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Toward a Sustainable Energy Future: Scenario-Based Analysis for North Macedonia

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Abstract – In this paper, three alternative scenarios are examined and presented for the possibilities of North Macedonia's transitioning energy sector toward renewable energy sources. Various combinations of photovoltaics, wind turbines, cogeneration plants, and hydropower plants are taken into consideration for analysing the technical, and environmental aspects. The results represent a comparison of CO_2 emissions, stability of the power grid, and energy imports and exports. According to the represented results, the scenarios with a dominant share of photovoltaics significantly reduce CO_2 emissions, while scenarios with increased involvement of wind turbines have a significant impact on export potential. Hydropower is a crucial factor for energy flexibility and stability. Also, cogeneration plants have an important role in grid balancing and import dependency reduction. The results indicate that the proper investments distribution is essential for a sustainable energy transition. Čebren, as a future planned project provide a baseline for better optimization of the energy system.

Keywords**:** carbon neutrality, electricity import and export, energy transition, grid stability, renewable energy.

1. Introduction

The energy sector in North Macedonia (MKD) is a baseline for the country's economic and social development. It primarily depends on the thermal power plants (TPP) operation that use fossil fuels such as coal and fuel oil. It is the largest share of electricity production and presents important challenges, including high greenhouse gas emissions and sensitivity to global price fluctuations [1].

In 2023, renewable energy sources such as hydropower plants (HPP), solar farms (SF), and wind turbines (WT) had a limited share in total energy production. However, they are essential for achieving energy independence and reducing environmental impact, as shown in Table 1 [2].

Table 1: Installed energy capacities in North Macedonia in 2023

2023						
Wind	PV	River HPP	Dammed HPP	CHP	TPP	Biogas
72.8 MW	506 MW	162.4 MW	557.4 MW	287.41 MW	1034 MW	12 MW

According to the International Paris Agreement obligation on fossil fuels, MKD faces notable challenges. According to the 2021 Revised Nationally Determined Contribution, the country aims to reduce greenhouse gas emissions for 51% by 2030 compared to 1990 levels [3]. Decarbonization and integration of renewable energy sources, need energy and climate regulation oriented to the European Green Deal. This prepares the country for integration into European energy markets [4].

Transitioning to renewable energy sources is very important but, numerous studies emphasize various critical aspects of the mentioned transition.

In [5] is represented an analysis of the environmental impact between the Bitola thermal and photovoltaic power plants (PPP). Both have identical annual electricity production. The results represent a reduction in greenhouse gas emissions and waste materials when using photovoltaic systems (PS). That describes the necessity of renewable energy technologies implementation.

The potential of reusing degraded and unused agricultural land for solar and wind energy installations is represented in [6]. The approach enables an increase in renewable energy production while taking care of natural resources. By optimizing the use of these areas, MKD could crucially reduce its dependency on energy imports and increase the overall stability of its energy system.

Examining the potential of solar and wind energy in Serbia by analysing meteorological data while identifying the most suitable regions for utilization is represented in [7]. Both renewable sources (the one in Serbia and the one in Macedonia) demonstrate the ability to improve the energy system stability.

This paper analyses potential scenarios for optimizing MKD's energy system. The main focus is phasing out the coal- and fuel-oil-based TPP. Renewable energy sources such as photovoltaics, wind turbines, and HPP are planned as their replacement. An increase in production capacity through the installation of new cogeneration plants operating on natural gas is also represented in this paper.

Simulation and analysis of various scenarios to assess how changes in the energy production structure impact the technical and environmental aspects of MKD's energy system are made in Energy PLAN software. This paper focuses on identifying the limitations and opportunities of the existing energy system during the transition toward a more sustainable model based on renewable energy sources.

2. Methodology

In this paper, Energy PLAN software is used. It is software designed for analyzing national energy systems and optimization of energy resource usage [8]. It also enables the integration of renewable energy sources and represents their impact on energy security, system stability, and CO_2 emissions [9].

The software provides modeling of efficient and sustainable solutions [10]. Developing effective policies and strategies for long-term energy sustainability can be done by taking into consideration the results from the software [11].

This paper includes primary data sources such as annual reports and databases from the Energy Regulatory Commission, AD ESM, and AD EVN. Installed capacities (renewable and non-renewable), energy and fuel imports and exports (coal, natural gas, oil), fuel prices, as well as data on electricity production and consumption are the information provided by the available sources.

Furthermore, seasonal and daily demand variations, along with consumption patterns by sector, were analyzed to enable a detailed calculation of energy dynamics and resource distribution.

Reports from relevant institutions, national and international databases, and official statistics are the data collection resources enabling reliable simulation and results.

Based on the data collected from the latest reports, represented are the results between the current state of the energy sector in the Republic of MKD and three proposed alternative scenarios. Each case highlights the potential impacts of its implementation on the energy system. All scenarios include the idea of complete phasing out of coal- and fuel-oil-based thermal power plants, replacing them with new capacities for electricity generation from renewable energy sources and gas-fired cogeneration plants. The total capacity of the new cogeneration plants is projected to be at least 200 MW. These new capacities are designed to match the electricity demand of 2023, 6.738 TWh.

The first scenario represents the potential for installing new capacities from WT and PPP. The total capacity, including the already existing renewable energy capacities, is limited to 1600 MW. The scenario includes three cases with varying ratios of installed capacity between photovoltaics and WT. From the existing 287.41 MW in 2023, the cogeneration capacity increases with an additional planned capacity of 200 MW, reaching a total of 487.41 MW.

Table 2 represents the analyzed scenario showing the ratio between wind, PV, and CHP capacities.

Table 2: Planned installed energy capacities according to Alternative Scenario 1

Case 1:	PV	**Case 2:**	PV	**Case 3:**	PV
	1200 MW		900 MW		600 MW
	Wind		Wind		Wind
	400 MW		700 MW		1200 MW
	CHP		CHP		CHP
	487.41 MW		487.41 MW		487.41 MW

The second scenario represents the potential for installing new capacities from photovoltaic and wind power plants (WPP). This scenario includes newly installed gas-fired cogeneration capacities. Varying the ratios of installed capacities among photovoltaics, WT, and gas-fired cogeneration plants is the focus of this scenario.

Table 3 represents the total installed energy capacity for each case, providing a detailed breakdown of the capacities in the energy system.

Table 3: Planned installed energy capacities according to Alternative Scenario 2

Case 1:	**Case 2:**	**Case 3:**	**Case 4:**	**Case 5:**	**Case 6:**	**Case 7:**
PV	PV	PV	PV	PV	PV	PV
1200 MW	1000 MW	1400 MW	1000 MW	1100 MW	1200 MW	1000 MW
Wind	Wind	Wind	Wind	Wind	Wind	Wind
800 MW	1000 MW	600 MW	800 MW	700 MW	600 MW	600 MW
CHP	CHP	CHP	CHP	CHP	CHP	CHP
487.41 MW	487.41 MW	487.41 MW	587.41 MW	587.41 MW	587.41 MW	687.41 MW

Increasing electricity production by fully requiring hydro resources is the final scenario. Four different combinations of installed capacities from run-of-river and pumped-storage HPP to evaluate their impact on the energy sector and the environment are represented.

In these scenarios, the installed capacities of photovoltaics and WT remain constant at 1100 MW and 700 MW, respectively.

The combination of HPP capacities in the energy system is represented in Table 4.

Table 4: Planned installed energy capacities according to Alternative Scenario 3

Case 1:	**Case 2:**	**Case 3:**	**Case 4:**
River HPP	River HPP	River HPP	River HPP
700 MW	600 MW	500 MW	400 MW
Pumped-back HPP	Pumped-back HPP	Pumped-back HPP	Pumped-back HPP
1115 MW	1215 MW	1315 MW	1415 MW
PV	PV	PV	PV
1100 MW	1100 MW	1100 MW	1100 MW
Wind	Wind	Wind	Wind
700 MW	700 MW	700 MW	700 MW
CHP	CHP	CHP	CHP
487.41 MW	487.41 MW	487.41 MW	487.41 MW

Technical, and environmental impacts on the energy system in MKD are represented in the three previous scenarios. The current state, includes electricity imports and CO_2 emissions, so another scenario evaluates CO_2 emissions, and energy imports because they include the current state of the electrical grid.

To identify the most optimal solutions for transitioning to a sustainable energy model, the results are represented in tabular format for easier comparison.

3. Results and Discussion

To identify the most optimal solutions for transitioning to a sustainable energy system, different scenarios were represented in the previous chapter. Regarding technical stability, and environmental sustainability, each scenario is analyzed through a series of cases.

The potential of alternative solutions to reduce import dependency, lower CO_2 emissions, and enhance grid stability compared to the current state are represented in the analysis below.

In Table 5, are represented the data and the results for each scenario.

Table 5: Results for the different scenarios

Scenarios	Cases	CO_2 emissions (Mt)	Electricity import (TWh/year)	Electricity export (TWh/year)	Grid stabilization check
2023 (The real situation)		6.04	0.185	0.318	✓
Alternative scenario 1	Case 1	4.21	0.44	0.95	X
	Case 2	4.12	0.30	0.74	✓
	Case 3	4.07	0.23	0.65	X
Alternative scenario 2	Case 1	4.03	0.22	1.02	✓
	Case 2	3.99	0.18	0.95	✓
	Case 3	4.09	0.29	1.13	✓
	Case 4	4.17	0.13	0.86	✓
	Case 5	4.13	0.12	0.81	✓
	Case 6	4.10	0.10	0.76	✓
	Case 7	4.22	0.05	0.61	✓
Alternative scenario 3	Case 1	3.83	0.05	2.63	✓
	Case 2	3.84	0.05	2.46	✓
	Case 3	3.84	0.06	2.28	✓
	Case 4	3.85	0.07	2.11	✓

Analyzing the different cases in scenario 1, it could be concluded that environmental and economic outcomes are not the same when photovoltaics and the wind have different shares. The higher the share of photovoltaic, the lower the CO_2 emissions, while the higher share of WPP, the smaller the electricity export. Maintaining a balance between CO_2 emission reduction and export efficiency is happening when combining 900 MW PV and 700 MW wind energy which leads to electricity export of 0.74 TWh/year. Increasing the capacity of WPP above the optimal levels leads to a decline in electricity exports. This indicates that strategic capacity planning is needed.

According to the results, the 900/700 configuration is considered as best solution among the analyzed options, balancing CO_2 emissions reduction, electricity imports minimization, and export growth.

A country's energy independence according to the second scenario is possible by involving cogeneration capacities. The combination of 687.41 MW cogeneration, 1000 MW photovoltaics, and 600 MW wind power reduces imports to just 0.05 TWh/year reduction of approximately 73% compared to 2023 levels. Across all analyzed scenarios this configuration achieves the lowest CO_2 emission.

Cogeneration systems are very important because they ensure balanced load distribution, especially in cases with higher shares of photovoltaics and wind power, where grid stability could be compromised. During periods of low renewable energy generation, such as winter months or days with minimal sunlight and wind, having a cogeneration plant provides continuous energy production.

Long-term benefits of a country having cogeneration capacity such as reduced energy imports and enhanced system resilience, explain the costs of investment in building such a plant. Contribution to reduction of CO_2 emissions makes them more efficient compared with traditional TPP. According to the results represented in all cases of scenario 2, CO_2 emissions are maintained below 5 Mt/year, which indicates an improvement in sustainability.

Different configurations of run-of-river hydropower plants and pumped-storage HPPs are represented in the third scenario. In Case 1, the capacity of run-of-river HPPs is 700 MW and it rises up to 400 MW in Case 4, while simultaneously increasing the capacity of pumped-storage HPPs from 1115 MW to 1415 MW.

In Case 1, run-of-river HPPs have a priority, and there the CO_2 emissions at 3.83 Mt/year are lowest, but electricity exports of 2.63 TWh/year are the highest. As the share of pumped-storage HPPs increases, CO_2 emissions slightly rise, and electricity exports decrease. In Case 4 recorded emissions are 3.85 Mt/year and exports are 2.11 TWh/year. All cases in this scenario represent important reductions in emissions compared to the 2023 reference value of 6.04 Mt/year.

All configurations in scenario 3 maintain a stable grid without requiring additional infrastructure investments. It makes this scenario suitable for enhancing system flexibility while accepting higher shares of renewables.

Preliminary results indicate that the proper allocation of the funds is crucial for the successful implementation of the energy transition, minimizing economic burdens while maximizing environmental and societal benefits.

Providing the best options for technical, and environmental sustainability through the successful implementation of the energy transition is represented with the results in this paper.

4. Conclusion

The results represent that the fossil fuel-based energy system transition to one focused on renewable energy sources is technically, and environmentally feasible. The analyzed scenarios provide benefits in CO_2 emissions reduction, improving the stability of the power grid, and decreasing the energy import dependencies.

The first scenario highlights that the proper balance between photovoltaic and wind capacities is crucial for achieving environmental and economic objectives. Among the configurations, the combination of 900 MW photovoltaics and 700 MW wind stands out as the most suitable, offering the best balance between reducing emissions, lowering imports, and increasing electricity exports.

The second scenario represents the importance of cogeneration plants for grid stability and imports reduction. The combination of 687.41 MW CHP, 1000 MW photovoltaics, and 600 MW wind is identified as optimal, achieving the lowest CO_2 emissions and the biggest reduction in electricity imports. Meanwhile, the third scenario underscores that the greatest progress in the energy transition can be achieved through the hydropower potential. Case 1, with 700 MW run-of-river HPPs and 1115 MW pumped-storage HPPs, achieves the lowest CO_2 emissions and the highest electricity exports, making it the most suitable for providing energy independence.

This is directly connected with the major state-planned project for constructing the pumped-storage HPP Čebren. It should have a key role as a "battery" for balancing consumption and production during critical periods. The Čebren HPP project represents the country's commitment to its energy infrastructure modernization. This project provides energy system flexibility and diversity, where currently dominates thermal power plants.

The planned implementation of Čebren is an excellent baseline for further research. Further studies can take into consideration not only the technical and economic aspects but also the environmental and social implications of these significant investments.

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