy availability. CO2 emissions are calculated linearly based on the energy generated by thermal power plants. On average, 427 kg of CO2 are emitted per MWh.

Fourth, the agents in the population are consumers, including both individual households and businesses. In each region, there is one agent for every 10,000 consumers. Each region has its own agent. Each agent in each region acts stochastically based on the same state transition diagrams described above. No agent in a region has its own behavior.

Fifth, the MWh consumption of a single agent in each region is approximated by a stochastic function based on regional monthly data for 2021. Agents in Tashkent, Samarkand, Fergana, and Termez cities each have their own stochastic function. Other regions are assumed to have the same function, derived from differential data calculated using consumption data for all of Uzbekistan.

The study conducted three simulation experiments based on the developed hybrid model:

1) validation of the model against actual data to ensure its behavior matches historical data.

2) analysis of model metrics, such as CO2 emissions and number of hours of downtime per day, for 20 different scenarios between 2022 and 2027.

3) comparative assessment of the effectiveness of changes in the number of solar panels and electric vehicles in Uzbekistan.

For model validation, the hybrid model was run 100 times using different initial random number seeds to compare the model's performance against actual data in 2021.

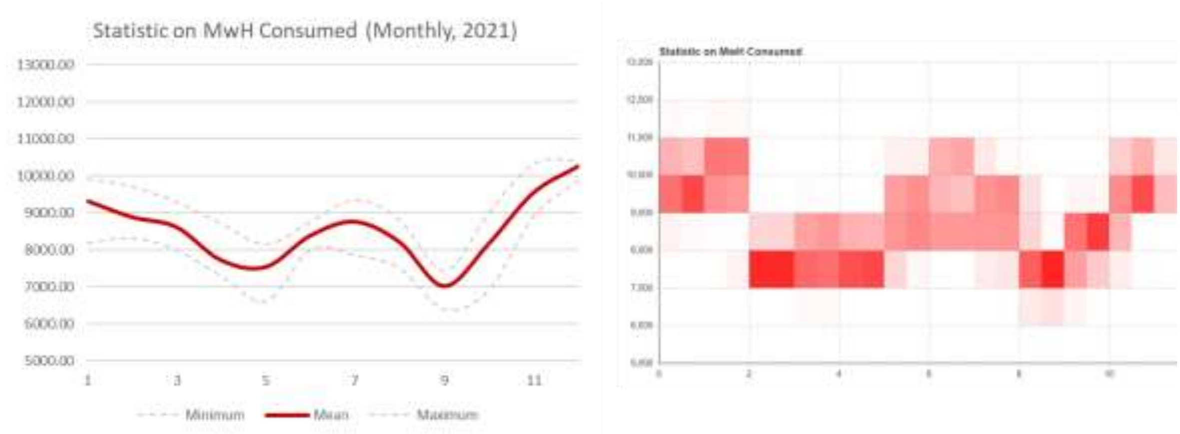


Figure 3. Model output data compared to monthly consumptions in 2021.

The diagram above (Figure 3) shows a curve on the right with the interval estimate of simulated MWh consumption from 100 runs with different initial random numbers. The left diagram displays the monthly minimum, average, and maximum values of actual consumption data. As we can see from the diagram, the actual and simulated data are consistent, we can validate the hybrid model.

The study compared modeled cumulative CO_2 emissions in metric tons for 2021 with data from another analytical study (Friedlingstein et al, 2022). Based on a comparison of these data with the modeling data, it can be suggested that total CO2 emissions from electricity generation account for 22.3% of the country's total carbon dioxide emissions (Figure 4).

Recognizing the fact of validation of the computer model, a scenario analysis was conducted for the period 2022–2027, running the operational model 100 times. In the diagram (Figure 5), the 95% confidence interval for the mean is indicated by the red line and bar, and the deviation of one standard deviation above and below the mean is indicated by the blue line and bar. As can be seen from the diagram, the variation is minimal, allowing us to conclude that the forecasting results using simulation modeling are statistically significant.

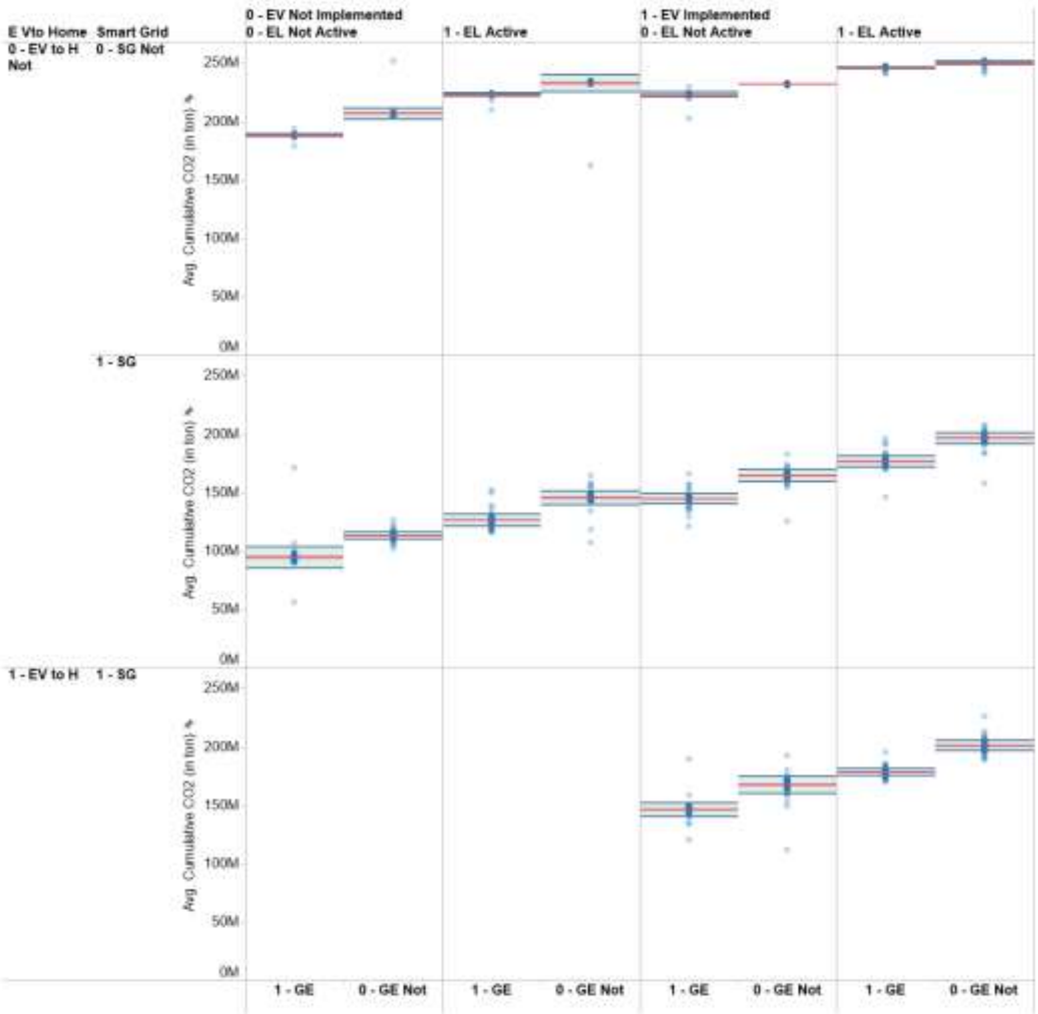
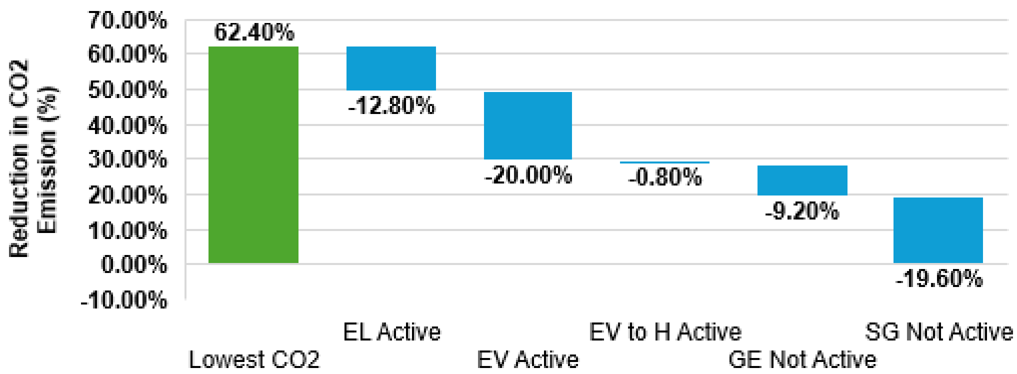


Figure 5. Interval estimated of simulated CO_2 emission scenarios.

The results of changing CO_2 emission scenarios (in metric tons) for the period from 2022 to 2027 are also determined (Figure 5).

The simulation results for the period from 2022 to 2027 (Figure 6) show that the highest cumulative CO2 emissions



are observed in the model without SG sources and green energy, but with grid losses and electric vehicles without household charging (250 million tons of CO2). The lowest CO2 emissions (94 million tons of CO2) are observed with SG and green energy, but without EVs and grid losses. The difference between these two scenarios represents a 62.4% reduction in CO2 emissions. This result indicates significant potential for CO2 emission reduction (Figure 6).

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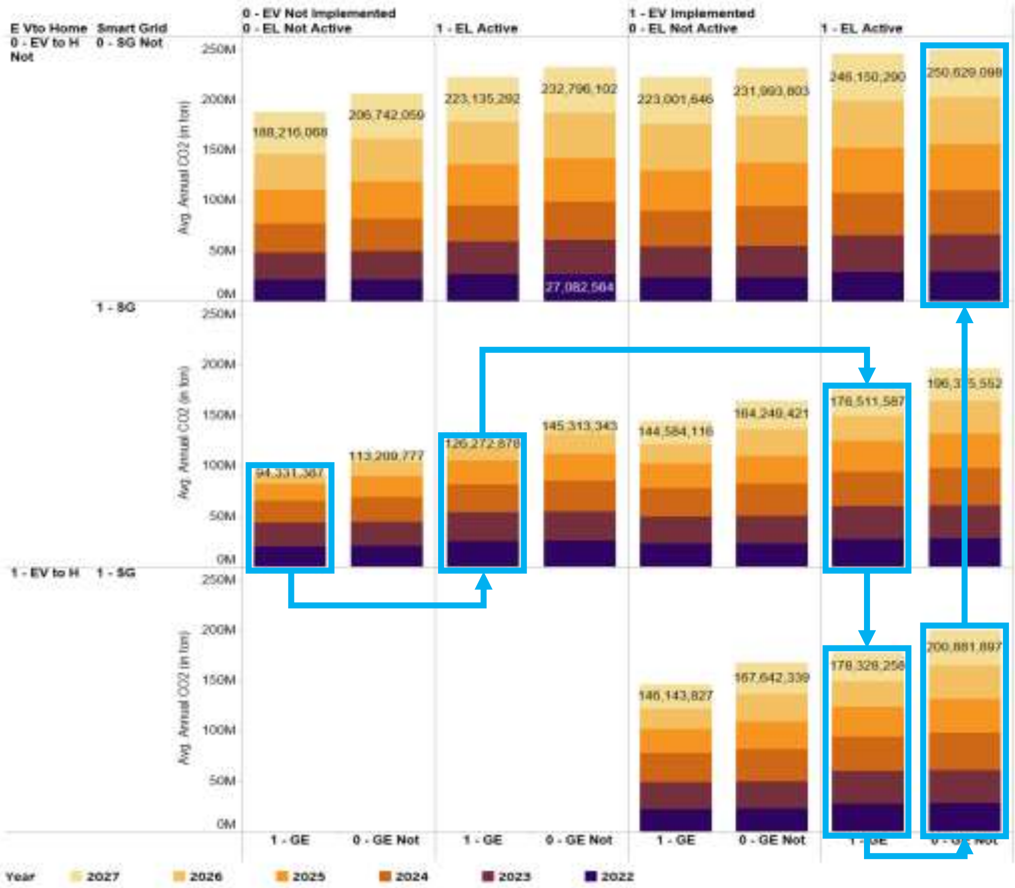

Figure 7. Output parameters of the simulated CO_2 emissions according to different scenarios.

As shown in Figure 7, the impact of electric vehicles and renewable energy is significant. The impact of losses is greater than that of green energy. EVs and renewable energy have a significant impact on reducing CO_2 emissions.

For the same scenarios discussed earlier in terms of CO_2 emissions (Figure 7), the average number of outage hours is relatively small, except for the last scenario, which had the highest CO_2 emissions.

4. CONCLUSION

Examining the modeling results, it can be concluded that scenarios without SGs exhibit the highest proportions of outages. Households are expected to experience outages with increasing frequency each year. In the worst case, by 2027, Uzbek citizens will experience power outages for 58% of the year. Although the availability of green energy and the absence of power losses improve the situation somewhat, considering the increased consumption caused by the growth of the electric vehicle fleet, the situation remains unpromising: over 40% of any given day of the year in Uzbekistan in 2027 will experience power outages. Even assuming that the impact of electric vehicles on the increase in consumption is minimal (EV=0), power outages will still occur on 10-20% of each day of the year, equivalent to 2.5-5 hours of daily life without electricity throughout Uzbekistan.

The solution to all these problems appears to be the implementation of a power grid. With the availability of electric vehicles and electric vehicles with household plug-in capability, the modeling predicts the lowest number of power outages in 2027 (2.8%). In this optimistic scenario, Uzbekistan appears to be outage-free from 2022 to 2026. The only relatively favorable scenario without outages is when the model excludes power losses and observes an increase in electric vehicle consumption, with all energy sources successfully implemented. This leads to an increase in outage days of 1.48% per year. This could also mean that any minor changes without the introduction of SG policies will lead to widespread outages across the country during the modeling period.

Based on the above studies, it can be concluded that the digital transformation of decision-making based on such complex computer simulation models facilitates the effective development of the most optimal and appropriate development scenarios for various prospective cases, not only for individual economic entities but also for industry planning and management as a whole.

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