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Comparative analysis of hydro energy determinants for European Economies using Golden Cut-oriented Quantum Spherical fuzzy modelling and causality analysis

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ABSTRACT

This article presents a comparative analysis of the determinants of hydropower for European economies using Golden Cut oriented Quantum Spherical fuzzy modelling and causality analysis in 24 European countries over the period 2001–2020. The indicators chosen for the analysis are inflation, population, GDP per capita, CO2 and hydropower consumption. The analysis shows that the selected groups of countries are characterised by an inverse relationship between GDP per capita and hydropower consumption, suggesting a bi-directional causal relationship, which also confirms the novelty of this paper. Furthermore, another analysis is carried out using the fuzzy decision-making methodology. In this framework, the directions of influence of the five selected indicators are constructed: GDP per capita (criterion 1, D = 88.656, E = 88.083), hydropower consumption (criterion 2, D = 89.471, E = 88.677), population (criterion 3, D = 87.705, E = 89.228), CO2 emissions (criterion 4, D = 88.578, E = 89.186) and inflation (criterion 5, D = 88.943, E = 88.180). The Quantum Spherical fuzzy methodology is used for this purpose. The values of D and E are measures of the sum of the rows and columns of the overall relationship matrix. Hydropower consumption is the main criterion. It is understood that two different analyses give similar results, namely the bidirectional causal relationship between criteria 1 and 2.

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Abbreviations

GDP	Gross domestic product
EROI	Energy return on investment
IEA	International Energy Agency
EU	European Union
REC	Renewable energy consumption
EG	Economic growth
CEN	Central executive network
ERM	Exchange-rate mechanism

1. Introduction

Hydroelectric power plants are facilities that produce electrical energy by using the flow rate of water. These power plants are important in many aspects for the social and economic development of countries. First, hydroelectric energy is a clean and renewable energy source. The main resource used for energy production in these power plants is water [1]. Since this resource is constantly renewed, it is possible to produce energy sustainably from these power plants. On the other hand, hydroelectric energy creates much lower levels of carbon emissions compared to other types of energy. This enables the problem of global warming to be combated more effectively. Besides these, hydroelectric power plants generally have long lifespans. This provides businesses with a significant cost advantage. Thus, the profitability of these projects will increase, which will significantly attract the attention of investors [2].

As can be understood from the above-mentioned issues, hydroelectric power plants need to be developed. In this context, some analyzes must be made and necessary measures must be taken. In this process, care should be taken to ensure that the projects developed do not harm the ecosystem. To achieve this goal, the water flow must be adjusted correctly. Similarly, the environmental impacts of hydropower projects must be accurately assessed [3]. Necessary precautions must be taken during the installation process to prevent these projects from causing natural disasters such as floods. On the other hand, hydroelectric projects have a significant impact on local people. Therefore, it is very necessary to ensure the acceptance of the people living in that region for these projects. Technological competence is also very important in increasing the performance of these projects [4]. Especially by using the latest technologies, the quality of the materials used in power plants can be ensured. This allows minimizing any technical disruptions that may occur during the operation of the project.

There are many factors that affect the performance of hydroelectric power plants. These factors need to be improved to increase the performance of these power plants. The most important problem here is that the improvements made increase the costs. Therefore, making many improvements to many variables can make costs uncontrollable [5]. This situation negatively affects the performance of the projects. Instead of doing this, it would be better for businesses to make improvements for more important factors first. To achieve this goal, it is necessary to determine the priority factors that affect the efficiency of these power plants.Table 1, 7 and 8

Accordingly, this study aims to evaluate key performance indicators of hydroelectric power plants. For this purpose, two different analyses have been conducted. In the first stage, a causality analysis is made for European countries. Moreover, the second stage includes a fuzzy multi-criteria decision-making analysis. For this purpose, five different variables are selected as criteria. The main motivation of this study is the need for a comprehensive evaluation with respect to the indicators of hydroelectric power investments. Most of the existing studies in the literature focused on either qualitative or quantitative analysis. However, there are limited studies

Table 1
Literature showing the different types of relationship between energy consumption and economic growth.

Authors	Research period	Country groups	Methods	Interconnection
Fang [12]	1978–2008	China	Multivariate OLS	RC ← EG
Glasure [14]	1961–1990	Korea	VECMs	RC ⇄ EG
Montfort (2007)	1970–2003	Turkey	ECM model	RC ← EG
Paul and Bhattacharya [13]	1950–1996	India	Engle-Granger cointegration	RC ⇄ EG
Chang et al. [39]	1990–2011	Canada, Italy, USA	Granger causality	RC ⊠ EG
Menegaki [40]	1997–2007	Europe	Multivariate panel framework	RC ⊠ EG
Azam [41]	1980–2012	ASEAN-5	Granger causality	RC ⇄ EG
Nanthakumar and Subramaniam (2010)	1971–2008	Malaysia	ARDL	RC ⇄ EG
Azam and Muhammad [42]	1990–2014	Asia	Fully modified ordinary least squares	RC → EG
Zheng et al. [43]	1990–2020	Bangladesh	VAR	RC → EG
Bandyopadhyay et al. [44]	1990–2023	India	ARDL	RC ⇄ EG
Zeren and Hizarci [45]	1979–2020	Newly Industrialized Countries	Durbin–Hausman	RC ⇄ EG

making these two different evaluations together. On the other side, finding the most crucial determinants of hydroelectric power plants is a very critic subject. Because of this situation, a comprehensive analysis is needed to reach the most optimal solutions. To fill this missing part in the literature, econometric analysis and fuzzy decision-making evaluations are combined in this study.

Section 2 presents the literature review; Section 3 presents the research methodology and a description of the data selected for analysis. Sections 4-5 describe the analysis and discussion.

2. Literature review

Hydropower use has a direct impact on economic growth in a country [6,7].

The growth hypothesis is used in this paper and assumes a direct relationship. In addition, the conservation hypothesis argues that a reduction in energy consumption, through policy measures, will not lead to an economic contraction and a decline in income [8–10].

2.1. Causal hypothesis

Causal hypothesis methodology plays a crucial role in scientific research, particularly in fields such as social sciences, epidemiology and experimental sciences, where understanding cause and effect relationships is essential.

Causal hypotheses allow researchers to test whether changes in one variable cause changes in another. This is fundamental to understanding the underlying mechanisms of different phenomena. Production and economic growth require a stable flow of energy for economic activity to take place. There is a relationship between the cost of energy and a country's real GDP, which is calculated by looking at the money invested in energy required to produce a unit of goods. Economic growth is characterised by a low ratio, while recessions are characterised by a higher ratio, around ten per cent. In addition, there is a proven relationship between the standard of living of the population and energy consumption, of which hydropower is a part. A study of various energy consumption in China shows that renewable energy has the highest contribution coefficient, based on the contribution coefficient obtained through contribution rate analysis [11].

Many studies have also been conducted for other countries around the world [12–14]. Causal hypotheses provide deeper explanations of phenomena. Rather than simply describing correlations, researchers can explain why and how variables influence each other.

The table shows three types of causality: evidence of unidirectional causality, evidence of bidirectional causality and evidence of neutral causality. Each study uses a different method to test the different hypotheses of the study. The results of the analysis are shown in the Interconnection column.

The unidirectional causality between globalisation in terms of GDP and hydropower consumption can be seen in the context of globalisation [15–19]. Causal studies are often used to inform policy decisions.

For the top 10 hydropower consumers, the study finds that there are different causal relationships in the periods before and after 1988. There is a unidirectional causal relationship for countries such as Turkey, Brazil, USA, Canada, China, France, Japan, Norway, Sweden and India in the first interval, while after 1988 the relationship is bidirectional. Of note is the causal relationship for indicators such as economic growth and clean energy consumption, which was examined using data from thirteen countries in Eurasia. The study used a multivariate panel data structure whose cointegration test showed a long-run relationship between net energy consumption, GDP, labour force and gross fixed capital formation [20,21]. Causal hypotheses are the basis for building scientific knowledge. They drive research by inspiring new questions, experiments and discoveries.

The impact of clean energy consumption, including hydropower, is also felt in terms of pollution, as many studies have shown. The positive impact of ICT and FDI on the environment is typical of countries in the Asia-Pacific region. The positive environmental impact of hydropower consumption is characteristic of Japan and the ACEAH-4 countries. This fact has also been confirmed for 16 developing countries for the period 2000–2018 [22–25].

In conclusion, the causal hypothesis methodology is a powerful tool in scientific research because it allows researchers to go beyond mere correlation and establish cause-and-effect relationships, which is essential for gaining a deeper understanding of the world and making informed decisions in various fields.

2.2. Determinants of hydropower

This study analyses the degree of interrelationship between the different determinants of hydropower development. It should also be noted that there is a large body of literature demonstrating this relationship for different factors and time periods.

There is a clearly traceable relationship between the financial development of countries and the consumption of different types of clean energy [5,26,27]

CO2 emissions as well as the use of fossil fuels are holding back the transition to clean energy. During the COVID-19 pandemic, the price of CO2 emissions increased. Data for the period 2012–2020 from the Thomson Reuters system shows the increasing cost of CO2 quotas, which reduces the attractiveness of non-renewable energy sources. This fact points to the attractiveness of clean energy sources. Hydropower has the highest EROI, despite higher capital costs compared to thermal power plant construction. This is an indication of the attractiveness of renewable energy as an investment, and also of the visible correlation between the consumption of clean energy and CO2 emissions.

The next factor is GDP per capita. The correlation between a country's income and energy use is widely discussed in the literature. It should also be noted that GDP per capita affects the possibility of adopting alternative energy sources and the development of technologies that promote scientific progress in this area [3].

Political factors play a major role in the diffusion and adoption of alternative energy. An example is SDG 7, which includes the development of the renewable energy sector [7].

3. Methodology

In this section, firstly, research area and limitations are discussed. Next, the extension of DEMATEL is given. The Causal Hypothesis and Golden Cut oriented Quantum Spherical Fuzzy Modelling methods are two research techniques and their advantages depend on the specific objectives and applications. The advantages of the Causal Hypothesis method lie in the identification of causal relationships. This method allows researchers to identify and analyze causal relationships between variables, which is particularly useful in areas where it is important to understand how some factors affect others. Causal hypotheses facilitate more rigorous hypothesis testing and determine whether changes in one variable actually cause changes in another. The advantages of the Golden Cut oriented Quantum Spherical Fuzzy Modelling method are the consideration of fuzziness and quantum aspects, adaptation to complex environments. This method combines fuzzy and quantum mechanics, which can be useful in modelling complex systems where uncertainty and quantum effects play a role.

3.1. Preliminaries

In this study, the authors consider indicators such as GDP per capita, CO2 emissions, population, hydropower consumption and inflation for the period 2001–2020 in 24 European countries, which were selected for analysis according to certain criteria to find the relationship between the indicators. Such time period is optimal because all countries publish statistics clearly in this time [27]. This list of indicators (GDP per capita, CO2 emissions, population, hydropower consumption and inflation) already used in several research [12–14].

The countries have been divided into two groups: the first group consists of the 17 euro-zone countries plus the Nordic countries and Switzerland: Austria, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Portugal, Slovakia, Slovenia, Spain, Iceland, Norway, Sweden, Switzerland and the United Kingdom. The second group includes 7 European countries that have kept their national currency: Bulgaria, Croatia, Czech Republic, Poland, Romania, Turkey, Ukraine. The selected time series of the data analysis provide the most accurate data.

Europe is the region with the highest share of world GDP and many European countries are among the countries with the highest GDP per capita in the world. The main purpose is to be able to compare these countries in order to demonstrate the fact that being part of the euro area has a positive impact on hydroelectricity generation, as well as the other indicators used by the authors of the article for their analysis. The choice of this grouping is based on the fact that one of the advantages of the euro is that it facilitates speculation with this currency, which helps to prevent negative consequences for the monetary system of the euro area countries, as happened on 16 September 1992 in the form of the “black environment” (ERM crisis). Currency speculation can have a negative impact on economic growth in the currency area as well as on inflation [28]. This distinction is necessary to show the positive impact of the use of the euro on the economies of the countries through political union. The scope and careful economic control in the euro area contribute to its economic stability, making it more resistant to fluctuations in the global currency markets. The highlighted division into groups of countries is also characterised by the specificity of water consumption and economic development.

Data on GDP per capita, inflation and population are taken from the World Development Indicators database. The data in the above source are published by the World Bank, which indicates that they are accurate and correct. GDP per capita excludes deductions for depreciation of manufactured goods and depletion of natural resources. It should also be noted that the data are in current US dollars. Inflation numbers are measured in terms of consumer prices, annual percentage change. This indicator measures the annual change in the cost of acquiring goods and services, characterised by a possible change over time. Population is the de facto population, which includes all residents regardless of citizenship or legal status. In addition, data on CO2 emissions in kt are provided by the British Petroleum website in the British Petroleum Annual Statistical Review of World Energy.

Installed electricity capacity for the country is presented in million tonnes of oil equivalent from the British Petroleum report. Data are based on gross generation excluding cross-border electricity supply.

3.2. Methods

Quantum theory evaluates the probability more effectively. Because of this situation, it provides some benefits to the decision-making methodology. The probability of quantum mass is explained in Equations (1)–(3). In these equations, ς represents the set of collective exhaustive events. On the other side, $|u_i>$, $|Q(|u>)| = \varphi^2$ gives information [29].

$$Q(|u>) = \varphi e^{j\theta} \tag{1}$$

$$|\varsigma> = \{|u_1>, |u_2>, \ldots, |u_n>\} \tag{2}$$

$$\sum_{|u>\subseteq|\varsigma>} |Q(|u>)| = 1 \tag{3}$$

Moreover, Spherical fuzzy sets $(\widetilde{A_S})$ are explained in Equations (4) and (5).

$$\widetilde{A}_S = \left\{ \langle u, \left(\mu_{\tilde{A}_S}(u), v_{\tilde{A}_S}(u), h_{\tilde{A}_S}(u)\right) | u \in U \right\} \tag{4}$$

$$0 \le \mu^2_{\tilde{A}_S}(u) + v^2_{\tilde{A}_S}(u) + h^2_{\tilde{A}_S}(u) \le 1, \forall_u \in U \tag{5}$$

in this context, $\varsigma_{\mu_{\tilde{A}_S}}$, $\varsigma_{v_{\tilde{A}_S}}$, and $\varsigma_{h_{\tilde{A}_S}}$ define the degrees.

$$|\varsigma_{\tilde{A}_S}> = \left\{ \langle u, \left(\varsigma_{\mu_{\tilde{A}_S}}(u), \varsigma_{v_{\tilde{A}_S}}(u), \varsigma_{h_{\tilde{A}_S}}(u) \right) | u \in 2^{|\varsigma_{\tilde{A}_S}>} \right\} \tag{6}$$

Additionally, Quantum Spherical fuzzy numbers (ς) are explained with Equations (7) and (8). Within this framework, ς_μ, ς_v, ς_h, φ^2 identifies the amplitude of membership [30].

$$\varsigma = \left[\varsigma_\mu . e^{j2\pi.\alpha}, \varsigma_v . e^{j2\pi.\gamma}, \varsigma_h . e^{j2\pi.\beta} \right] \tag{7}$$

$$\varphi^2 = \left| \varsigma_\mu(|u_i>) \right| \tag{8}$$

in this study, the degrees are computed with golden cut to reach more effective results. Equation (9) gives information about golden ratio in which a and b refer to the large and small quantities [31].

$$G = \frac{a}{b} \tag{9}$$

Equations (10)–(13) identify the mathematical form of this ratio.

$$G = \frac{1+\sqrt{5}}{2} = 1.618\ldots \tag{10}$$

$$\varsigma_v = \frac{\varsigma_\mu}{G} \tag{11}$$

$$\varsigma_h = 1 - \varsigma_\mu - \varsigma_v \tag{12}$$

$$\alpha = \left| \varsigma_\mu(|u_i>) \right| \tag{13}$$

Equation (14) gives information about the phase angle of non-member degrees γ.

$$\gamma = \frac{\alpha}{G} \tag{14}$$

Equation (15) includes the phase angle of hesitancy degrees β.

$$\beta = 1 - \alpha - \gamma \tag{15}$$

X_1 and X_2 are two universes and $\widetilde{A}_\varsigma = (\varsigma_{\mu_{\tilde{A}}} e^{j2\pi.\alpha_{\tilde{A}}}, \varsigma_{v_{\tilde{A}}} e^{j2\pi.\gamma_{\tilde{A}}}, \varsigma_{h_{\tilde{A}}} e^{j2\pi.\beta_{\tilde{A}}})$ and $\widetilde{B}_\varsigma = (\varsigma_{\mu_{\tilde{B}}} . e^{j2\pi.\alpha_{\tilde{B}}}, \varsigma_{v_{\tilde{B}}} . e^{j2\pi.\gamma_{\tilde{B}}}, \varsigma_{h_{\tilde{B}}} . e^{j2\pi.\beta_{\tilde{B}}})$ are two quantum spherical fuzzy sets. The mathematical details are identified in Equations (16)–(19).

$$\lambda * \tilde{A}_\varsigma = \left\{ \left(1 - \left(1 - \varsigma_{\mu_{\tilde{A}}}{}^2\right)^\lambda\right)^{\frac{1}{2}} e^{j2\pi.\left(1-\left(1-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^2\right)^\lambda\right)^{\frac{1}{2}}}, \varsigma_{v_{\tilde{A}}}{}^\lambda e^{j2\pi.\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^\lambda}, \left(\left(1 - \varsigma_{h_{\tilde{A}}}{}^2\right)^\lambda - \left(1 - \varsigma_{\mu_{\tilde{A}}}{}^2 - \varsigma_{h_{\tilde{A}}}{}^2\right)^\lambda\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(1-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^2\right)^\lambda - \left(1-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^2-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^2\right)^\lambda\right)^{\frac{1}{2}}} \right\}, \lambda > 0 \tag{16}$$

$$\tilde{A}_{\varsigma}^{\lambda} = \left\{ \varsigma_{\mu_{\tilde{A}}}^{\lambda} e^{j2\pi.\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{\lambda}}, \left(1-\left(1-\varsigma_{v_{\tilde{A}}}^{2}\right)^{\lambda}\right)^{\frac{1}{2}} e^{j2\pi.\left(1-\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}\right)^{\frac{1}{2}}}, \left(\left(1-\varsigma_{v_{\tilde{A}}}^{2}\right)^{\lambda}-\left(1-\varsigma_{v_{\tilde{A}}}^{2}-\varsigma_{h_{\tilde{A}}}^{2}\right)^{\lambda}\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}-\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}\right)^{\frac{1}{2}}} \right\}, \lambda > 0 \tag{17}$$

$$\tilde{A}_{\varsigma} \oplus \tilde{B}_{\varsigma} = \left\{ \left(\varsigma_{\mu_{\tilde{A}}}^{2}+\varsigma_{\mu_{\tilde{B}}}^{2}-\varsigma_{\mu_{\tilde{A}}}^{2}\varsigma_{\mu_{\tilde{B}}}^{2}\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}+\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}}, \varsigma_{v_{\tilde{A}}}\varsigma_{v_{\tilde{B}}} e^{j2\pi.\left(\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)\right)}, \left(\left(1-\varsigma_{\mu_{\tilde{B}}}^{2}\right)\varsigma_{h_{\tilde{A}}}^{2}+\left(1-\varsigma_{\mu_{\tilde{A}}}^{2}\right)\varsigma_{h_{\tilde{B}}}^{2}-\varsigma_{h_{\tilde{A}}}^{2}\varsigma_{h_{\tilde{B}}}^{2}\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(1-\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}+\left(1-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}} \right\} \tag{18}$$

$$\tilde{A}_{\varsigma} \otimes \tilde{B}_{\varsigma} = \left\{ \varsigma_{\mu_{\tilde{A}}}\varsigma_{\mu_{\tilde{B}}} e^{j2\pi.\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)}, \left(\varsigma_{v_{\tilde{A}}}^{2}+\varsigma_{v_{\tilde{B}}}^{2}-\varsigma_{v_{\tilde{A}}}^{2}\varsigma_{v_{\tilde{B}}}^{2}\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}+\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}}, \left(\left(1-\varsigma_{v_{\tilde{B}}}^{2}\right)\varsigma_{h_{\tilde{A}}}^{2}+\left(1-\varsigma_{v_{\tilde{A}}}^{2}\right)\varsigma_{h_{\tilde{B}}}^{2}-\varsigma_{h_{\tilde{A}}}^{2}\varsigma_{h_{\tilde{B}}}^{2}\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(1-\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}+\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}} \right\} \tag{19}$$

3.3. DEMATEL

Multi-Criteria Decision-Making (MCDM) approaches are systematic methods and techniques used to make decisions when multiple criteria or factors need to be considered. These approaches are particularly valuable when making complex decisions involving competing objectives or alternatives [32].

There are various competitive MDMC approaches. AHP is a structured decision-making method that involves decomposing complex problems into a hierarchical structure and assessing the relative importance of criteria and alternatives. It is particularly useful for decision problems involving multiple, often conflicting, criteria [33,34]. TOPSIS is a method used to determine the best alternative among a set of options by calculating the distances between each alternative and the ideal solution (best possible outcome) and the worst solution (worst possible outcome) [35]. Dominance-based Rough Set (DR) is a method extends rough set theory. It involves identifying lower and upper approximations for each alternative with respect to the criteria. These approximations help classify alternatives as "certainly preferred," "possibly preferred," or "indeterminate" based on their dominance relationships [36].

It primarily focuses on understanding the interrelationships among various criteria or factors in a decision-making problem. DEMATEL is designed to analyze and visualize the cause-and-effect relationships among different criteria or factors in a complex decision-making problem. It helps in understanding which criteria influence others directly or indirectly. DEMATEL assigns numerical values to quantify the strength and direction of causal relationships between factors. These values are used to construct the Direct Relation Matrix. Through DEMATEL analysis, decision-makers can identify key factors that have a significant impact on the overall decision or problem. This helps in prioritizing actions or interventions [37].

$$\varsigma_k = \begin{bmatrix} 0 & \varsigma_{12} & \cdots & \cdots & \varsigma_{1n} \\ \varsigma_{21} & 0 & \cdots & \cdots & \varsigma_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \varsigma_{n1} & \varsigma_{n2} & \cdots & \cdots & 0 \end{bmatrix} \tag{20}$$

The aggregated values ς can be calculated as in Equation (21).

$$\varsigma = \left\{ \left[1-\prod_{i=1}^{k}\left(1-\varsigma_{\mu_i}{}^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}} e^{2\pi \cdot \left[1-\prod_{i=1}^{k}\left(1-\left(\frac{\alpha_i}{2\pi}\right)^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}}, \prod_{i=1}^{k}\varsigma_{v_i}{}^{\frac{1}{k}} e^{2\pi \cdot \prod_{i=1}^{k}\left(\frac{\gamma_i}{2\pi}\right)^{\frac{1}{k}}}, \left[\prod_{i=1}^{k}\left(1-\varsigma_{\mu_i}{}^2\right)^{\frac{1}{k}} - \prod_{i=1}^{k}\left(1-\varsigma_{\mu_i}{}^2-\varsigma_{h_i}{}^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}} e^{2\pi \cdot \left[\prod_{i=1}^{k}\left(1-\left(\frac{\alpha_i}{2\pi}\right)^2\right)^{\frac{1}{k}} - \prod_{i=1}^{k}\left(1-\left(\frac{\alpha_i}{2\pi}\right)^2-\left(\frac{\beta_i}{2\pi}\right)^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}} \right\} \tag{21}$$

Thirdly, the defuzzified values $Def\ \varsigma$ can be calculated with Equation (22) [38].

$$Def\ \varsigma_i = \varsigma_{\mu_i} + \varsigma_{h_i}\left(\frac{\varsigma_{\mu_i}}{\varsigma_{\mu_i}+\varsigma_{v_i}}\right) + \left(\frac{\alpha_i}{2\pi}\right) + \left(\frac{\gamma_i}{2\pi}\right)\left(\frac{\left(\frac{\alpha_i}{2\pi}\right)}{\left(\frac{\alpha_i}{2\pi}\right)+\left(\frac{\beta_i}{2\pi}\right)}\right) \tag{22}$$

Fourthly, the direct relation matrix are normalized by Equations (23) and (24).

$$B = \frac{\varsigma}{max_{1\le i\le n}\sum_{j=1}^{n}\varsigma_{ij}} \tag{23}$$

where, $0 \le b_{ij} \le 1$ (24)

Fifthly, Equation (25) is taken into consideration for the generation of the total relation matrix.

$$\lim_{k\to\infty}\left(B+B^2+\ldots+B^k\right) = B(I-B)^{-1} \tag{25}$$

Sixthly, the sum of rows and columns are computed in Equations (26) and (27).

$$D = \left[\sum_{j=1}^{n} e_{ij}\right]_{nx1} \tag{26}$$

$$E = \left[\sum_{i=1}^{n} e_{ij}\right]_{1xn} \tag{27}$$

The values of (D + E) and (D-E) are considered for criteria weighting and creation of the impact relation map. Equation (28) is also used to calculate causal relationship.

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[e_{ij}\right]}{N} \tag{28}$$

4. Results

In this part, firstly, causality analysis is performed. After that, a comparative analysis is made for the determinants.

4.1. Causality analysis

Indicators such as hydropower consumption and CO2 emissions for the 12 countries that make up the Eurozone as well as Switzerland and the Nordic countriesCountries with incomplete hydropower potential are Austria, Finland, Greece, Ireland, Latvia, Portugal, Slovakia, Slovenia, Iceland, Norway, Sweden, Switzerland. It should be noted that countries with hydropower growth indicators above the trend line have high hydropower potential. This fact indicates that in France, Germany, Italy, Spain and the UK there is a direct correlation between economic growth and hydropower consumption.

There is a similar relationship only for European countries whose national currency is not the euro and excluding Switzerland and

Nordic countries. Thus, for economic growth, the incomplete realization of hydropower resources can be seen for the countries below the trend line: Croatia, Czechia, Romania and Ukraine. And the opposite trend can be seen for the other 3 countries.

4.2. Comparative analysis of the determinants

Secondly, a comparative analysis is applied to weight and construct the influence directions of the selected 5 indicators entitled GDP per capita (criterion 1), hydropower consumption (criterion 2), population (criterion 3), CO2 emissions (criterion 4) and inflation (criterion 5) (Table 2).

Linguistic evaluations of Decision Makers for GDP per capita (criterion 1), hydropower consumption (criterion 2), population (criterion 3), CO2 emissions (criterion 4) and inflation (criterion 5) are in Table 3. Table 4 gives information about the results.

Average values of quantum spherical fuzzy numbers for GDP per capita (criterion 1), hydropower consumption (criterion 2), population (criterion 3), CO2 emissions (criterion 4) and inflation (criterion 5) are in Tables 4 and 5.

Score function for GDP per capita (criterion 1), hydropower consumption (criterion 2), population (criterion 3), CO2 emissions (criterion 4) and inflation (criterion 5) is in Table 5.

Normalized relation matrix for GDP per capita (criterion 1), hydropower consumption (criterion 2), population (criterion 3), CO2 emissions (criterion 4) and inflation (criterion 5) is in Table 6

Total relation matrix for GDP per capita (criterion 1), hydropower consumption (criterion 2), population (criterion 3), CO2 emissions (criterion 4) and inflation (criterion 5) is in Table 6.

It is understood that hydropower consumption (criterion 2) is the most significant criterion. Similarly, CO2 emissions (criterion 4) also plays a critical role in this framework.

Additionally, population (criterion 3) and inflation (criterion 5) are on the third and fourth ranks.

The fact that hydropower consumption and carbon dioxide (CO2) emissions have the largest impact on GDP per capita in European countries can be explained by a number of factors. As a clean energy source, hydropower can have a significant impact on a country's GDP. European countries that actively use hydropower can ensure a more stable and affordable energy supply. This encourages production growth and economic development. Reduced CO2 emissions associated with hydropower contribute to environmental compliance and climate change mitigation. This can contribute to bonuses or subsidies for countries that support clean energy sources. Countries in Europe are actively working to meet environmental regulations and standards.

Comparing the two methodologies, criterion 2, i.e. hydropower consumption, was found to be the most influential factor by the DEMATEL approach. Graphs 5(d) and 6(d) show the strongest correlation between criteria 1 and 2 for the euro area countries. The two methods of analysis show the highest importance of the hydropower consumption criterion, indicating that the results of the analysis are similar.

5. Discussion

There are studies proving the neutrality hypothesis for indicators [46,47].

The neutrality hypothesis is present in many studies, which prove that there is no relationship between the above-mentioned indicators. Menegaki [40] states the existence of this relationship for 27 countries in Europe. Chang et al. [39] proves the neutrality hypothesis for countries such as Canada, Italy and the USA[48–50]. A next group of conclusions can be considered evidence of an inverse relationship between the above indicators. For example, a study for 24 European countries proves increased use of renewable energy sources in the period 1990–2007. For Poland there is also a high importance of hydropower for sustainable growth, which can be complemented by the fact that the country ranks among the first in Europe in terms of hydroelectricity production [51,52].

Also of note are the challenges to increasing the use of the fullest potential of hydropower in Europe, such as the unequal distribution of water resources for hydropower production, which significantly slows down the transition to clean energy. Also, despite the many studies documenting the positive environmental impact of hydropower by reducing CO2 emissions, some articles have argued for the negative impact of hydropower in depleting European water resources [53,54].

This paper proves the novelty of this work - the inverse relationship between GDP per capita and hydropower consumption, which proves a bidirectional-cause-effect relationship between the indicators. The study also shows the relationship between various economic growth factors and CO2 emissions and hydropower use over the period 2001–2020. The analysis is based on two groups of countries in Europe - the Eurozone countries, including Switzerland and the Nordic countries, and the remaining countries using national currency. This subdivision is necessary to show the positive effects of using the euro on the economies of the countries,

Table 2
Linguistic scales summary.

Linguistic Scales for Criteria	Possibility Degrees	QSFNs
No influence (n)	0.40	$[\sqrt{0.16}\,e^{j2\pi.0.4}, \sqrt{0.10}\,e^{j2\pi.0.25}, \sqrt{0.74}\,e^{j2\pi.0.35}]$
somewhat influence (s)	0.45	$[\sqrt{0.20}\,e^{j2\pi.0.45}, \sqrt{0.13}\,e^{j2\pi.0.28}, \sqrt{0.67}\,e^{j2\pi.0.27}]$
medium influence (m)	0.50	$[\sqrt{0.25}\,e^{j2\pi.0.50}, \sqrt{0.15}\,e^{j2\pi.0.31}, \sqrt{0.60}\,e^{j2\pi.0.19}]$
high influence (h)	0.55	$[\sqrt{0.30}\,e^{j2\pi.0.55}, \sqrt{0.19}\,e^{j2\pi.0.34}, \sqrt{0.51}\,e^{j2\pi.0.11}]$
very high influence (vh)	0.60	$[\sqrt{0.36}\,e^{j2\pi.0.6}, \sqrt{0.22}\,e^{j2\pi.0.37}, \sqrt{0.42}\,e^{j2\pi.0.03}]$

Table 3
Linguistics summary.

Decision Maker 1					
	C1	C2	C3	C4	C5
C1		H	S	S	VH
C2	VH		S	VH	VH
C3	S	M		H	VH
C4	VH	S	VH		H
C5	H	H	S	VH	
Decision Maker 2					
	C1	C2	C3	C4	C5
C1		H	VH	S	VH
C2	VH		H	VH	VH
C3	S	M		H	VH
C4	VH	VH	VH		H
C5	S	H	H	VH	
Decision Maker 3					
	C1	C2	C3	C4	C5
C1		H	S	M	VH
C2	VH		S	S	M
C3	S	M		H	VH
C4	VH	S	VH		H
C5	S	M	M	M	

Table 4
Average values summary.

	C1	C2	C3	C4	C5
C1		$\left[\sqrt{0.30}e^{j2\pi.0.55},\sqrt{0.19}e^{j2\pi.0.34},\sqrt{0.51}e^{j2\pi.0.11}\right]$	$\left[\sqrt{0.27}e^{j2\pi.0.51},\sqrt{0.16}e^{j2\pi.0.31},\sqrt{0.60}e^{j2\pi.0.22}\right]$	$\left[\sqrt{0.22}e^{j2\pi.0.47},\sqrt{0.13}e^{j2\pi.0.29},\sqrt{0.65}e^{j2\pi.0.25}\right]$	$\left[\sqrt{0.36}e^{j2\pi.0.60},\sqrt{0.22}e^{j2\pi.0.37},\sqrt{0.42}e^{j2\pi.0.03}\right]$
C2	$\left[\sqrt{0.36}e^{j2\pi.0.60},\sqrt{0.22}e^{j2\pi.0.37},\sqrt{0.42}e^{j2\pi.0.03}\right]$		$\left[\sqrt{0.24}e^{j2\pi.0.48},\sqrt{0.14}e^{j2\pi.0.30},\sqrt{0.62}e^{j2\pi.0.22}\right]$	$\left[\sqrt{0.32}e^{j2\pi.0.56},\sqrt{0.18}e^{j2\pi.0.34},\sqrt{0.52}e^{j2\pi.0.15}\right]$	$\left[\sqrt{0.33}e^{j2\pi.0.57},\sqrt{0.20}e^{j2\pi.0.35},\sqrt{0.49}e^{j2\pi.0.11}\right]$
C3	$\left[\sqrt{0.20}e^{j2\pi.0.45},\sqrt{0.13}e^{j2\pi.0.28},\sqrt{0.67}e^{j2\pi.0.27}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50},\sqrt{0.15}e^{j2\pi.0.31},\sqrt{0.60}e^{j2\pi.0.19}\right]$		$\left[\sqrt{0.30}e^{j2\pi.0.55},\sqrt{0.19}e^{j2\pi.0.34},\sqrt{0.51}e^{j2\pi.0.11}\right]$	$\left[\sqrt{0.36}e^{j2\pi.0.60},\sqrt{0.22}e^{j2\pi.0.37},\sqrt{0.42}e^{j2\pi.0.03}\right]$
C4	$\left[\sqrt{0.36}e^{j2\pi.0.60},\sqrt{0.22}e^{j2\pi.0.37},\sqrt{0.42}e^{j2\pi.0.03}\right]$	$\left[\sqrt{0.27}e^{j2\pi.0.51},\sqrt{0.16}e^{j2\pi.0.31},\sqrt{0.60}e^{j2\pi.0.22}\right]$	$\left[\sqrt{0.36}e^{j2\pi.0.60},\sqrt{0.22}e^{j2\pi.0.37},\sqrt{0.42}e^{j2\pi.0.03}\right]$		$\left[\sqrt{0.30}e^{j2\pi.0.55},\sqrt{0.19}e^{j2\pi.0.34},\sqrt{0.51}e^{j2\pi.0.11}\right]$
C5	$\left[\sqrt{0.24}e^{j2\pi.0.48},\sqrt{0.14}e^{j2\pi.0.30},\sqrt{0.62}e^{j2\pi.0.22}\right]$	$\left[\sqrt{0.29}e^{j2\pi.0.54},\sqrt{0.18}e^{j2\pi.0.33},\sqrt{0.54}e^{j2\pi.0.15}\right]$	$\left[\sqrt{0.27}e^{j2\pi.0.51},\sqrt{0.16}e^{j2\pi.0.31},\sqrt{0.60}e^{j2\pi.0.22}\right]$	$\left[\sqrt{0.33}e^{j2\pi.0.57},\sqrt{0.20}e^{j2\pi.0.35},\sqrt{0.49}e^{j2\pi.0.11}\right]$	

Table 5
Score function summary.

	C1	C2	C3	C4	C5
C1	0.000	1.236	1.297	1.243	1.236
C2	1.236	0.000	1.263	1.300	1.269
C3	1.236	1.236	0.000	1.236	1.236
C4	1.236	1.297	1.236	0.000	1.236
C5	1.263	1.243	1.256	1.269	0.000

Table 6
Matrix summary.

	C1	C2	C3	C4	C5
C1	0.000	0.244	0.256	0.245	0.244
C2	0.244	0.000	0.249	0.257	0.250
C3	0.244	0.244	0.000	0.244	0.244
C4	0.244	0.256	0.244	0.000	0.244
C5	0.249	0.245	0.248	0.250	0.000

Table 7
Total relation summary.

	C1	C2	C3	C4	C5	Impact directions
C1	17.456	17.770	17.887	17.872	17.671	C1→(C2,C3,C4)
C2	17.813	17.736	18.045	18.042	17.836	C2→(C1,C3,C4,C5)
C3	17.465	17.582	17.493	17.681	17.484	C3→(N/A)
C4	17.637	17.762	17.864	17.659	17.656	C4→(C2,C3)
C5	17.712	17.828	17.939	17.932	17.532	C5→(C2,C3,C4)

Table 8
Influence summary.

	D	E	D + E	D-E	Weighting results	Weighting priorities
C1	88.656	88.083	176.739	0.573	0.1993	5
C2	89.471	88.677	178.148	0.794	0.2009	1
C3	87.705	89.228	176.933	−1.522	0.1995	4
C4	88.578	89.186	177.765	−0.608	0.2005	2
C5	88.943	88.180	177.123	0.764	0.1998	3

through political union [55–60].

Also, the EU's extensive investment policy in the field of alternative energy allows countries to ensure economic growth. This fact indicates that the EU is a major player in the market of clean investments. In addition, it should be noted the creation of a directive through which the use of alternative energy is encouraged [3] It should be noted that most of the available studies describe the current situation in Europe regarding renewable energy sources [6,7,61]. Undoubtedly, there are also studies proving the existence of various links between the various determinants of renewable energy [41,42].

6. Conclusion

This paper contributes to future studies comparing the impact of realizing hydropower potential on economic growth in countries around the world. The lack of sufficient empirical knowledge in this area confirms the importance of this study. The novelty of the study is confirmed analytically. This article has contributed to a body of knowledge.

The main benefits of this paper are below. Firstly, the analysis of 24 European countries was made by dividing them into two groups, based on certain criteria. This division helps to increase the accuracy of the study, since the countries included in each of the groups are characterized by some similarity in the factors that were taken for the study [41,42,51].

In addition to this issue, another analysis is also performed by using fuzzy decision-making methodology. Hence, a comparative evaluation can be performed. Within this framework, the influence directions of the selected 5 indicators entitled GDP per capita (criterion 1), hydropower consumption (criterion 2), population (criterion 3), CO2 emissions (criterion 4) and inflation (criterion 5) are constructed. In this process, Quantum Spherical fuzzy DEMATEL methodology with golden cut is implemented. It is concluded that hydropower consumption (criterion 2) is the most significant criterion. Similarly, CO2 emissions (criterion 4) also plays a critical role in this framework. Additionally, population (criterion 3) and inflation (criterion 5) are on the third and fourth ranks. However, GDP per capita (criterion 1) has the lowest weight in comparison with other criteria.

Undoubtedly, the political component of Europe's energy sector should also be mentioned in this part of the article. The political factor has a great impact on hydropower consumption and CO2 emissions. Alternative energy is an important component in promoting economic growth in Europe. From a policy perspective, this study addresses the need to reduce countries' dependence on imported fossil energy. The study found that hydropower consumption is one of the main criteria for the transition to green energy. Also, countries should pay special attention to the level of CO2 emissions, which also plays an initial role in the transition process. Policymakers and governments could consider introducing measures and incentives to encourage the expansion of hydropower production and use. European countries can cooperate internationally to develop and disseminate advanced clean energy technologies and knowledge. This can include the exchange of experience and best practices between countries. Research can help identify regions and countries that can benefit most from hydropower development. Policy makers can focus on supporting the development of these regions, creating new jobs and stimulating economic development. Thus, the study can inform policy development to increase hydropower use, reduce CO2 emissions and ensure economic and environmental well-being.

Some limitations of this analysis should also be noted, as no data are available for many European countries, and the unstable economic situation in many countries due to the Covid-19 pandemic in 2020–2021 included in the timeframe of the study. Lack of available data can reduce the accuracy and breadth of these analyses. Not all the data needed to fully understand the situation are always available or up to date. The study covers a specific time period (2001–2020), which may limit its ability to take into account longer-term trends or changes that occurred before or after this period. In addition, the analysis is limited to certain countries, which may not take into account the diversity of situations and factors operating in other parts of the world. To improve the quality of the analysis and the understanding of the situation, further research is planned for the future, taking into account these limitations and changes in data and events over time. The study should be continued through further time periods, as different political and economic situations will undoubtedly affect the data needed for analysis.

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CRediT authorship contribution statement

Polina Datsyuk: Writing – original draft. **Hasan Dinçer:** Conceptualization. **Serhat Yüksel:** Validation. **Alexey Mikhaylov:** Writing – original draft. **Gabor Pinter:** Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e26506.

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