AGRICULTURAL UNIVERSITY PLOVDIV
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SUSTAINABLE ELECTRICITY GENERATION FROM PHOTOVOLTAIC SYSTEMS

AUTHOR'S ABSTRACT

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I. GENERAL CHARACTERISTICS OF THE DISSERTATION

1. Relevance of the Topic

Energy is a strategic resource of key importance for economic development, industrialization, and the improvement of living standards. In the context of increasing global consumption, the depletion of fossil fuels, and intensifying environmental challenges, the issue of sustainable energy resource management is gaining particular significance. Modern economies are facing the need to transition to a low-carbon development model that ensures economic efficiency, energy security, and environmental protection.

The negative consequences of the traditional energy model, including climate change, pollution, and biodiversity loss, require the implementation of sustainable solutions based on renewable energy sources. In this context, photovoltaic technologies are emerging as one of the most promising directions for clean energy production. They combine environmental benefits, technological flexibility, and opportunities for decentralized generation.

The relevance of the study is also determined by European and national policies aimed at decarbonizing the energy sector, including the European Green Deal and related strategic documents. For Bulgaria, as a country with favorable natural conditions for the development of solar energy, the effective and sustainable deployment of photovoltaic systems is of particular importance.

2. Aim, Object, Subject and Research Tasks

In the context of the global transition to low-carbon energy systems, a critical analysis of the potential of photovoltaic technologies as a key element in the sustainable transformation of the energy sector is of crucial importance. In this regard, the present study is motivated by several factors: the instability and projected depletion of conventional energy sources; the ambitious climate targets of the European Union under the Green Deal; and the growing societal demand for independent, clean, and secure energy sources.

The aim of the study is to assess the sustainability of photovoltaic energy production in Bulgaria through an analysis of technological, economic, and institutional factors influencing the development, implementation, and operation of photovoltaic systems.

The object of the study is the process of sustainable energy production through photovoltaic systems in the context of the Bulgarian and European energy transition.

The subject of the study encompasses the technological, institutional, and economic dimensions that determine the feasibility and long-term sustainability of the implementation of photovoltaic systems.

The research thesis is based on the understanding that photovoltaic systems represent a key element of the sustainable energy transition in Bulgaria, and that their long-term effectiveness and applicability are determined by the interaction between technological, economic, and institutional factors.

To achieve the stated objective, the study addresses the following tasks:

1. Development of a theoretical framework through a review of existing literature on renewable energy and a critical analysis of conceptual approaches to sustainable energy use;
2. Synthesis of European climate and energy strategies, particularly those related to the European Green Deal, and their implications for national-level decarbonization;
3. Presentation of a methodological framework aimed at assessing the effectiveness of solar project implementation;
4. Analysis of trends in the European and Bulgarian energy sectors, including current technological status, production capacity, market structure, and challenges;
5. Evaluation of different types of solar parks in terms of efficiency and impact;
6. Identification of sustainable models for energy production from photovoltaic power plants in Bulgaria;
7. Formulation of conclusions and recommendations for improving the development potential of solar energy in Bulgaria.

3. Research Methods

The methodological framework of the study is based on an integrated research approach combining qualitative and quantitative methods, enabling a comprehensive analysis of the sustainability of photovoltaic systems. Within the theoretical analysis, the method of document analysis is applied to examine the regulatory, strategic, and institutional framework of the energy sector at both European and national levels. This includes the analysis of policies, directives, and strategic documents related to the transition to renewable energy.

For the empirical research, the case study method is employed, allowing for an in-depth examination of specific photovoltaic projects and an assessment of their effectiveness and applicability in real-world conditions. Additionally, unstructured and in-depth interviews with sector experts are conducted to gather qualitative insights into the key factors influencing the development and sustainability of photovoltaic systems.

The assessment of economic efficiency is based on the application of investment analysis methods, including cash flow analysis, calculation of financial performance indicators. These methods allow for the evaluation of returns and risks associated with various investment decisions.

Furthermore, a systemic and comparative analysis is applied to identify key trends, dependencies, and interrelationships in the development of photovoltaic systems in Bulgaria and the European Union. This approach enables the synthesis of results and the formulation of conclusions and recommendations regarding the sustainable development of the sector.

II. MAIN STRUCTURE AND CONTENT OF THE DISSERTATION

CHAPTER ONE: ENERGY RESOURCES – CLASSIFICATION, CHARACTERISTICS, AND TECHNOLOGICAL AND INSTITUTIONAL POTENTIAL FOR SUSTAINABLE UTILIZATION

1.1. Nature and Importance of Energy for Economic Development

Energy is a fundamental factor in the development of modern economies and society as a whole. It underpins all production processes, technological innovations, and socio-economic transformations. Historically, the development of human civilization has been inseparably linked to the discovery, utilization, and efficient use of various energy sources—from biomass and hydropower to fossil fuels and contemporary renewable technologies.

The Industrial Revolution marks a key turning point, during which the use of coal, and later oil and natural gas, created the conditions for accelerated economic growth, urbanization, and technological progress. This process led to the establishment of modern industrial systems but also laid the foundation for a significant dependence on finite natural resources.

In contemporary conditions, energy is no longer viewed solely as a production factor but as a strategic resource that influences economic security, competitiveness, and geopolitical stability. Energy dependence, price volatility, and access to resources have become key challenges for countries and economic systems.

1.2. Classification of Energy Sources and Their Importance

Energy sources are traditionally classified into renewable and non-renewable. Non-renewable sources, including coal, oil, and natural gas, are characterized by limited reserves and a significant environmental impact. Their use is associated with high levels of greenhouse gas emissions, pollution, and degradation of natural resources.

In contrast, renewable energy sources, such as solar, wind, hydropower, geothermal energy, and biomass, are characterized by virtually inexhaustible potential and lower environmental impact. They are playing an increasingly important role in the energy mix of modern economies, contributing to the reduction of the carbon footprint and the enhancement of energy independence.

Among renewable sources, solar energy occupies a particularly important place due to its wide geographical availability, technological flexibility, and potential for decentralized production. The development of photovoltaic technologies enables the conversion of solar radiation into electricity, making them a key component of the energy transition.

1.3. External Effects and Limitations of the Traditional Energy Model

The traditional energy model, based on the use of fossil fuels, is associated with significant external effects that negatively impact the environment and society. Among the most substantial of these are climate change, air, water, and soil pollution, as well as biodiversity loss.

The combustion of fossil fuels leads to the emission of significant amounts of carbon dioxide and other greenhouse gases, contributing to global warming. This, in turn, results in changes in climatic conditions, an increased frequency of extreme natural events, and negative consequences for agriculture, water resources, and human health.

In addition to environmental effects, the traditional energy model also generates economic risks related to the volatility of energy prices, geopolitical conflicts, and dependence on energy imports. This necessitates the transformation of energy systems towards more sustainable and diversified models.

1.4. The Concept of Sustainable Development and the Energy Transition

The concept of sustainable development has become a leading paradigm in modern economics and policymaking. It implies achieving a balance between economic growth, social equity, and environmental protection. In the energy sector, this translates into a transition towards systems that ensure reliable and affordable energy supply with minimal environmental impact.

The energy transition involves processes of decarbonization, increased energy efficiency, and a growing share of renewable energy sources. In this context, photovoltaic technologies are considered one of the most effective tools for achieving sustainable development.

They enable the reduction of emissions, the creation of new economic opportunities, and the stimulation of innovation. At the same time, their implementation requires consideration of a number of factors, including technological constraints, economic efficiency, and institutional support.

1.5. European and National Framework for the Development of Renewable Energy

European Union policies play a key role in promoting renewable energy and sustainable development.

Table 1: Policies and Initiatives Supporting Renewable Energy

Policy/Initiative	Scope	Main Objectives	Mechanisms	Impact on RES
Sustainable Development Goal 7 (SDG 7)	Global (UN)	Universal access to energy by 2030	Targets, national planning	Promotes clean energy
Paris Agreement	Global (UNFCCC)	Limiting global warming below 2°C	Nationally Determined Contributions (NDCs), review mechanisms	Encourages national RES commitments
IRENA (International Renewable Energy Agency)	Global	Advancement of global RES development	Policy support, cooperation	Knowledge and cooperation hub
CEM (Clean Energy Ministerial)	Global	Promotion of clean energy	Cooperation platforms	Supports best practices and innovation
RE100	Corporate	100% renewable electricity	Voluntary commitments	Increases private sector demand for RES
GBEP (Global Bioenergy Partnership)	Global	Sustainable bioenergy	Capacity building, guidelines	Supports bioenergy in low-income countries
European Green Deal	EU	Climate neutrality by 2050	Investments, legislative reforms	Accelerates RES deployment across the EU
Fit for 55	EU	55% emission reduction by 2030	RED III Directive, regulatory updates	Sets national targets
RED III (Renewable Energy Directive)	EU	42.5% RES share by 2030	Binding targets	Promotes sectoral RES growth
EU ETS (Emissions Trading System)	EU	Carbon pricing	Cap-and-trade system	Reduces competitiveness of fossil fuels

Source: Own survey based on regulatory documents

The European Green Deal, the “Fit for 55” package, and renewable energy directives set ambitious targets for reducing greenhouse gas emissions and increasing the share of clean energy. These policies create a framework for the transformation of national energy systems and stimulate investments in new technologies. Bulgaria, as an EU Member State, follows these priorities through the development of national strategies and plans, including the Integrated National Energy and Climate Plan.

Despite favorable natural conditions for solar energy development, the country still lags behind other Member States in terms of renewable technology deployment. The main challenges are related to administrative barriers, limited electricity grid capacity, and the need for infrastructure investments.

1.6. Role of Photovoltaic Systems in the Sustainable Energy Transition

Photovoltaic systems are increasingly recognized as a key element in the energy transition process. They offer a number of advantages, including low operating costs, scalability, and the ability to be integrated across different economic sectors.

At the same time, their sustainability depends on several factors, including technological efficiency, access to financing, the regulatory environment, and public acceptance. Issues related to the life cycle of photovoltaic panels, including their production and recycling, are also of significant importance.

In this context, the application of an integrated approach is necessary, taking into account not only the economic benefits but also the environmental and social implications of deploying these technologies.

1.7. Challenges in the Implementation of Photovoltaic Projects

Despite their undeniable advantages, the implementation of photovoltaic projects is associated with a complex set of social, technical, economic, environmental, and institutional challenges. One of the most debated issues is the so-called “green grabbing,” which refers to the appropriation of land and resources for environmental purposes without sufficient consideration of local rights, livelihoods, and consent (Fairhead et al., 2012). In the context of renewable energy, this is observed in the development of solar parks on agricultural land or common territories, which may lead to social conflicts, particularly in the absence of transparent consultation processes and fair benefit-sharing mechanisms (Corson & MacDonald, 2012; Scheidel & Sorman, 2012; Scheidel et al., 2020). Even within the EU, concerns are growing regarding competition between energy production, agriculture, and biodiversity conservation (IEA, 2024; IRENA, 2022).

A significant group of challenges is related to storage, flexibility, and system integration. Due to the intermittent nature of solar energy, high penetration of photovoltaics can cause voltage fluctuations, frequency instability, and grid congestion, particularly in distribution systems (Lund et al., 2015; IEA, 2023). Although batteries and pumped-storage hydropower are considered key solutions, they are constrained by high capital costs, resource dependence, environmental risks, and geographical limitations (Zakeri & Syri, 2015; Vidal et al., 2013; Harper et al., 2019; IRENA, 2022). Supply chains and dependence on critical minerals are also of major importance, as PV technology production is highly concentrated, particularly in China, increasing geopolitical and resource risks (IEA, 2022; IRENA, 2023; EC, 2023).

Photovoltaic systems also pose environmental challenges throughout their life cycle. Although they generate low emissions during operation, their production is energy-intensive and depends on raw materials whose extraction is associated with habitat loss, pollution, and high resource intensity (Peng et al., 2013; Green et al., 2021; UNEP, 2020). Some technologies involve risks related to hazardous substances, while the growing volume of end-of-life panels requires the development of effective recycling systems and extended producer responsibility schemes (Fthenakis & Kim, 2011; IRENA, 2016; Xu et al., 2018).

Additional economic challenges include price cannibalization, the decline in the market value of solar electricity as its share in the energy mix increases (Hirth, 2013; Cludius et al., 2014; Zhou et al., 2022). This creates revenue uncertainty and complicates investment returns, especially in the absence of mechanisms such as PPAs, CfDs, or storage solutions (Aurora Energy Research, 2021; IEA, 2023).

At the institutional level, legislative and permitting frameworks represent major barriers. Despite the existence of a European regulatory framework, its transposition at the national level is often uneven. In Bulgaria, administrative procedures, overlaps between environmental, construction, and energy legislation, as well as challenges related to grid connection, delay projects and undermine investor confidence (EU, 2022; Petrova & Tsvetkova, 2023; SolarPower Europe, 2022; BNEF, 2023).

Financial constraints, including high upfront costs, complex risk allocation, and unequal access to capital, particularly for smaller actors, municipalities, and energy communities (IRENA, 2022; IEA, 2023; Bauwens et al., 2022; Carley & Konisky, 2020) further compound these challenges. Finally, the increasing digitalization of PV systems introduces cybersecurity risks related to vulnerabilities in inverters, SCADA systems, IoT devices, and supply chains.

This necessitates the implementation of stricter standards, incident-reporting mechanisms, and capacity building to protect energy infrastructure (Liu et al., 2021; Khalid et al., 2022; ENISA, 2022; NIST, 2020; SolarPower Europe, 2022).

CHAPTER TWO: METHODOLOGICAL FRAMEWORK FOR RESEARCH AND ANALYSIS OF THE SUSTAINABILITY OF PHOTOVOLTAIC SYSTEMS

The second chapter of the PhD thesis is related to the methodological framework applied to outline the analysis of sustainable generation of electricity from photovoltaic systems. The methodological framework is built on an integrated research approach that combines qualitative and quantitative methods, enabling the simultaneous examination of the macroeconomic, institutional, and project-applied aspects of photovoltaic technology development. This approach makes it possible to follow the driving forces, barriers, and effects of the implementation of photovoltaic systems both at the level of policies and regulations and at the level of specific investment decisions.

2.1. Document Analysis

The first main method applied in the study is **document analysis**. It is defined as a qualitative research technique for the systematic review and interpretation of documents with the aim of extracting meaning, developing understanding, and generating empirical knowledge (Bowen, 2009). In the context of sustainable photovoltaic energy production, this method is particularly valuable because it allows the political, regulatory, and strategic environment shaping the opportunities for the implementation and development of photovoltaic systems in the European Union and Bulgaria to be examined.

In the PhD thesis, document analysis covers EU legislative texts, national energy and climate plans, strategic documents of the European Commission, as well as reports from international organizations such as IRENA, IEA, and SolarPower Europe. Through these sources, changes in policies, strategic priorities, and support models for renewable energy are traced. Bowen (2009) emphasizes that document analysis enables the identification of trends, changes over time, and thematic interconnections, which is essential when studying long-term goals such as climate neutrality and decarbonization.

In the field of energy transitions, this approach is also used by Sovacool (2014) and Geels et al. (2016), who demonstrate that document analysis has strong potential for revealing the frameworks through which sustainability is understood, defined, and applied in practice. In this way, document analysis serves as the foundation for building the macro-framework of the study and for linking policy decisions with the subsequent analysis of specific projects and investments.

2.2. Case Study Analysis

The second main methodological approach is **case study analysis**, which is widely recognized as suitable for the in-depth examination of real phenomena in their specific context. According to Zainal (2007), this method allows for a detailed examination of data within a clearly defined contextual boundary, which is particularly useful for complex processes such as the development of photovoltaic systems. Unlike quantitative studies that seek generalizability, case study analysis is directed towards depth, contextual understanding, and interpretation of the interrelationships between various factors.

Krusenvik (2016) notes that this method is particularly suitable for examining a small number of units across a wide range of variables, making it applicable in the evaluation of specific investment projects, self-consumption models, electricity sales, or hybrid solutions. According to Baxter and Jack (2008), the main advantage of this approach is that it allows the integration of contextual conditions, which are often decisive for the proper understanding of the studied phenomenon. This is especially important in photovoltaic projects, where the market environment, grid access, location, investment costs, and regulatory framework strongly influence the final outcome.

Several case studies are used in the dissertation, enabling the applicability of different investment models for photovoltaic systems to be traced. Methodologically, this approach follows the logic of Yin (2002; 2004), according to whom case studies may be either single or multiple, with the latter providing opportunities for comparison, replication logic, and broader analytical validity. The use of multiple data sources within the case study—documents, financial indicators, interviews, and technical parameter, further enhances the reliability of the analysis (Tasci et al., 2020). Despite the method's limitations related to a lower degree of generalizability and the possibility of interpretive bias, Flyvbjerg (2006) emphasizes that, with sufficient methodological rigor, case study analysis remains an extremely valuable tool for generating theoretical and practical knowledge.

2.3. Unstructured and In-Depth Interviews

The third component of the methodological framework is the use of **unstructured and in-depth interviews** as qualitative research techniques through which expert knowledge, perspectives, and assessments of stakeholders are extracted. These methods are particularly suitable for exploratory and interpretive studies in fields characterized by high dynamics, multiple actors, and complex interactions, such as renewable energy.

Unstructured interviews are characterized by an open format and the absence of a strictly fixed questionnaire, allowing for a freer flow of conversation and the emergence of unexpected but significant themes (Fontana & Frey, 2005). In the PhD thesis, this method is directed toward investors, project developers, grid operators, and representatives of local communities in order to reveal their perceptions regarding the regulatory environment, administrative barriers, social acceptance, and institutional constraints. Kvale (2007) emphasizes that unstructured interviews are particularly suitable for exploring the “lifeworld” of participants and for the co-construction of meaning, rather than merely testing predefined hypotheses.

In-depth interviews, in turn, represent a more systematized form of qualitative data collection aimed at eliciting detailed narratives, evaluations, and interpretations (Boyce & Neale, 2006). Within the framework of the study, they are organized around several key thematic areas: strengths and weaknesses of existing policies, economic and technical feasibility of investments, social and environmental effects, as well as the role of innovation, digitalization, and grid integration. According to Patton (2002), this method is particularly effective for understanding the way key actors experience and influence the processes under consideration. The combination of unstructured and in-depth interviews allows for a balance between analytical focus and freedom of response, thereby increasing the interpretive validity of the study (Mason, 2002).

2.4. Investment Project Evaluation

A substantial part of the second chapter is related to the evaluation of investment projects, as the sustainability of photovoltaic systems cannot be examined solely from the perspective of environmental and policy aspects, but also requires an assessment of their economic and financial viability. In this regard, a multicriteria investment evaluation framework has been developed, integrating financial, technical, environmental, and social dimensions.

2.5. Financial Profitability Indicators

To assess economic efficiency, the dissertation considers both static and dynamic methods. Among the static indicators are the payback period and the accounting rate of return. These methods are easier to calculate and interpret and may be useful for forming an initial assessment, particularly when the contracting authority or investor does not possess specialized knowledge in investment analysis. However, their limitations are clearly defined: they do not account for the time value of money and often neglect the distribution of cash flows over time (Boardman et al., 2014).

For this reason, the primary emphasis is placed on dynamic methods, which incorporate the time value of money and provide a more reliable assessment of the project's long-term efficiency. Of greatest importance are the Net Present Value (NPV) and the Internal Rate of Return (IRR). NPV is regarded as the preferred method, as it measures the absolute increase in value for the investor and captures cash flows throughout the entire life cycle of the project (Damodaran, 2012; Brealey, Myers, & Allen, 2020). IRR, in turn, is valuable because it presents profitability in relative terms; however, it may lead to methodological issues in cases of unconventional cash flows or when comparing mutually exclusive projects of different scales (Ross et al., 2019).

The second chapter establishes the methodological foundation of the study by combining document analysis, case study analysis, interviews, and investment appraisal into a unified analytical framework. This integrated approach enables the examination of the political and regulatory environment, institutional mechanisms, stakeholder perspectives, and the economic viability of specific photovoltaic projects. It is precisely through this methodological framework that the prerequisites are created for a robust empirical investigation of the sustainability of photovoltaic systems and for the formulation of scientifically grounded conclusions and recommendations.

CHAPTER THREE: INVESTMENTS IN PHOTOVOLTAIC SYSTEMS. ANALYSIS SUSTAINABILITY IN BULGARIA

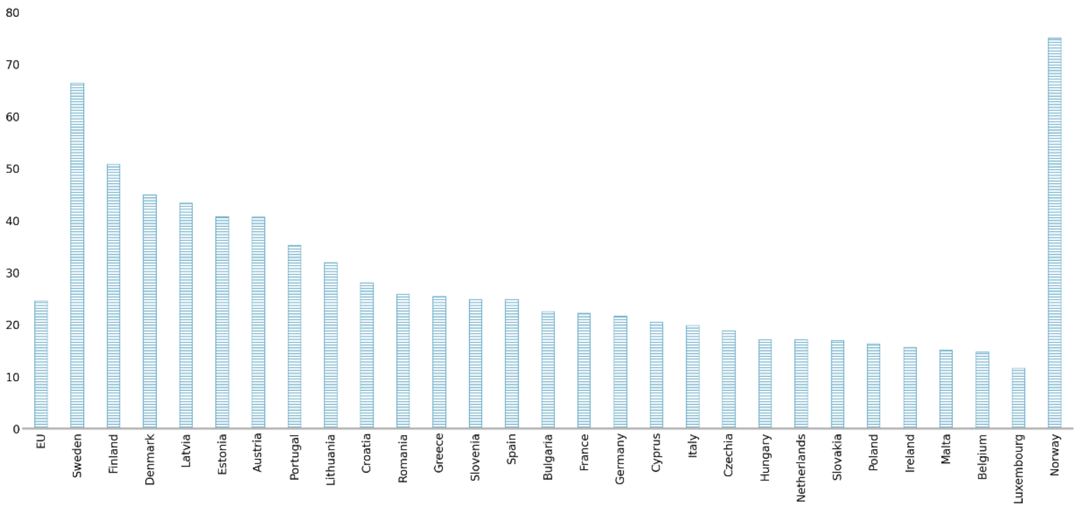
The third chapter aims to provide an empirical validation of the formulated research thesis through the analysis of investment projects, market trends, and financial indicators characterizing the development of photovoltaic systems in Bulgaria. It presents the empirical framework of the study through an examination of four real photovoltaic projects covering different scales and business models, from self-consumption systems to utility-scale plants oriented toward electricity sales. By applying investment analysis and scenario modelling, their economic efficiency is assessed, with the results demonstrating that photovoltaic investments are economically viable and possess significant potential for sustainable development. The analysis highlights the crucial importance of scale, market conditions, and risk management for achieving long-term efficiency, thereby confirming the research thesis regarding the key role of photovoltaic systems in Bulgaria's sustainable energy transition.

3.1. Role and Importance of Renewable Energy in the Energy Mix of the EU and Bulgaria

Under conditions of an accelerated energy transition and intensified decarbonization policies, renewable energy sources (RES) are becoming a key instrument for achieving energy security, reducing dependence on fossil fuels, and limiting greenhouse gas emissions.

According to the latest Eurostat data for 2023, renewable energy accounted for 24.5% of the EU's gross final energy consumption. Among Member States, Sweden ranked first with 66.4%, followed by Finland with 50.8% and Denmark with 44.9%. The lowest shares were recorded in Luxembourg (11.6%), Belgium (14.7%), and Malta (15.1%).

Figure 1: Share of Energy from RES in Gross final energy consumption, 2023 (%)



Source: Eurostat

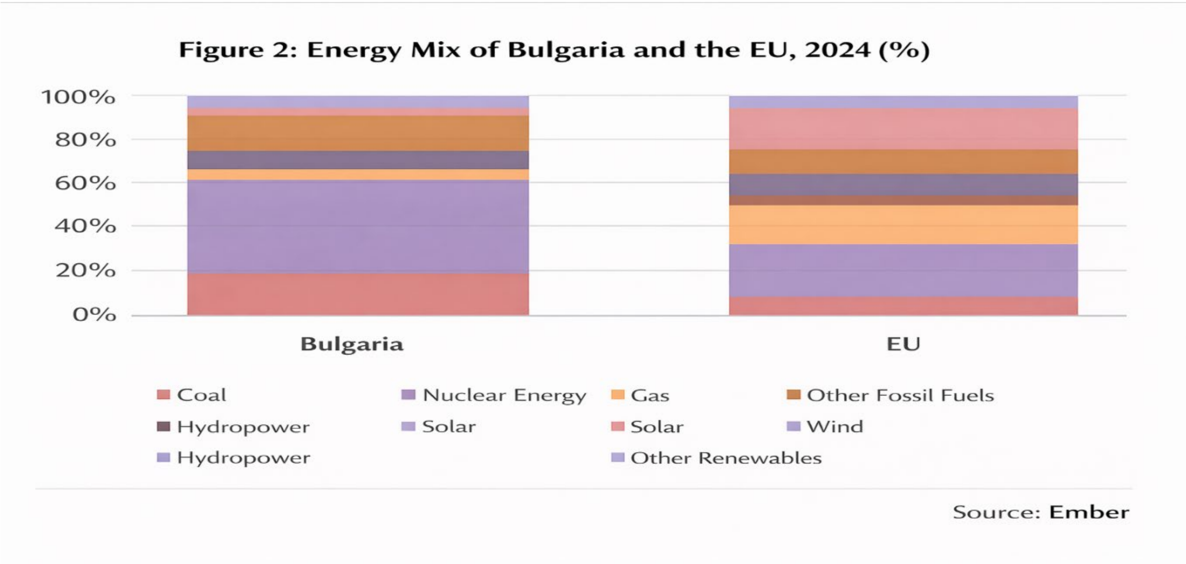
Among these technologies, photovoltaic systems occupy a leading position due to their technological maturity, rapidly declining costs, and broad applicability at both industrial and decentralized scales.

Bulgaria remains around the EU average and has slightly exceeded it in recent years, showing growth over the last two years. However, the transition toward green energy remains a significant challenge. Recent years have seen substantial growth in the shares of wind and solar energy, yet the country is progressing from a relatively low starting base.

The data indicate a gradual transformation of Bulgaria's energy mix over the past decade, with renewable sources increasingly displacing non-renewable ones. Nevertheless, the country's dependence on fossil fuels remains substantial. A particularly notable feature is that over 80% of fuel-based electricity generation continues to be formed by coal**,** which is widely recognized as one of the largest contributors to atmospheric air pollution.

In the context of electricity generation from coal, it accounts for approximately 10% of the total energy mix of the European Union, while Bulgaria demonstrates a considerably higher degree of dependence. At the same time, natural gas forms around 16% of electricity production in the EU compared to only 5% in Bulgaria, further emphasizing the structural differences in the energy systems and the strategic significance of accelerating photovoltaic deployment in the Bulgarian context.

Figure 2: Energy Mix of Bulgaria and the EU, 2024 (%)



Source: *Ember*

Therefore, the EU demonstrates a more diversified and balanced energy mix, whereas Bulgaria's energy structure remains strongly dominated by coal**.**

Nuclear energy plays a central role in electricity generation in both the EU and Bulgaria. However, its significance is considerably greater in the Bulgarian context.

Hydropower contributes 13% to electricity generation in the EU, compared to 8% in Bulgaria, reflecting the comparatively lower capacity for utilizing hydroelectric resources in the country. Solar energy accounts for 11% of the EU mix and 14% in Bulgaria, thus slightly exceeding the EU average.

Wind energy, which constitutes 18% of electricity generation in the EU, represents only 4% in Bulgaria**.** This substantial difference indicates untapped wind energy potential in the country. Other renewable sources, such as biomass and geothermal energy, account for 5.8% of the EU energy mix and 4.9% in Bulgaria, showing only a marginal difference.

In summary, Bulgaria exhibits higher relative shares of coal, nuclear energy, and solar energy compared to the EU average. At the same time, the EU demonstrates significantly higher shares of gas, wind, hydropower, and other renewable energy sources. These differences underline the structural divergences in the energy mix of Bulgaria and the EU, with important implications for future strategies of energy diversification and sustainability.

Bulgaria's energy mix is dominated by coal and nuclear energy. Solar energy performs comparatively well, yet wind and hydropower remain underdeveloped. Bulgaria therefore demonstrates less diversity in its energy structure and significant potential for the development of clean technologies**,** particularly wind and hydropower, compared to the EU-27.

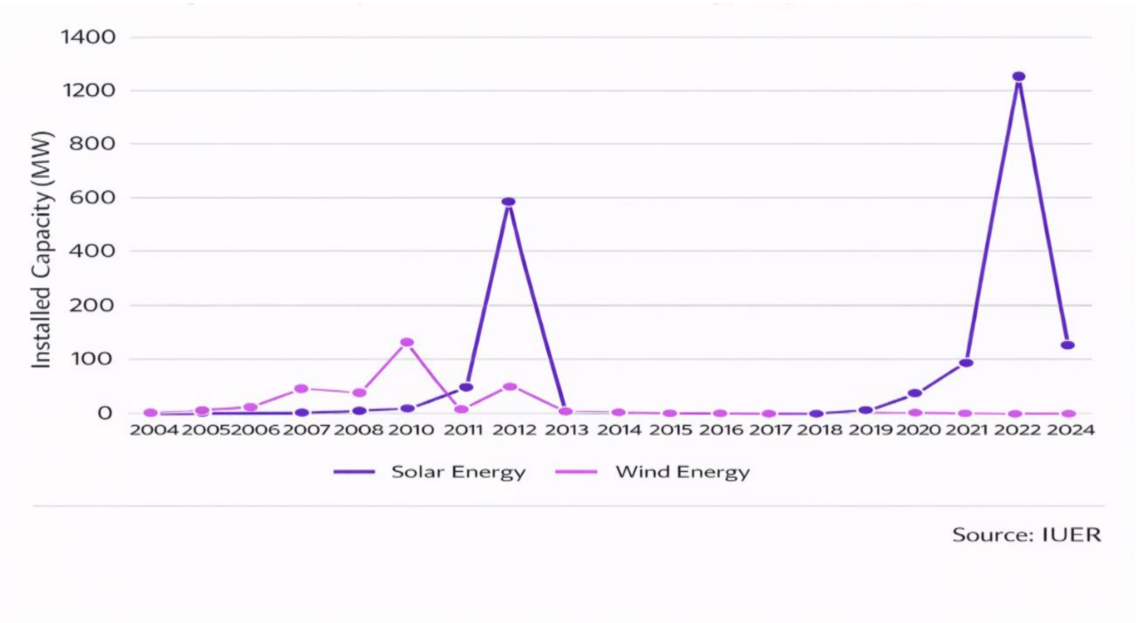
3.2. Current State of the Photovoltaic Energy Production Sector in Bulgaria

Bulgaria has a high solar irradiation potential, particularly in the southern part of the country. The country began expanding renewable energy in 2007, with the largest share initially coming from hydropower. Solar energy deployment started in 2009 and reached a total of 100 megawatts (MW) by 2011. However, subsequent installations slowed significantly, with only around 12 MW added between 2013 and 2014, and the capacity did not increase substantially until 2020.

According to data from the Institute of Hydrology and Meteorology at the Bulgarian Academy of Sciences, the country's solar energy potential is estimated at approximately 12,995 million metric tons of oil equivalent. It is estimated that Bulgaria has never utilized its solar capacity to its full potential. Such a high potential is expected to provide significant future market opportunities for solar energy companies. The main drawback remains the relatively high installation costs, which continue to limit market entry for new companies. In order to overcome this barrier, the government has updated its investment promotion policies.

The data on newly installed solar and wind capacities reveal divergent trends. Clearly distinguishable phases of growth, stagnation, and revival can be observed, closely linked to policy developments, economic incentives, and technological maturity.

Figure 3: Newly Installed Renewable Energy Capacities by Year



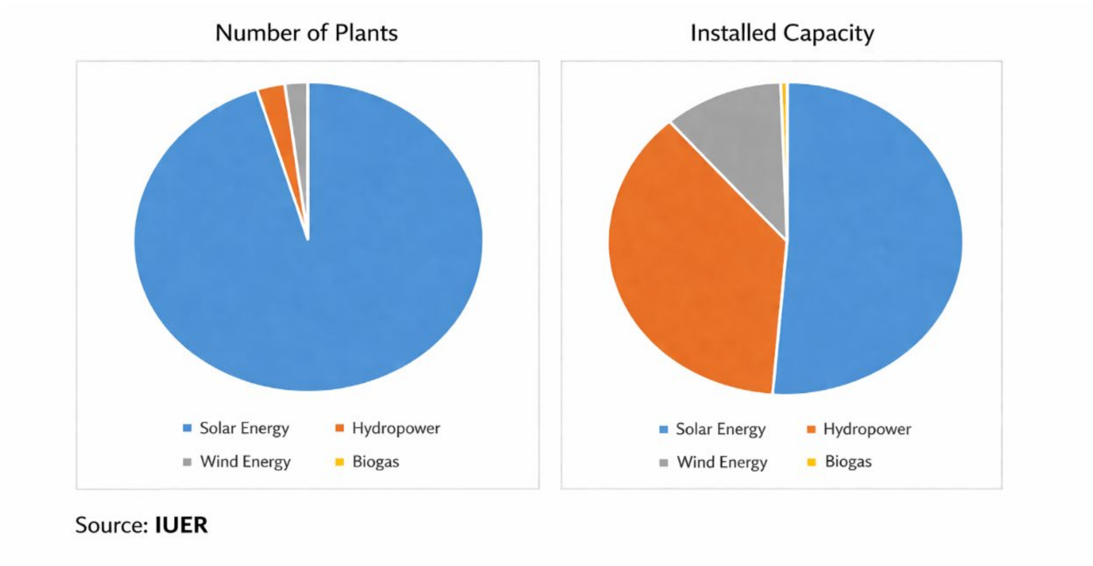
Source: Institute for Sustainable Energy Development (IUER)

The deployment of solar energy in Bulgaria can be divided into three stages: **(1) Initial phase (2004–2010):** This period was characterized by minimal capacity additions. The slow uptake can be explained by high investment costs, limited technological diffusion, and the absence of targeted national support schemes. **(2) Second phase (2011–2012):** A sharp increase was observed in 2012, when installed capacity reached approximately 800 MW. This trend is related to the introduction of feed-in tariffs and alignment with the European Union's renewable energy targets (EU, 2010). **(3) Third phase (2013–2024):** Following the withdrawal of subsidies and regulatory changes in 2013, solar installations declined dramatically and remained at low levels until 2020. From 2021 onwards, however, a second wave of growth began, peaking in 2023 with more than 1,300 MW of new capacity. This revival is aligned with the EU Green Deal and the increased availability of low-cost photovoltaic (PV) technologies (IEA, 2023). The shift reflects Bulgaria's strategic turn toward solar energy as a dominant pillar of its decarbonisation efforts.

In contrast, wind energy in Bulgaria experienced a more modest and shorter growth cycle. Wind installations grew steadily, peaking in 2011 at approximately 250 MW. This period reflected growing investor confidence in wind technologies and the initial implementation of national support mechanisms. After 2011, however, additional wind capacity declined sharply and remained practically stagnant. Several factors may explain this trend, including restrictive spatial planning regulations, public opposition in certain regions, and a policy shift toward solar photovoltaic systems (IRENA, 2022). In addition, lower capacity factors and higher upfront costs may have made wind projects less attractive compared to solar alternatives.

The contrasting trends in solar and wind deployment reflect the broader dynamics of Bulgaria's energy policy. The dominance of solar energy, particularly after 2020, suggests a strategic reorientation toward technologies that offer shorter deployment times, declining costs, and strong alignment with EU financing mechanisms. Furthermore, the data underline the critical role of regulatory stability and market incentives in stimulating renewable energy investments.

Figure 4: Number of Renewable Energy Plants in Bulgaria and Installed Capacity by 2024



Source: IUER

The number of renewable energy plants demonstrates the dominance of solar energy, which accounts for the majority of installed renewable capacity. This distribution indicates the rapid deployment of photovoltaic systems across the country, driven by opportunities arising from the EU Green Deal and the National Recovery and Resilience Plan (Ministry of Energy, 2022). However, such a high concentration raises concerns regarding seasonal and daily variability, given the intermittent nature of solar energy generation.

On the other hand, the installed capacity data indicate a more balanced contribution to actual electricity production. While solar energy still holds the largest share, it is followed by hydropower and wind energy, while biogas contributes only marginally.

This discrepancy between installed capacity and actual production highlights a key reality in energy planning: installed capacity does not directly translate into energy output. This underscores the importance of a diversified energy mix. Although Bulgaria's strategy has rightly prioritised solar deployment due to its cost-effectiveness, the data show that hydropower and wind remain indispensable for maintaining grid stability and ensuring year-round renewable energy supply.

Furthermore, the small but notable role of biogas suggests an underutilised resource with considerable growth potential, particularly in the context of the circular economy and the valorisation of agricultural waste.

3.3. Empirical Analysis of Photovoltaic Projects

Within the empirical part of the study, four photovoltaic projects were examined, reflecting different investment models, scales, and implementation objectives. The selection of these case studies makes it possible to observe how the theoretical concepts of sustainability and economic efficiency is implemented in a real environment, while also enabling a comparative analysis of different types of photovoltaic systems**.**

The first case concerns a photovoltaic power plant with a capacity of 8.64 MW, aimed at electricity generation and sale. The analysis demonstrates a clearly positive dynamic in economic performance, with revenues increasing significantly, from BGN 573 000 to BGN 1,227 000. At the same time, the project moves from an initial loss of BGN –45 000 to a profit of BGN 170 000**.** These results confirm that large-scale photovoltaic investments can achieve high economic efficiency, particularly under favorable market conditions.

The second case examines a photovoltaic self-consumption system with the possibility of future sale of excess energy**.** Here, the main effect is expressed less in the generation of direct revenues and more in the reduction of electricity costs. The analysis shows that the system covers approximately 30–40% of the enterprise's energy consumption, leading to increased energy independence and improved cost efficiency. This model is characterized by lower risk**,** as it is less dependent on market fluctuations.

The third case study involves a small photovoltaic plant with a capacity of 50 kWp**,** entirely oriented toward electricity sales. The results indicate that the project remains sustainable under different scenarios, with the Internal Rate of Return (IRR) varying between 6% and 22%, while the payback period ranges from 5 to 10 years. This demonstrates that even small-scale projects can be economically justified, although they are more sensitive to external factors.

The fourth case presents a 500 kW photovoltaic project**,** also oriented toward electricity sales. This project demonstrates the highest profitability among the analyzed cases, with an IRR reaching 10–27% and a payback period between 4 and 9 years. This confirms that medium-scale projects may achieve an optimal balance between investment risk and return**.**

Overall, the empirical analysis demonstrates that photovoltaic investments are economically viable and possess significant potential for sustainable development. At the same time, the results clearly show that their effectiveness depends on several factors, including project scale, chosen business model, market conditions, and natural circumstances**.**

Table 2: Summary of the case studies

Case	Project Type	Capacity	Main Objective	Financial Results	Key Findings
Case 1	Large PV Plant	8.64 MW	Electricity sale	Revenue: BGN 573k → 1,227k; from loss to profit	High profitability, strong market dependence
Case 2	Self-consumption	–	Cost reduction	Covers 30–40% of consumption	Lower risk, high energy independence
Case 3	Small PV Plant	50 kWp	Sale	IRR: 6–22%; PBP: 5–10 years	Sustainable project, but factor-sensitive
Case 4	Medium PV Plant	500 kW	Sale	IRR: 10–27%; PBP: 4–9 years	Highest profitability, strong risk-return balance

Source: Author's own research based on information provided by the companies.

Self-consumption projects provide greater stability and predictability, whereas projects oriented toward electricity sales offer higher profitability but are associated with greater risk. In this context, the successful implementation of photovoltaic systems requires a balanced approach that considers economic, technological, and market parameters simultaneously**.**

CHAPTER FOUR: PROSPECTS FOR THE DEVELOPMENT OF SOLAR ENERGY

The fourth chapter builds upon the theoretical and empirical analyses carried out in the previous sections by placing emphasis on the future prospects for the development of solar energy and on the formulation of applicable conceptual models for the sustainable deployment of photovoltaic systems. In the context of the deepening energy transition and the growing importance of renewable energy sources, photovoltaic technologies are becoming established as a key component of decarbonization strategies and the enhancement of energy independence.

The analysis is based on the strategic documents of the European Union, in particular the European Green Deal, the Integrated National Energy and Climate Plans (NECPs), as well as the results of the empirical analysis of investment projects examined in Chapter 3. In this sense, the fourth chapter performs a synthesizing function, deriving models that combine economic efficiency, technological applicability, and institutional compatibility.

4.1. Strategic Context and the Role of Photovoltaic Systems

Within the European Union, the development of renewable energy is directly linked to the objectives of climate neutrality by 2050 and the reduction of greenhouse gas emissions. Bulgaria, as part of this process, must significantly increase the share of renewable energy sources in its energy mix, with solar energy being considered one of the most significant resources due to favorable natural conditions and relatively low technological barriers.

The Integrated National Energy and Climate Plan (INECP) outlines clear priorities related to the accelerated deployment of photovoltaic capacity, the development of decentralized systems, and the stimulation of investments in energy efficiency. In this context, photovoltaic systems are not merely a technological solution, but rather an instrument for the structural transformation of the energy sector.

4.2. Conceptual Models for the Sustainable Development of Photovoltaic Systems

Based on the analysis of investment projects and the existing market and regulatory conditions, three main conceptual models are identified, defining the operating logic and economic rationale of photovoltaic systems.

Self-Consumption Model

The self-consumption model is aimed at covering the internal energy consumption of enterprises or households. Its main economic logic is based on the reduction of electricity costs rather than on revenue generation.

The results of the empirical analysis indicate that this model allows the coverage of a significant share of consumption (30–40%), leading to cost stabilization and reduced dependence on external suppliers. This makes it particularly suitable in conditions of high electricity price volatility**.**

At the same time, the limitations of the model are associated with the inability to efficiently commercialize excess energy, which restricts the potential for generating additional revenues.

Hybrid Model

The hybrid model represents a combination of self-consumption and electricity sales. Part of the generated energy is used for internal needs, while the surplus is sold on the market.

This model is characterized by greater flexibility and allows the optimization of both costs and revenues. From the perspective of investment efficiency, it combines the advantages of the two extreme models and ensures better risk distribution.

Its main drawback is related to higher initial investments, especially when there is a need to deploy energy storage systems and intelligent energy management solutions.

Feed-in Model (Sales-Oriented Model)

The model fully oriented toward electricity sales is applied mainly in larger photovoltaic projects**.** Its primary objective is the generation of revenues through participation in the electricity market**.**

Table 3: Comparative Characteristics of the Conceptual Models

Model	Main Objective	Key Advantage	Main Risk / Limitation
Self-consumption	Covering own consumption	Reduces costs and dependence on the grid	Limited revenues from excess generation
Hybrid model	Balance between consumption and sales	Flexibility and resilience	Higher CAPEX
Feed-in model	Electricity sales	High profitability and stable cash flows	Market and regulatory risk

Source: Author's own research based on expert assessments

The empirical results from Chapter Three demonstrate high levels of profitability under this model, including significant values of the Internal Rate of Return (IRR) and relatively short payback periods. This makes it particularly attractive for investors.

However, the main risk is associated with its dependence on market prices, the regulatory framework, and access to the electricity transmission grid**.**

The comparative analysis demonstrates that the choice of model should be aligned with the specific characteristics of the project, including its scale, consumption structure, and market environment**.**

4.3. Decentralized Models and Innovations

In addition to traditional conceptual models, contemporary trends in the development of photovoltaic systems include decentralized solutions such as energy communities and agrivoltaics.

Rural areas should benefit from the new economic opportunities created by renewable energy (EC, 2021). Renewable energy sources are particularly suitable for decentralized and local energy production through the expansion of small-scale energy projects aimed at promoting sustainable energy generation (Caramizaru et al., 2020).

In this context, the concept of energy communities has emerged. Although it began to take shape in the 1990s, it has entered the political agenda more prominently in recent years. Directive (EU) 2018/2001 and the Electricity Market Directive (EMD, Directive (EU) 2019/944) introduced new electricity market rules to enable Europe to achieve its climate and energy objectives and to facilitate the more active participation of citizens, public authorities, and small and medium-sized enterprises (SMEs) through energy communities. EU law recognizes two main models: renewable energy communities and citizen energy communities under the EMD (RECAH, 2023a; Abouaiana, 2022).

Renewable and citizen energy communities could make a substantial contribution to the energy transition in line with the initiatives and objectives of the European Green Deal. They can play a particularly important role in renewable energy generation and in promoting energy efficiency (RECAH, 2023a, 2023b), including the renovation of buildings. Energy communities involve the engagement of local authorities, businesses, and citizens, together with the integration of key policies related to the Common Agricultural Policy, rural development, and farm modernization. The active participation of local authorities and citizens, combined with the implementation of local development plans, can help ensure that rural areas are not left behind, thereby fostering a just and inclusive energy transition. Well-designed energy communities can facilitate access to stable and affordable prices while ensuring energy autonomy, resilience, and security.

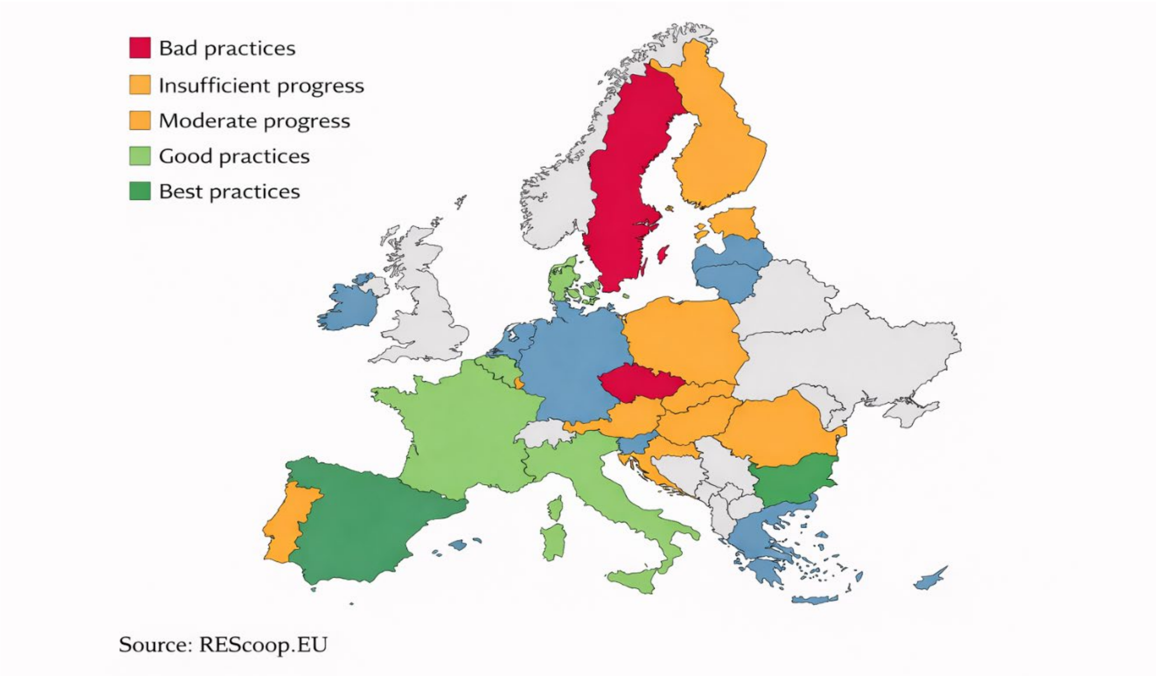
In general, the benefits of energy communities have been systematized in the reports of the JRC (2020) and IRENA (2021). These include:

- Socio-economic benefits

- Energy and financial security
- Citizen participation in decision-making
- Awareness raising and mobilization

Energy communities also serve as local incubators for climate literacy and sustainability awareness. They frequently cooperate with schools, non-governmental organizations, and municipalities, thereby multiplying their mobilization effect (IRENA, 2021).

Figure 5: Assessment of Member States' Efforts to Develop an Enabling Framework for Renewable Energy Communities as of January 2024



EU policy initiatives and regulatory frameworks support the development of decentralized energy systems, and to varying degrees these have been transposed into the national policies of Member States. Member States are expected to promote the clean energy transition through existing or new support schemes while ensuring that energy communities can participate on equal terms with larger players in the electricity market.

However, many European countries, including Bulgaria, face challenges in the effective implementation of laws promoting renewable energy sources.

Agrivoltaic systems are emerging as an innovative dual land-use model that combines agricultural production with renewable energy generation. According to the Solar Europe Handbook (2024), they create additional income, employment, and tax revenues for farms, while simultaneously reducing energy costs and dependence on volatile electricity prices. A major advantage lies in their ability to improve the resilience of agriculture to climate risks, including droughts, high temperatures, floods, and hail, through shading, reduced evaporation, and improved water retention.

The study systematizes three main business models:

- a model in which the energy producer owns and operates the photovoltaic system;
- a farmer-owned and farmer-operated model; and
- a joint ownership model.

The first model is the most widespread, as it allows financial and technical risks to be borne by a specialized investor, while the farmer retains revenues from agricultural activity. Joint ownership is emerging as a promising and inclusive model, particularly in the context of energy cooperatives and community-based initiatives.

For Bulgaria, the potential of agrivoltaics is considerable, especially in the southern and central regions. However, its development remains constrained by a restrictive legal framework, complex administrative procedures, the absence of specific incentives, and limited grid capacity. This necessitates legislative reforms, the introduction of targeted financial instruments, pilot projects, and clear grid access rules. With adequate institutional support, agrivoltaics could become a key instrument for a sustainable energy transition and rural development in Bulgaria.

4.4. Institutional Projections for the Development of Renewable Energy in the EU and Bulgaria

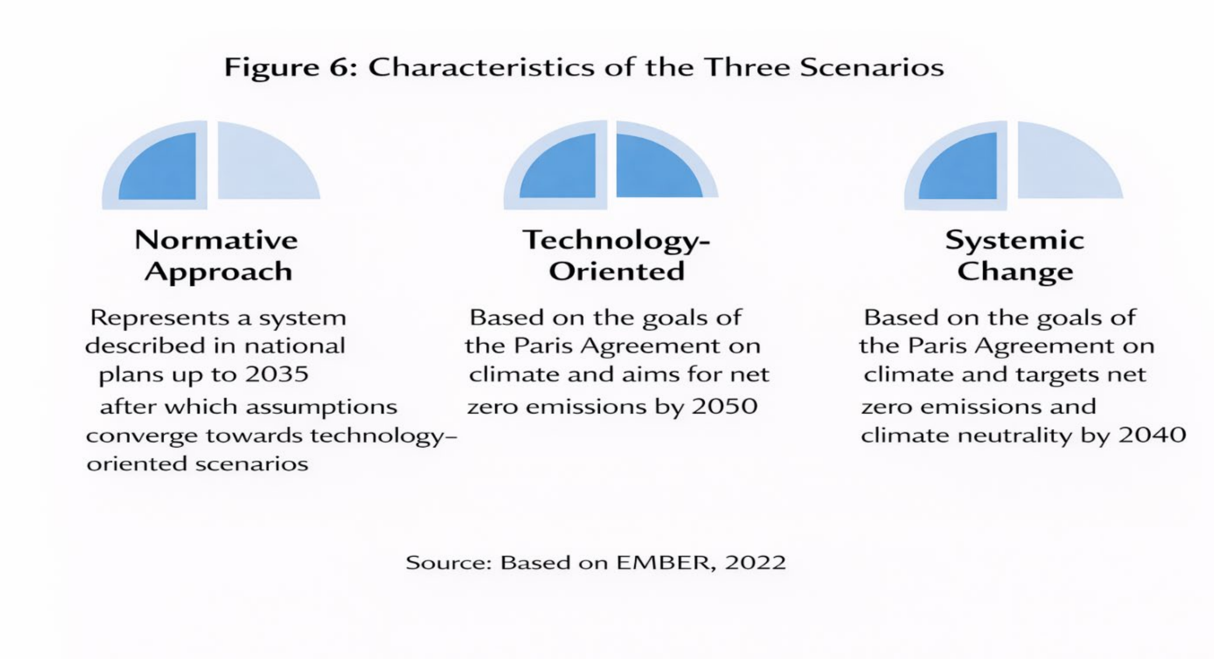
The Ember report outlines three main scenarios for the development of renewable energy in Europe and Bulgaria: a policy-based scenario, a technology-driven scenario, and a system transformation scenario.

The policy-based scenario follows the current government plans until 2035 and is characterized by the lowest level of ambition. Beyond this period, development is modeled toward net-zero emissions and minimum costs by 2050.

The technology-driven scenario envisages faster electrification, higher energy savings, and the achievement of a net-zero energy system by 2050, while allowing investments in new nuclear energy and carbon capture technologies.

The most ambitious is the system transformation scenario, which foresees a net-zero energy system as early as 2040, an accelerated phase-out of coal by 2030, other fossil fuels by 2035, and greater energy savings resulting from behavioral changes and the application of circular economy principles.

Figure 6: Characteristics of the Three Scenarios



Source: Based on EMBER, 2022

According to the analysis, total electricity generation in Europe by 2035 increases substantially under the two more ambitious scenarios, while the share of clean energy reaches 94% under the technology-driven scenario and 96% under the system transformation scenario, compared to approximately 86% under the policy-based scenario.

Wind and solar energy become the dominant sources of electricity generation, with their combined share reaching 52% in the policy-based scenario, 68% in the technology-driven scenario, and 78% in the system transformation scenario.

Bulgaria is among the countries with high potential for solar energy development, yet its national targets and policies remain insufficiently ambitious and do not allow for the full utilization of this resource.

The analysis shows that Europe must significantly accelerate the pace of new wind and solar capacity deployment, as under the policy-based scenario only 45–65% of the required combined capacity will be secured by 2035. This highlights the need for more ambitious national policies and more targeted investments, especially in countries such as Bulgaria, where there is a strong economic and resource base for expanding clean energy.

The fourth chapter demonstrates that the sustainable development of photovoltaic systems requires an integrated approach that combines different conceptual models and takes into account the specific characteristics of each investment. The analysis shows that there is no universally optimal solution, and that efficiency depends on the proper combination of technological, economic, and institutional factors.

III. CONCLUSIONS AND RECOMMENDATIONS

Based on the research and the analysis, the following main conclusions and recommendations can be highlighted:

- The energy sector is fundamental to economic development and exerts a substantial impact on the environment. The research demonstrates that energy is not merely a physical resource, but rather a strategic determinant shaping economic growth, industrial structure, and geopolitical stability. Historically, industrialization, globalization, and urbanization have been accompanied by an increasing dependence on energy resources, predominantly fossil fuels. This has generated a range of environmental and social externalities, including climate change, pollution, and social inequality in access to resources.
- The growing level of energy consumption and the exhaustibility of non-renewable resources require a transition toward a sustainable energy sector, based on decarbonization, efficiency, and decentralization. In this context, the concept of sustainable development, together with its goals, the Paris Agreement, and the European Green Deal provide the normative framework for this transition.
- Renewable energy sources can be regarded as the foundation of the energy transformation. In this regard, solar energy plays a particularly important role, as it offers high energy security, low external costs, and potential for innovative business models, including energy cooperatives and agrivoltaic solutions.
- The legislative framework plays a substantial role in the development of photovoltaic energy. Policies such as the European Green Deal, REPowerEU, RED III, and broader decarbonization strategies define ambitious objectives and provide mechanisms for their achievement.
- Renewable energy is a major driver of the EU's transition toward a sustainable low-carbon economy. Progress toward the 2030 target of at least 42.5% renewable energy contributes to reducing greenhouse gas emissions, increasing energy security, and creating green jobs. For Bulgaria, the transition to renewable energy is a priority. Although its share remains below the EU average, investments in solar technologies are generating measurable progress. The country possesses untapped potential in both solar and wind energy, which may strengthen energy independence and regional

development. The integration of renewable energy is therefore crucial for achieving climate objectives and reducing dependence on imported fossil fuels.

- The contribution of solar energy to the EU energy mix continues to grow, driven by technological advancement and supportive renewable energy policies. In countries such as Germany, Spain, and Italy, solar energy has become a central pillar of the transition toward clean energy.
- Bulgaria’s energy mix remains largely dependent on coal and nuclear energy. Solar energy is relatively well developed, while wind and hydropower continue to lag behind. Bulgaria therefore exhibits a less diversified energy structure and significant potential for the further development of clean technologies.
- The solar energy market in Bulgaria is expanding, yet it continues to face structural barriers. Despite the continuous increase in installed capacity and investor interest, Bulgaria’s solar market remains comparatively underdeveloped relative to the EU. The study reveals that this is largely due to administrative obstacles, regulatory uncertainty, and limited grid capacity. Although Bulgaria’s overall solar potential is considerable, its realization will require both legal reforms and targeted financial incentives.
- Rural areas contain unrealized opportunities for solar energy development. The analysis highlights the untapped potential of rural regions in both the EU and Bulgaria for the implementation of solar projects. The study suggests that well-designed policies and support mechanisms for rural solar development could stimulate local economies while simultaneously supporting national climate goals.
- The analyzed case studies demonstrate the diversity of solar energy investment projects in Bulgaria, ranging from small self-consumption systems to large-scale projects. These studies reveal that financial outcomes are strongly dependent on factors such as project size, access to financing, local electricity demand, and grid connection conditions.
- Projects oriented toward self-consumption provide long-term savings and energy autonomy. By contrast, projects designed primarily for electricity sales demonstrate lower initial risk and more stable returns.
- Large solar parks developed for electricity export to the grid are more exposed to market risks and technical barriers, such as limited grid capacity. These projects also face longer permitting periods and higher upfront costs. The findings indicate that improving access to grid infrastructure and simplifying permitting procedures are essential for the expansion of this segment of the photovoltaic market.

- Different development scenarios have been identified, on the basis of which distinct trends in the evolution of renewable energy in Europe, and particularly in Bulgaria, can be outlined. The normative scenario follows the existing national energy plans until 2035 and is associated with the lowest level of ambition, targeting net-zero emissions in the energy sector and minimum costs by 2050. The technology-oriented pathway envisages a zero-emission energy system by 2050, with faster electrification and higher energy savings compared to the normative scenario. This pathway allows investments in new nuclear energy and carbon capture technologies, without mandatory renewable energy targets. The system transformation pathway is the most ambitious, aiming for net-zero emissions by 2040, substantial savings through behavioral change and the circular economy, the phase-out of coal by 2030, and the elimination of other fossil fuels by 2035. Transport electrification is likewise accelerated. These three scenarios describe different trajectories and strategic opportunities for the European economy.
- The Integrated National Energy and Climate Plan requires more ambitious perspectives. It provides a framework for aligning Bulgaria’s energy policy with EU climate objectives. However, the analysis reveals that its current benchmarks remain below the level of ambition required under the EU’s “Fit for 55” package. Furthermore, the plan does not contain sufficiently detailed implementation mechanisms, particularly for the deployment of solar energy. Strengthening sectoral integration and aligning financing instruments with policy objectives will be crucial for fulfilling Bulgaria’s long-term decarbonization commitments.
- Decentralized energy models provide a pathway toward energy security and resilience. Their rise in the form of energy communities, prosumer-based systems, and municipal energy cooperatives represents a paradigm shift in the energy system. The research highlights their potential to improve access to energy, enhance citizen engagement, and strengthen local energy resilience. The participation of municipalities and civil society in solar development may also address issues related to social acceptance and promote just energy transitions, particularly in rural and post-coal regions.
- Energy communities are a critical yet underutilized policy instrument. The examination of pilot initiatives such as “Energy Community Gabrovo” and “Izgrey BG” demonstrates the viability of citizen-led solar projects in Bulgaria. These cases reveal that energy communities can mobilize local investments, raise awareness, and provide economic benefits for households and small businesses. However, the lack of clear legal

definitions, registration procedures, and financial support mechanisms hinders the replication of such models.

- Agrivoltaics represent the intersection of energy and agriculture. They offer the dual benefits of clean energy production and sustainable agricultural models. The research emphasizes their significance in the Bulgarian context, where rural depopulation remains a pressing challenge. Nevertheless, important barriers remain, including regulatory gaps, insufficient financial incentives, and legal restrictions imposed by the Constitutional Court on the use of arable land for photovoltaic systems.
- One of the most significant challenges for solar energy development is the limited capacity of transmission and distribution networks. Many regions in Bulgaria are already facing challenges that prevent new photovoltaic connections. Strategic investments in digitalized, flexible, and intelligent grid infrastructure are required to absorb distributed generation, improve grid stability, and enable energy sharing between producers and consumers.
- Bulgaria must align its solar energy trajectory with the priorities of the EU Green Deal. The development of solar energy in Bulgaria should not be isolated pathway, but rather as a central component of the broader green transition.
- The dissertation demonstrates that the sustainable generation of electricity from photovoltaic systems is not merely a technological possibility, but a strategic priority for both Bulgaria and the EU. Sustainability requires a holistic approach combining appropriate regulation, access to finance, local community participation, and a stable market environment.
- The research thesis is confirmed, as the results of the analysis demonstrate that the sustainable generation of electricity from photovoltaic systems in Bulgaria is feasible under conditions of technological efficiency, economic profitability, and adequate institutional support.

Based on the conducted research, the following **recommendations** can be identified:

1. Strengthening Policy Alignment with EU Climate and Energy Objectives

To ensure long-term sustainability, national objectives for the deployment of photovoltaic systems must be fully aligned with the overarching EU frameworks, including the European Green Deal, Fit for 55, and REPowerEU. In Bulgaria, national strategies should reflect the updated Renewable Energy Directive (RED III), which requires a renewable energy share of at least 42.5% across the EU by 2030. The development of concrete roadmaps with binding intermediate milestones for solar deployment is essential to ensure compliance and sustainable progress.

2. Facilitating Grid Integration and Modernization

The expansion of photovoltaic capacity must be accompanied by investments in grid infrastructure. This includes enhancing the capacity, flexibility, and digitalization of transmission and distribution networks in order to accommodate the variable nature of solar generation. In Bulgaria, the current grid saturation and lack of transparency in connection procedures constitute major barriers. National operators should therefore introduce standardized and digitalized permitting and grid-connection processes.

3. Promoting Decentralized Energy Systems and Energy Communities

Decentralized solar installations, including rooftop photovoltaic systems and energy communities, provide resilience and strengthen local ownership. The EU should encourage Member States to:

- simplify regulatory frameworks for prosumers and cooperatives;
- guarantee priority grid access and fair remuneration for shared energy;
- introduce citizen-oriented financial instruments tailored to households, SMEs, and municipalities.

Bulgaria should fully transpose the EU legal definitions and protections for energy communities, while simultaneously addressing the legal gaps related to registration, grid access, and support mechanisms.

4. Stimulating Agrivoltaics

These systems represent a sustainable land-use model combining agriculture and energy production. At the EU level, it is recommended to:

- review land-use policies to allow the controlled deployment of photovoltaic systems on agricultural land;
- support pilot projects through differentiated financial support under the Common Agricultural Policy (CAP);
- increase research and development funding in agrivoltaic technologies.

In Bulgaria, the recent decisions of the Constitutional Court restricting photovoltaic systems on arable land should be reconsidered in light of emerging European best practices.

5. Ensuring Financial Accessibility and Equity

The sustainable production of solar energy requires broad access to financing mechanisms. Key recommendations include:

- expanding low-interest loans and subsidy schemes;
- prioritizing vulnerable groups and low-income households in support measures;
- introducing fiscal incentives for self-consumption and energy storage systems.

Bulgaria should streamline access to EU funds for municipal, cooperative, and residential photovoltaic initiatives, thereby ensuring broader participation in the solar transition.

6. Simplifying and Accelerating Administrative Procedures

Administrative barriers remain a common challenge across the EU. In this regard, it is recommended to:

- introduce digital one-stop-shop platforms for permitting procedures;
- establish statutory deadlines for each phase of the project approval process;
- provide municipalities with capacity-building resources and administrative support.

In Bulgaria, delays in the issuance of environmental permits and the unclear distribution of responsibilities among institutions discourage private investment. A national coordinating body should therefore be established to harmonize permitting procedures and improve institutional efficiency.

7. Promoting Technological Innovation and Workforce Development

The sustainable growth of the photovoltaic industry depends on continuous innovation and human capital development. Key recommendations include:

- supporting advanced photovoltaic technologies;
- investing in energy storage systems and hybrid photovoltaic solutions;
- developing educational and training programs for solar technicians, engineers, and project designers.

In Bulgaria, public universities and vocational training centers should be integrated into the national solar development strategy in order to address the growing skills shortage in the sector.

In summary, the results of the research confirm that the pursuit of energy independence, environmental sustainability, and the accelerated deployment of renewable energy sources constitutes a strategic priority for Bulgaria. The country's favorable geographical location and significant solar potential create strong preconditions for the development of photovoltaic systems as a sustainable instrument for the decarbonization of the energy sector and the strengthening of energy security.

Photovoltaic technologies are increasingly established as a flexible and efficient solution, owing to their modularity and applicability at different scales, from households to industrial projects. Nevertheless, their deployment is associated with significant upfront investment costs, which necessitate careful planning, economic appraisal, and the optimal selection of technological and market parameters.

In this context, the development and implementation of an integrated methodological framework for the analysis of investment projects emerges as a key factor for improving the efficiency and sustainability of photovoltaic initiatives. The combination of technological, economic, institutional, and environmental dimensions is a necessary condition for realizing the full potential of solar energy.

As a result of the conducted research, it may be concluded that photovoltaic systems represent not only a technological opportunity, but also a strategic instrument for the transition toward a low-carbon economy, while their successful development depends on consistent policy support, an improved regulatory environment, access to finance, and the active participation of local communities.

The research thesis is confirmed to a significant extent, as the analysis demonstrates that the sustainable generation of electricity from photovoltaic systems in Bulgaria is feasible under conditions of technological efficiency, economic profitability, and adequate institutional support.

IV. CONTRIBUTIONS OF PHD THESIS

1. Scientific and Theoretical Contributions

- An integrated theoretical framework for analyzing the sustainability of photovoltaic systems has been developed, combining economic, technological, and institutional dimensions, thereby contributing to the expansion of existing scientific approaches to the evaluation of renewable energy sources.
- The theoretical propositions regarding the role of renewable energy sources in the context of sustainable development have been systematized and enriched, with their significance for the energy transition, economic efficiency, and climate neutrality within the European Union being substantiated.
- A conceptual typology of photovoltaic system operating models has been justified, identifying their structural characteristics, economic logic, and specific risk profiles.
- The relationship between the selected operating model and the economic efficiency of photovoltaic investments has been revealed, demonstrating that different models generate substantial differences in profitability indicators, risk exposure, and financial sustainability.
- The theoretical understanding of decentralized energy systems as an element of the sustainable energy transition has been further developed, including through the conceptualization of the role of energy communities and agrivoltaic solutions.

2. Scientific and Applied Contributions

- An empirical analysis of real investment projects in photovoltaic systems in Bulgaria has been carried out, covering different scales and operating models, which enables an assessment of their economic viability and sustainability.
- An applicable methodological toolkit for the evaluation of investments in photovoltaic systems has been developed, based on cash flow analysis and the use of dynamic efficiency indicators, adapted to the specificities of the energy sector.
- The key factors influencing the efficiency of photovoltaic projects have been identified and systematized, including market, technological, and natural determinants, thereby contributing to more precise investment appraisal.
- Conceptual models for selecting investment strategies in the deployment of photovoltaic systems have been proposed, which may be used by economic actors and public institutions in managerial decision-making.

- Practical guidelines for improving policies and the regulatory framework have been formulated, aimed at stimulating investments in renewable energy and increasing the efficiency of the energy sector**.**

V. PUBLICATIONS RELATED TO THE DISSERTATION

1. **Lavchiev, S.**, 2023. *Perspectives and challenges in the use of renewable energy sources*. **Scientific Works of the Agricultural University, Plovdiv**, 65(1), pp. 136–143.
2. **Hristov, K., Beluhova-Uzunova, R., Atanasov, D., Lavchiev, S., Mrankov, G.**, 2024. *Green Deal and solar energy: prospects for Bulgarian rural areas*. **Scientific Papers Series Management, Economic Engineering in Agriculture & Rural Development**, 24(2), pp. 529–536.
3. **Lavchiev, S. and Beluhova-Uzunova, R.**, 2025. *Solar energy in rural areas: potential and challenges*. **Trakia Journal of Sciences**, 23(Supplement 2), pp. 290–297.