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APPLICATION OF RENEWABLE ENERGY EFFICIENCY TECHNOLOGIES FOR SUSTAINABLE URBAN DEVELOPMENT: THE CASE OF IOANNINA, GREECE

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ABSTRACT

Climate change has become a major topic of discussion in all societies and the transition to a sustainable environment is now considered necessary. Renewable Energy Sources (RES) are an alternative solution for environmental protection. This article focuses on the application of RES technologies in the city of Ioannina, a city in northwestern Greece rich in natural resources, with the aim of becoming energy neutral and independent. Ioannina faces many problems in its urban environment, such as high energy consumption during the winter, which is produced from fossil fuels, as well as aging energy infrastructure. In order to provide answers on how to achieve this goal, a literature review was carried out on similar cases in Greece and abroad, as well as an investigation of the main factors that contribute comprehensively to the energy transition of a region. In addition, interviews were conducted with the municipal authorities and executives of the region, to collect data on the city's energy problems. The aim of this research is to achieve the city of Ioannina environment protection from polluting forms of energy, in combination with economic development and social prosperity.

KEYWORDS: Renewable energy sources, efficiency energy technologies, sustainable development, City of Ioannina.

1. INTRODUCTION

Fossil fuels have played an important role in the economies of countries at an international level, during the development of the second industrial revolution since the mid-19th century, offering significant benefits. At the same time, the use of fossil fuels has also created negative impacts, such as their involvement to a large extent in climate change. Many are the tensions and conflicts that have arisen from the negative impacts caused by their use, leading to the transition to a new energy system (Christophers, 2022).

As fossil fuel reserves dwindle and the environmental and climate crisis worsens, the transition to energy production from Renewable Energy Sources (RES) is a challenge and a priority for a "sustainable society". The main reasons the global energy system is being transformed are to fight climate change, to reduce greenhouse gas emissions and sustainability, and to ensure energy security for future generations. One of the most important factors in the energy transition is the rapid development of technology, through new forms of energy sources, which, through the improvement of their efficiency and economic viability, constitute competitive solutions compared to traditional energy systems (Serrano and Zaveri, 2020). Innovations in photovoltaic systems, wind energy, hydroelectric power and bioenergy have accelerated the transition towards a low-carbon economy at a global level (Frolova et al., 2015; Frantzeskaki and de Haan, 2009; Nanaki and Xydis, 2018). This necessary change in the energy model is not just about technology, but a process that affects the economy, the institutional framework and social priorities at a global level. The greatest environmental priority is the transition from fossil fuels to cleaner and more sustainable energy solutions such as renewable energy sources and advanced energy technologies, constituting an economic and technological revolution that is reshaping industries, policies and societies at a global level (Midilli et al., 2006; Council of Europe, 2000).

The phenomenon of climate change has increasingly concerned society in recent years, since extreme weather phenomena are observed worldwide, which are mainly amplified by the rise in the average temperature of the planet (Cheirchanteri, 2024). In particular, the rise in sea level is among the factors that constitute a challenge for an immediate transition to a sustainable society and by extension to sustainable sources of energy production. In fact,

investments in renewable energy sources are now being observed all over the world, aiming for climate neutrality (Bashir et al., 2025).

Moreover, a basic factor in the energy transition is the storage of solar and wind energy in batteries, through innovative technologies, such as the use of artificial intelligence, which, with the help of digitized business data, enhances smart energy management, so that it is efficient and economically sustainable (Erdiwansyah et al., 2025). Additionally, the economy is another key factor accelerating the energy transition. Since the cost of energy produced from renewable sources has been significantly reduced in recent years, especially from solar and wind energy, it is becoming increasingly competitive compared to energy production from fossil fuels. Many countries now recognize the economic benefits of investing in clean energy, such as job creation, energy independence and long-term economic growth (Hassan et al., 2024).

In Greece, renewable energy sources and the old, low-quality building stock create the conditions for a transition to low-carbon energy. However, there are many uncertainties, such as the effects of the economic crisis, technological limitations, legal instability and public acceptance, creating barriers and economic consequences (Nikas et al., 2020).

A similar energy transition problem is facing Nigeria, an African country, which is struggling to address its energy challenges like grid mismanagement, aging infrastructure, etc., despite its rich fossil fuel reserves. An important solution to this problem is to integrate renewable energy sources, such as solar, wind and hydroelectricity, thereby diversifying its energy mix while reducing its use of fossil fuels. Nigeria's strategy is for the country to be electrified 100%, adopting a mix of renewable and non-renewable energy sources (Ishaku and Quadri, 2025).

The energy transition is the greatest challenge of the 21st century, as cities are oriented towards the adoption of sustainable practices. The use of RES in Greece and in particular in the city of Ioannina, aims at a zero-carbon footprint from fossil fuels and at the same time achieving energy autonomy. In fact, the city of Ioannina, due to its geographical location and the climatic conditions prevailing in the wider area, has significant potential for the exploitation of various forms of RES (Municipality of Ioannina, 2023), as shown below:

a) Solar Energy, with the installation of photovoltaic systems in public and private buildings and infrastructure, even during the winter months, due to the high sunshine in the area.

b) Wind Energy, where the mountainous areas surrounding the basin of the city of Ioannina are suitable for the installation of wind farms.
c) Hydroelectric Energy, due to the existence of large and small rivers in the wider area of Ioannina, it is possible to develop small-scale hydroelectric projects, as well as the exploitation of the geothermal energy of Lake Pamvotida.
d) Energy from biomass of organic waste, due to the increased agricultural and livestock activity in the Epirus Region.

The present research focuses on the benefits of utilizing RES in the city of Ioannina, in order to become energy independent and lead to a green energy and sustainable model. By using RES, Ioannina can reduce the import of electricity from other places and gradually ensure energy stability and autonomy, while contributing to the environmental benefits of the region, since environmental pollution caused by the combustion of fossil fuels, such as carbon dioxide (CO_2), is reduced. Building on these considerations, the study introduces a renewable energy model tailored to the specific geographical area of Ioannina. The model proposal focuses on hydropower exploitation, wind energy utilization, biomass applications, solar energy integration, and innovative energy harvesting systems from road infrastructure.

2. THEORETICAL BACKGROUND

To achieve a sustainable transition, it is not enough to simply reduce carbon emissions, but it is also necessary to calculate the broader impacts on the living environment and society (Buchmayr, 2022). Energy transitions are not only about changing how energy is produced and used, but also affect energy policy, the economy, society and technological developments. However, these changes occur at different times and in different ways, depending on the region in which they are implemented (Vlachou and Pantelias, 2022). The geographical location of a region is also an important factor. Climatic conditions and soil morphology directly affect the practices and technologies that can be applied for its energy transition to green energy. The role of state actions and policies through government actions as well as laws enacted in the field of energy and environmental law play a decisive role in the energy transition (Serrano and Zaveri, 2020).

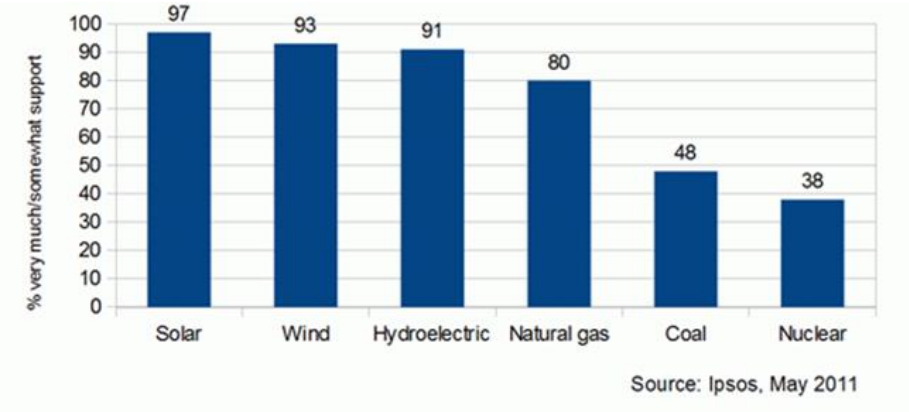

Figure 1: Global public support for energy sources.

According to a survey by Ipsos (Fig. 1), the social acceptance of RES is positive compared to traditional forms, such as coal (48%) and nuclear energy (38%). We observe that the highest rates of support are shown by solar energy (97%), followed by wind (93%) and hydroelectric energy (91%), which also have quite high acceptance rates.

Another determining factor for the energy transition and the green economy is the market, through investments in green energy (Serrano and Zaveri, 2020). According to Midilli et al. (2006), both private and public financial support for green energy significantly contributes to a country's economic development.

Society and citizens, through information and environmental awareness, are also a key factor influencing the transition to green energy. Many times, social actions of Non-Governmental Organizations (NGOs) and social movements can influence the energy transition to a greater extent than the government of a country itself. However, society is not strong enough to exert a direct and substantial influence on its own for the energy transition and the development of RES, but in any case, it influences the process (Serrano and Zaveri, 2020).

Finally, technology and the significant progress it has made in recent years in the field of green energy make it one of the most important factors in the energy transition and the utilization of RES. Innovations in the development of new forms of energy, in its safe and stable supply, in the development of energy storage systems as well as in energy efficiency, significantly enhance the energy transition (Serrano and Zaveri, 2020). Below are presented the most basic RES technologies, analyzing their technical characteristics, advantages and limitations.

3. PRODUCTION AND CONSUMPTION OF RENEWABLE ENERGY SOURCES IN GREECE

Greece is a country with a great diversity of landscapes and geographical relief, which allows it to support a wide range of installation and operation of RES. Although the country plans to develop its energy system through RES, in the last decade, lignite-fired power plants played an active role until 2019. At that time, the government decided to almost immediately stop the burning of domestic lignite in the country's power plants and to proceed with the energy transition towards the use of RES to meet electricity needs. As a transitional technology, natural gas plants would be used until zero carbon emissions were achieved. However, the penetration of RES in electricity generation was so great that it even managed to significantly limit the competitiveness of natural gas plants and their contribution to electricity production (Stavrakas et al., 2021).

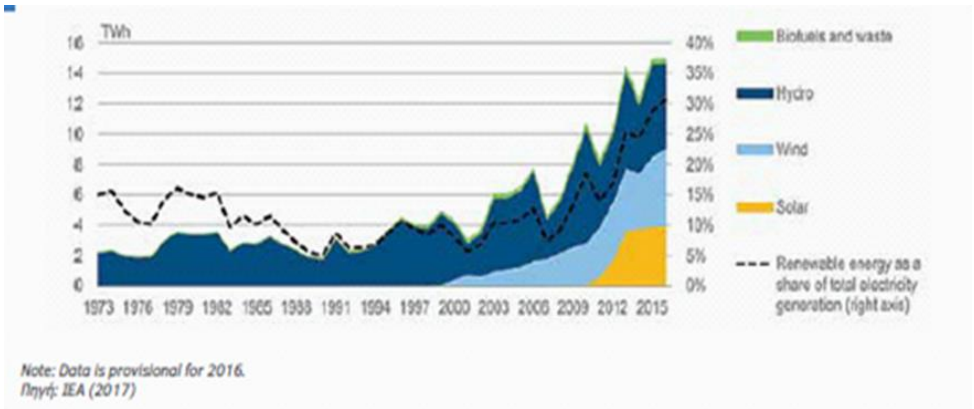

Figure 2: Share of RES in Total Electricity Generation in Greece, 1973-2015.

In Greece, the most widespread forms of renewable energy sources are thermal solar systems and biomass, which mainly cover domestic needs (hot water supply and heating) (Fig. 2). In addition, Greece has been a pioneer in the use of both wind turbines and photovoltaic systems for the production of electricity (Ministry of Environment, 2010). Nevertheless, the potential for the use of RES remains largely unexploited, as the development of competitive industrial production from RES has not yet been achieved. In fact, the total gross primary energy supply from renewable energy sources, especially wind and photovoltaic, has increased significantly over the last decade or so. This is due to the reduction in the cost of technologies used in the production of renewable energy sources and in their appropriate storage tariffs (feed-in-tariffs). However, to this day, the largest percentage of energy consumption nationwide is covered by conventional and polluting fuels (Nikas et al., 2020; Stavrakas et al., 2021).

	Gross Inland Consumption in Greece							
	1990		2004		2012		2017	
Fuel Type	*Mtoe*	%	*Mtoe*	%	*Mtoe*	%	*Mtoe*	%
Solid fossil fuels	8.07	36.3	9.11	30.0	8.13	30.1	4.82	19.9
Oil and petroleum products	12.82	57.8	17.17	56.6	12.64	46.7	11.76	48.5
Natural gas	0.14	0.6	2.23	7.3	3.66	13.5	4.20	17.3
Renewables and biofuels	1.10	5.0	1.57	5.2	2.45	9.1	2.92	12.0
Other	0.06	0.3	0.28	0.9	0.17	0.6	0.54	2.2
TOTAL	22.19	100	30.35	100	27.06	100	24.23	100

Note: The "Other" category consists of Electricity and Waste (non-renewable). The "Electricity" category derives from net electricity imports.

Source: EC, 2019.

Figure 3: Gross Inland Consumption by Type of Fuel in Greece for Selected Years, in Mtoe and Percentage (%) of Total.

Given that, based on the development programs of the period 2007–2013, wind and solar energy exploitation facilities were completed and put into operation, RES showed an unprecedented increase in energy production in Greece (Fig. 3). Specifically, according to statistical data for 2017, energy production from RES reached 10.5 TWh, i.e., 20.1% of total electricity production. In fact, as shown in Figure 4, solar energy production has grown significantly since 2010, reaching 3.5 TWh in 2017, i.e., 25 times higher, while the low levels of wind energy in 1990 reached 5.5 TWh in 2017. However, hydroelectric power production holds the lead in the production of electricity from renewable energy sources, although its performance is not constant throughout the year, reaching 3.5 TWh in 2017, covering 5.4% of the total production in the country. It also appears that biofuels are not widely used in Greece, since in the same period they covered only 1% of the total electricity production (Hellenic Association for Energy Economics, 2019).

In Greece, 2008, when electricity demand was stable, the highest electricity consumption rates reached 58.8 TWh, while the economic crisis period was decreasing until 2013. A relative recovery was noted in 2017, with electricity consumption reaching 51.9 TWh. According to 2015 statistics, 38% of electricity consumption was attributed to the commercial sector, 33.4% to households and 24.2% to industry, while the remaining energy and transport sectors recorded much lower consumption rates (Hellenic Association for Energy Economics, 2019).

When comparing the development of RES in Greece, Israel and Portugal, three countries of similar size, clear differences were observed, which are due to geographical, political and socio-economic factors. Greece is a country that has significantly exploited RES, especially on islands, which relied on fossil fuels for electricity generation, while facing reactions from local society to large-scale RES projects. In contrast, Portugal promotes decentralized energy systems, strengthening self-production at the level of energy local communities that allow citizens to produce and share energy, making it a pioneer in the energy transition in Southern Europe (Prados et al., 2022).

Israel on the other hand, due to its geopolitical situation and concerns about its energy security, the development of RES is seen by its residents as a means of strengthening national control, rather than as a purely environmental initiative. In the case of Israel, the limited participation of residents has hindered public acceptance of RES projects within the framework of a centralized energy policy, highlighting the challenges of implementing government-initiated energy developments. However, the case of Portugal has proven more effective in pursuing a decentralized approach to energy transition to renewable energy, while Greece and Israel face local and political obstacles (Ntanos et al., 2018).

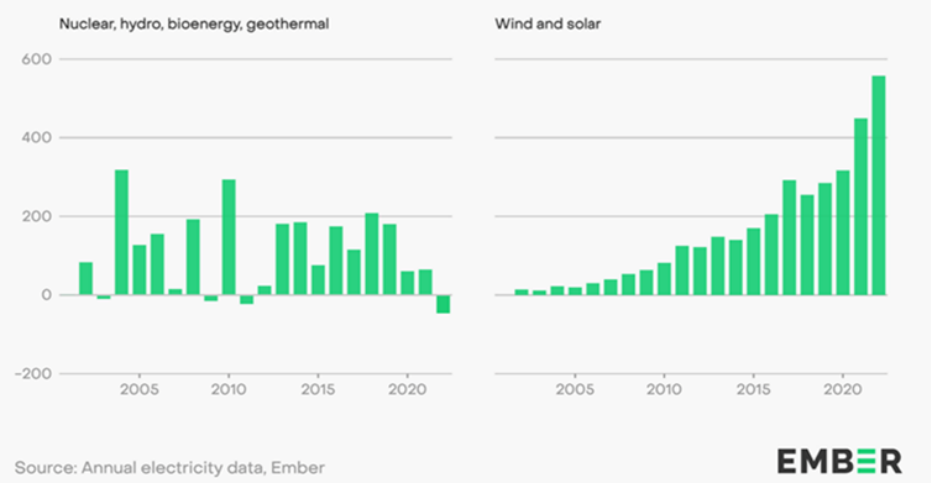

Figure 4: Clean electricity, excluding solar and wind, fell in 2022. Yearly change in electricity generation (TWh).

According to the 2019 Annual Report of the South East Europe Energy Institute (SEEI) and data from the Hellenic Ministry of Environment and Energy, between 2010 and 2016 the share of renewable energy consumption in Greece increased by approximately 50% in gross final energy consumption. Accordingly, the share of electricity generation from RES rose to

26.5% of total electricity generation in 2016, while the share of uncontrolled RES plants in electricity generation rose to 19%. This is due to the rapid increase in photovoltaic and wind system installations, combined with the decrease in total electricity demand during the decade 2010–2020 (Fig. 4). Of course, despite the disastrous environmental impacts, the use of lignite continues to be the main domestic fuel ın a large proportion to this day (Ember, 2023).

4. METHODOLOGY

This article presents a brief bibliographic analysis of key renewable energy technologies, their scientific foundations, their advantages and the challenges they face, based on the most recent research data. This study seeks to constitute a research proposal for the utilization of these technologies in the city of Ioannina, contributing to the green transition of the region. In this context, a qualitative methodological approach was applied through interviews, with the aim of capturing the opinions and strategies of local actors regarding the green energy transition of the city.

The methodology initially focused on the qualitative research approach, as the energy transition of the city of Ioannina to the utilization of RES, requires an investigation into the emergence of socio-political and institutional issues of green energy. The research design included the technique of semi-structured interviews for data collection, in order to investigate in depth the problems that arise.

Subsequently, the selection of participants was made based on the intended sampling. The sample included: (a) The Mayor of the city of Ioannina and (b) Executives of the Epirus Region, including regional councilors and those responsible for energy and environment issues. The interviews focused on four main axes: (1) Participation of the city in the European Union (EU) Mission for 100 Climate-Neutral Cities, (2) Existing and Potential Energy Production from RES, (3) Challenges and obstacles to implementation and (4) Opportunities for participation of citizens and local bodies.

5. THE CASE OF IOANNINA

5.1. Description of Ioannina City

Ioannina is the capital and largest city of the Epirus Region, in northwestern Greece. The city is built on the shores of Lake Pamvotida (Fig. 5), at an altitude of 500 meters. The Municipality of Ioannina has a population of approximately 130,000 inhabitants, an airport, a university, two large university hospitals, adequate hospitality infrastructure as well as

quality business and conference infrastructure. The city of Ioannina stands out as a multicultural center with a rich history, in which three communities coexisted and left their mark: The Christian, the Muslim and the Jewish. These multicultural characteristics are visible in the architecture and traditions of the city, which has been a renowned center of commerce, education and craftsmanship throughout history. It is important to emphasize that Ioannina, despite its long and often turbulent history, continues to be a vibrant and dynamic city, with an active commercial community and citizens interested in improving their quality of life and protecting the environment (Tzortzi and Cheirchanteri, 2025).

It is the most urbanized and populous municipality in Epirus and consists of the Municipal Units (MUs) of Perama, Pamvotida, Anatoli, Vezakia (Vizani), Ioannina, as well as the Community of the Island of Ioannina. The area of the Municipality is approximately 390 sq. km. and its population are 112,486 inhabitants, according to the 2011 census. The seat of the Municipality is the city of Ioannina. It borders the Municipalities of Zitsa, Kentrika Tzoumerka, Zagori and Metsovo. Although Ioannina is the dominant urban center of the region, there are also smaller urban residential centers, such as Anatoli, Katsika, Pedina and Perama, which have significant population potential due to their proximity to the city of Ioannina and, in combination with it, form a wider residential complex (Municipality of Ioannina, 2023).

Figure 5: Lake Pamvotida in Ioannina city, Greece.

5.2. RES Efficiency Energy in The City of Ioannina

The city of Ioannina (Fig. 5), located in northwestern Greece, is characterized by a diverse and rich geomorphological landscape, which combines mountains, lakes, rivers and plains,

making it ideal for the implementation of RES technologies. The Ioannina region is surrounded by significant mountain ranges, which play a decisive role in shaping its geomorphology. To the north and east, the landscape is dominated by the Pindos mountain range. Significant peaks include Grammos (2,520 m), Smolika (2,637 m), Vasilitsa (2,249 m), Mavrovouni (2,160 m) and Lakmos (2,295 m) in southern Pindos, as well as the Athamanika Mountains (2,469 m). To the west, Tymfi (2,497 m) and Mitsikeli (1,810 m) rise, the latter acting as a natural windbreak, influencing the local climate. Despite the dominance of mountainous areas, the Ioannina region also includes some flat areas with gentle and small slopes, which constitute only 3.3% of the total area. With the ever-increasing global demand for clean energy and the EU's commitment to climate neutrality, if Ioannina properly exploits its geographical advantages and integrates RES technologies to improve electricity production, always aiming to reduce carbon emissions and ensure the energy security of its citizens, it will have the potential to become a model city for the sustainable energy transition (Municipality of Ioannina, 2023).

In addition, the Ioannina region has several RES projects, mainly in the field of wind and hydroelectric facilities, due to the altitude and weather conditions prevailing in the region. According to the Energy Regulatory Authority (RAE) (February 2024 data), there are 165 licensed RES projects in the Regional Unit of Ioannina, which include wind farms, small hydroelectric projects (SHPs), photovoltaic systems and biomass processing units. In order to illustrate the proposed renewable energy model for Ioannina, the following subsections present in detail the city's potential in hydropower and geothermal exploitation, wind energy utilization, biomass applications, solar energy integration, and innovative energy harvesting systems from road infrastructure.

5.2.1. Hydropower Potential and Geothermal Energy Production from Lake Pamvotida for Ioannina

Hydropower technologies account for more than 16% of global electricity production, converting the kinetic and potential energy of water into electricity through hydroturbines and generators, with applications ranging from large dams and reservoirs to small hydroelectric projects and pumped storage systems (World Bank, 2023; Karapici et al., 2024; Papadakis et al., 2023). It is important to emphasize that large-scale hydroelectric dams can achieve efficiencies of over 90%. Hydropower is efficient, lasts for many years and has low operating costs, but it can affect the environment by changing ecosystems and river conditions.

The hydrological network of Ioannina and Lake Pamvotida offer possibilities for the development of hydroelectric projects and the production of clean energy. The rivers of the region (Aoos, Arachthos and Kalamas) can be exploited for the production of electricity through small run-of-river hydroelectric projects, which have a small environmental footprint. Furthermore, in Lake Pamvotida (Fig. 6), floating photovoltaics could be installed and combined with hydroelectric applications. Also, the constant temperature of the lake throughout the year makes it ideal for geothermal heat pumps (GHP), in order to provide heating in winter and cooling in summer to public buildings and residences located in the lakeside area. In addition, a storage system can be created to store excess thermal energy (STES), so that the excess energy can be used during periods of greater demand, such as in winter for heating school buildings (Municipality of Ioannina, 2023).

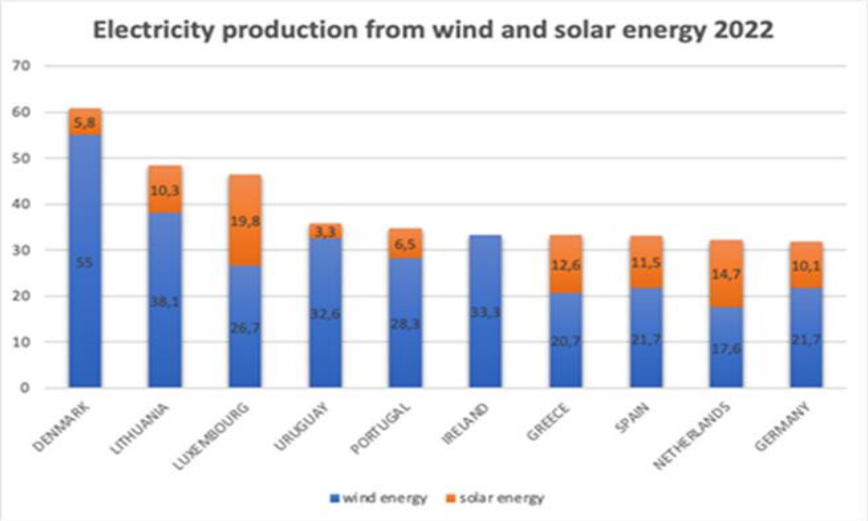

Figure 6: Electricity production from wind and solar energy in EU during 2022.

5.2.2. Wind Energy Utilization

Wind power is one of the least harmful renewable energy technologies and the third largest source of renewable energy worldwide, with a total installed capacity of approximately 837 gigawatts (GW) by the end of 2021 (Summerfield-Ryan and Park, 2023). Figure 6 shows the percentage of electricity produced in 2022 from wind and solar energy in various EU countries. Greece is around the average wind energy production of 20.7% and solar energy of 12.6%, while it is observed that most countries prefer wind energy over solar energy. There are various types of wind turbines, but depending on the orientation of their rotation axis, they are mainly divided into two categories, horizontal axis wind turbines (HAWT) and

vertical axis wind turbines (VAWT). There are also offshore platforms that exploit stronger winds as well as hybrid systems that can combine wind energy with other forms of RES.

The Ioannina basin, surrounded by high mountains with strong and constant winds, offers ideal conditions for wind energy production. The installation of wind farms in the Pindos mountain range and other high areas and points with strong and constant wind currents can produce a stable and significant amount of electricity. Wind turbines are designed to withstand strong winds, but not excessive torques or rotational speeds, which is why they have a "stop speed", above which they stop to avoid any damage to the blades and their mechanical parts (Rogaa et al., 2022). By placing wind turbines in points with strong and constant wind currents, the city can ensure continuous and reliable production of renewable energy, increasing the energy security of the city (Municipality of Ioannina, 2023).

5.2.3. Biomass applications

The International Energy Agency (IEA) has defined bioenergy as the neglected giant of renewable energy sources. In 2017, it accounted for 10.3% of total gross final energy in million tonnes of oil equivalent (119 Mtoe) and 59% of total renewable energy consumption in the EU, keeping Europe as a leader in this sector. Biomass, a globally available renewable energy source, when harvested sustainably does not contribute to CO_2 emissions, and can produce heat, electricity and transport fuels (Anca-Couce et al., 2021). Combustion and gasification of biomass produce heat and electricity, while anaerobic digestion produces biogas (methane).

The city of Ioannina has rich biomass materials, such as agricultural residues and waste from the intense livestock farming activity in the area, which can be utilized for bioenergy production. The installation of biomass power plants will provide an additional renewable energy source and reduce organic waste (Municipality of Ioannina, 2023). The main advantages of bioenergy are carbon neutrality, as biomass renewal offsets emissions, and the utilization of agricultural and industrial waste, which supports the principles of the circular economy.

5.2.4. Solar Energy Integration

Solar energy, compared to other renewable sources, is the cheapest method of producing green energy with very low negative impacts on health and the environment (Waqar et al., 2017). There are two ways to convert solar energy into electricity, photovoltaic (VP) and

concentrated solar power (CSP) technology (Sharma et al., 2018). VP uses semiconductor materials, usually based on silicon, and are made either from thin, flat crystalline elements, or from a continuous glass layer supported on bases, while a large area is required for their installation. The efficiency of silicon-based photovoltaics yields more than 22%. A typical solar power plant consists of solar cell collectors, turbines, generators, condensers and the distribution system of the generated electricity. Whereas, CSP systems consist of the concentrator solar thermal system, the heat absorption and transfer system, the heat storage system, the steam generation system and the power generation system (Waqar et al., 2017).

Although the region experiences frequent and heavy rainfall, the solar radiation it receives throughout the year is sufficient for PV parks, which can be installed in open areas around the city to produce clean energy. In addition, the installation of solar panels on public buildings, schools, residential roofs and outdoor public parking lots which could be covered with greenery and photovoltaic panels can significantly contribute to the diversification of the city's energy supply. Hybrid solutions, such as solar street lighting or the use of solar energy for public transport infrastructure, can also enhance the sustainability and energy efficiency of the urban environment (Municipality of Ioannina, 2023).

5.2.5. Energy Harvesting Systems from Road Infrastructure

In recent years, the city of Ioannina has undergone major road construction projects, with the construction of new road surfaces and large circular at-grade and grade-separated junctions. The use of innovative energy harvesting systems from road infrastructure can contribute to improving energy efficiency and supporting sustainable resilient infrastructure (Tzortzi et al., 2025). On roads with high traffic loads, it is possible to install piezoelectric sensors under the road surface, which convert mechanical energy from vehicle movement into electrical energy. The energy produced can be used for street lighting, the operation of electronic traffic lights and "smart" crossings, as well as for charging electric vehicles at selected points. The city has already built cycle paths, and the local authorities are considering extending them around the lake.

The city centre has been pedestrianized, and there are sufficient public parking spaces. Consequently, in cycle paths, pavements, the central square and the lakeside area, as well as in public parking spaces and low-traffic roads with an appropriate surface, photovoltaic panels can be integrated into the road surface to generate electricity from solar radiation. The application of these technologies can make Ioannina a model in energy utilization, enhancing

the city's sustainability and resilience, and serving as an example at least at the national level in Greece (Vlachou and Pantelias, 2022).

6. RESULTS AND DISCUSSION

The findings of this study indicate that the city of Ioannina can evolve into an energy autonomous city, using renewable energy sources (solar, wind, hydroelectric and biomass). These findings mainly include the data collected from interviews with local stakeholders and experts in energy and environmental issues, which at the same time highlighted the problems of a potential energy transition of the city (Serrano and Zaveri, 2020; Daszkiewicz, 2020). The main topics discussed were RES technologies that can be applied in the city's fabric and within its administrative boundaries. The analysis of the different RES options for Ioannina highlights the following opportunities and challenges.

A closer examination of each RES technology in the context of Ioannina reveals specific potentials and constraints. Solar energy represents a significant opportunity, as installing PV systems on the roofs of public buildings could cover a large part of the city's electricity needs. Despite the high annual rainfall, solar power remains a viable option, especially when combined with hybrid energy solutions. In fact, photovoltaics emerges as the second-best option after biomass, since there are available areas suitable for installation that would not be visible, would not affect the microclimate, and are located near the existing network or potential substations.

Similarly, the city's mountainous terrain creates conditions for wind energy production, and the installation of wind farms around Ioannina could contribute to clean energy generation. The production of wind turbines faces technical difficulties, such as generating current with the correct frequency and voltage, and withstanding changes and extremes in wind. Wind turbines consist of a tower, whose height usually ranges between 80 and 120 meters, a shaft (horizontal or vertical type) that connects the blades to the transmission system, and a chamber (nacelle) that contains the generator, gearbox and control systems (Rogaa et al., 2022). However, despite this potential, the lack of a sufficient transmission network in the region remains a major obstacle to investment in this sector.

The hydrological and geothermal resources of the area also provide promising opportunities. While the region's rivers could support small hydroelectric projects, the absence of a river within the urban fabric limits the development of such installations in the city itself.

Regarding geothermal exploitation of Lake Pamvotida, although technically feasible for heating and cooling, no studies have yet been carried out, and implementation is hindered by unclear responsibilities among the relevant authorities.

By contrast, biomass utilization appears to be the most appropriate and immediately applicable option for Ioannina. The region's intensive agricultural and livestock activities ensure abundant raw material, which can reduce organic waste and support clean energy production. Although often misunderstood by the local community, biomass has the potential to become a cornerstone of the city's energy transition.

Finally, innovative approaches such as energy harvesting from infrastructure could further enhance Ioannina's sustainability. Technologies like piezoelectric energy collection from the road network can play a complementary role, especially given the extensive road construction projects of recent years. However, such applications require comprehensive feasibility studies and strong coordination among stakeholders before they can be effectively implemented.

Overall, the proposed RES initiatives can reduce the city's energy dependence on fossil fuels, improve the environment and strengthen the local economy. The transition to RES in Ioannina presents many opportunities, but also challenges and obstacles that need careful management to overcome. The assessment of challenges begins with some technical and infrastructure aspects. The intermittent nature of solar and wind power generation requires advanced storage solutions, while the city's electricity grid needs upgrades. At present, the existing infrastructure cannot accommodate RES, making the construction of new substations and the adoption of interoperability solutions essential. Furthermore, the lack of trained municipal staff in implementing new RES technologies highlights the need for targeted training programs and additional recruitment (Zahari and Esa, 2016; Tsagarakis et al., 2018).

Beyond the technical and infrastructure dimension, economic and financial challenges also arise. Although RES technologies are now more affordable, the initial cost remains high. Attracting funding through European programs, government subsidies and private investment is crucial. Long-term economies of scale from reducing dependence on fossil fuels need to be effectively communicated to policymakers and stakeholders (Katsaprakakis et al., 2022a).

In addition, the policy and regulatory framework shapes the conditions for the effective implementation of RES projects. There is no spatial planning framework for RES, which makes it difficult to plan and implement new projects. Local and national legislation should

facilitate the implementation of RES projects. By simplifying the licensing process, providing tax incentives and increasing the return to the local community, residents and businesses will switch to renewable energy sources more quickly. The creation of energy communities can reduce disagreements, strengthening cooperation between local actors and residents. In this context, the presence of the University of Ioannina is of particular importance, as it can assume not only a leading research role through pilot projects, but also an educational role by informing citizens in the city's green transition (Katsaprakakis et al., 2022b).

Finally, the dimension of information and social acceptance is critical, as local community support is essential for RES projects to succeed. Informing citizens about the environmental and economic benefits of clean energy can increase participation and reduce disagreements. Concerns about landscape changes from wind farms and large-scale photovoltaics need to be addressed through citizen involvement and open planning. For this reason, residents are kept informed about the benefits, while local authorities promote awareness campaigns and encourage open dialogue between scientific institutions and the public (Kyriakopoulos et al., 2019).

In summary, through appropriate planning and cooperation of all stakeholders and citizens, the city of Ioannina can evolve into an energy-autonomous and sustainable city, adopting RES technologies, with the aim of reducing the carbon footprint in the wider region.

7. CONCLUSION

Climate change was the reason for the planet's shift to sustainable energy sources (solar, wind, hydroelectric), from the burning of polluting fossil fuels, such as lignite and natural gas. Greece's geographical location and climate favor the production of electricity from RES systems, for the creation of a sustainable urban environment in the country. Furthermore, RES are renewed naturally, without the requirement of primary materials, and this results in a country gradually becoming energy independent. However, there is a disadvantage of RES, which is the difference in their efficiency compared to fossil fuels, since weather conditions determine their production, which is covered by increasing the production capacity to produce the same amount of energy.

This study focused on the transition of the city of Ioannina to RES technologies, with the aim of becoming an energy independent city, so that innovative energy production systems contribute to the zero-footprint energy targets set by the European Union. The Ioannina basin

has rich natural resources, which, combined with technological developments in the field of RES, constitute a strong incentive for the sustainable development of the city. However, the energy transition of Ioannina to a sustainable city also requires investments in RES infrastructure, along with political support and financial incentives. Equally important is the social acceptance of the residents of a place for the installation and use of RES energy production systems, by promoting the environmental and economic benefits.

In particular, the installation of RES technologies is accompanied by legal and environmental challenges. These include competition with agricultural land for food production, land-use changes that may lead to biodiversity loss, emissions affecting air quality, and the high initial costs of investment. Addressing such concerns through careful spatial planning and stakeholder dialogue is crucial to ensure long-term acceptance and feasibility. At the same time, the Municipality of Ioannina needs to secure energy autonomy through interoperability policies by modernizing infrastructure, adopting smart grid solutions, and integrating local energy communities.

In conclusion, Ioannina needs to develop an innovative electricity production system by installing various forms of RES, such as solar, wind, hydropower and biomass. Through this approach, the city can achieve energy independence and emerge as a model for RES development among similar-sized mainland Greek cities. Beyond environmental protection, the transition to RES is expected to strengthen the local economy by creating new jobs, reducing energy costs for households and businesses. The University of Ioannina can also play a key role in this process by attracting specialized human resources, advancing scientific research, and supporting innovation in green energy. Ultimately, sustainable energy solutions not only enhance economic and social well-being but also improve public health by reducing pollution and creating a more sustainable urban environment.

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