Krzysztof Zamasz

COST OF CAPITAL IN THE ASSESSMENT OF ECONOMIC EFFICIENCY OF RENEWABLE ENERGY PROJECTS IN POLAND

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Scientific review:
prof. dr hab. Krzysztof Jajuga
prof. dr hab. inż. Waldemar Kamrat

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Introduction

Renewable energy sources (RES) are assuming an increasingly critical role in the Polish power system. This shift is driven by national strategic goals focused on sustainable development and the transition towards a zero-emission economy. Like other European nations, Poland is accelerating its efforts to expand renewable energy infrastructure in response to climate change challenges and the need to mitigate the environmental impact of human activities. These efforts encompass investments in modern renewable energy technologies and the active promotion of zero-emission solutions. Increasing the share of renewable energy in electricity generation is a key priority outlined in all strategic documents concerning energy sector development, at both national and international levels.

In recent years, Poland has witnessed particularly rapid growth in the installed capacity of solar photovoltaic and onshore wind farms. However, the inherent variability of electricity production from these technologies presents significant challenges to maintaining power grid stability, a challenge further complicated by specific Polish climatic conditions. Unlike conventional power plants, these renewable sources do not offer a consistently predictable and dispatchable energy supply. Consequently, investments in renewable energy projects – where capacity factors are directly dependent on fluctuating wind conditions or solar insolation – carry a higher degree of risk for investors.

For investors in the energy sector, the economic viability of planned and ongoing projects remains a key issue. Balancing long-term sustainability benefits with financial performance is essential. Renewable energy investments are particularly subject to multiple sources of uncertainty and risk, affecting their economic viability. Key concerns include the potential for rising capital expenditures, the volatility of electricity prices, and regulatory uncertainty. Changes in strategic documents or climate and energy policy instruments may unexpectedly alter RES projects' profitability. Additionally, the inherent variability in the generation of renewable electricity, driven by weather conditions, significantly affects the economic efficiency of investments. To navigate these risks, investors require a thorough analysis of sector dynamics and a clear understanding of the potential economic and environmental benefits associated with high-risk projects involving renewable energy.

Methods used to assess the economic efficiency of renewable energy investments are crucial for understanding their profitability and inherent uncertainty. The standard approach to such evaluation is the discounted cash flow (DCF) method, which calculates a project's net present value (NPV) by discounting future cash flows using an appropriate interest rate. This rate reflects both the cost of capital and project-specific risks.[1] When applied in the renewable energy sector, DCF analysis allows for the incorporation of standard financial parameters and sector-specific factors, including those reflecting support mechanisms designed for renewable technologies.

Support mechanisms for renewable energy projects are essential for balancing economic efficiency with environmental and social objectives. These instruments provide additional financial stability for investors, mitigating the higher risks associated with RES projects compared to conventional power plants. Support mechanisms include, among others, auction systems where renewable electricity producers compete for contracts to supply electricity. This model simultaneously enables projects to improve economic efficiency and reduce consumer costs. Other key support mechanisms include feed-in tariffs or feed-in premiums, which guarantee a fixed price for the electricity produced or provide a bonus above the market price.

Given these sectoral challenges and theoretical considerations, this monograph focuses on the role of risk in renewable energy projects. As renewable energy encompasses a broad range of technologies, this study concentrates on selected technologies particularly relevant to Poland's power system.

The primary objective of this monograph is to analyse the importance and role of risk in evaluating the economic efficiency of renewable energy projects in Poland, taking into account existing support mechanisms. An integral element of the research is the development of an economic assessment model for renewable

[1] Being aware that the cost of capital and the discount rate are not exactly the same terms (the cost of capital serves as a baseline for the discount rate) – however, since they are closely related, it was decided to use these terms interchangeably to make the text easier to read and understand.

energy projects, alongside the evaluation of selected technologies through different case studies and sensitivity analysis with the developed research tool.

Understanding risk is crucial not only for investors but also for policymakers and industry stakeholders aiming to foster sustainable energy sector development. Therefore, the utilitarian goal of this monograph is to provide the scientific community, investors, policymakers, and other stakeholders with the practical knowledge and tools necessary to assess economic efficiency and understand the implications of risk in RES investments. This study offers insights into the profitability and risk associated with renewable energy projects by examining the role of renewables in achieving climate policy objectives, the variability of electricity generation resulting from weather conditions, and the effectiveness of support mechanisms. The findings presented in this monograph aim to support more informed investment decisions and risk minimisation strategies, which, in turn, may lead to more effective planning and implementation of economically efficient and sustainable energy projects.

The monograph is structured into an introduction, four main chapters, and a conclusion.

The first chapter provides an overview of the current state of renewable energy in the Polish power system and presents strategic objectives for RES development, drawing on European and national climate and energy policy documents. This chapter also analyses support mechanisms as a key tool for mitigating risk in renewable energy projects. It focuses, in detail, on auction systems (RES auctions where electricity is traded) and the capacity market (where net available capacity is traded). Additionally, given the advanced plans for offshore wind farm construction, the chapter examines the contracts for difference mechanisms applicable to producers of offshore wind energy.

The second chapter outlines the theoretical foundations and practical applications of risk analysis methods for evaluating the economic efficiency of investment projects. It presents the discounted cash flow method and various approaches to estimating the cost of equity. The chapter also explores sensitivity analysis, scenario analysis, and Monte Carlo simulation as tools for assessing economic efficiency.

The third chapter introduces the research framework: an economic assessment model for renewable energy projects in Poland. It defines case studies representing selected RES technologies and presents the underlying input data assumptions. The analysed technologies include solar photovoltaics, onshore and offshore wind farms, biogas plants, and geothermal heating plants.

The fourth chapter presents the results of the study, focusing on the role of risk in evaluating renewable energy projects. It provides an in-depth analysis of five case studies covering various renewable energy technologies.

The conclusion presents the key findings from the conducted research, covering both theoretical and applied dimensions.

1.

Renewable energy and the decarbonisation of the Polish power system

The transition towards a zero-emission economy requires a fundamental shift in how electricity is generated, with renewable energy playing a central role in achieving strategic climate and energy goals. Understanding this transformation involves analysing changes in installed capacity and electricity production within the Polish power system. Tracking these dynamics provides the context for the research, helps to identify dominant renewable energy technologies, and serves as a foundation for further investigation. These aspects are explored in Section 1.1.

Beyond assessing the current state of the power system, effective planning for investment requires a clear understanding of energy and climate policies. Regulatory frameworks, at both national and European levels, are particularly important in shaping the uncertainty surrounding investment in renewable energy projects, especially over medium- and long-term horizons. A detailed analysis of these regulations is the focus of Section 1.2.

The expansion of renewable energy presents specific challenges related to the intermittency of electricity production, which is often dependent on weather conditions. Compared to conventional technologies, renewable energy projects carry a significantly higher investment risk. To increase the share of renewables in total energy generation while ensuring financial viability, public support mechanisms are often introduced to mitigate these risks by providing additional financial support. These mechanisms, their role, and their effectiveness in balancing risk and return are discussed in Section 1.3.

1.1. Renewable energy sources: Characteristic and role in the power system

Renewable energy sources are defined as naturally replenishing sources of energy whose resources are continuously restored despite human consumption.[2] These include wind energy, solar radiation, geothermal energy, hydropower, wave energy, ocean currents, and tidal energy, as well as energy derived from biomass, biogas, and bioliquids.[3] Unlike fossil fuels, renewable energy resources are inexhaustible, making them a key component of energy strategies. Furthermore, converting renewable energy sources into usable energy generates significantly lower greenhouse gas emissions and fewer harmful pollutants released into the atmosphere.[4] From an economic perspective, while renewable energy installations require higher initial investment costs compared to conventional power plants, they generally offer lower long-term operating costs. This is due to the lack of fuel costs, costs of carbon dioxide emission allowances and environmental fees.[5]

Nevertheless, renewable energy sources – primarily those dependent directly on weather conditions – also present operational challenges. Their lower capacity factors compared to conventional power plants, and the lack of controllability of the units, necessitate reserve and balancing capacities in the system, currently provided by fossil fuel units. In the long term, battery storage systems or hydrogen-based solutions are expected to assume this role.[6]

At the end of 2024, the installed capacity of renewable energy sources in Poland amounted to 27.23 GW, representing 44.6% of the total installed capacity of the national electricity system (61.09 GW) (Figure 1.1). This figure corresponds to the total installed capacity of all RES technologies, regardless of the primary energy carrier. However, when considering individual energy carriers, units using hard coal for electricity production still constituted the dominant

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[2] Twidell, J., & Weir, T. (2006). *Renewable Energy Resources* (2nd ed.). Taylor & Francis Group.

[3] Rahman, A., Farrok, O., & Haque M.M. (2022). Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. *Renewable and Sustainable Energy Reviews*, 161, 112279. https://doi.org/10.1016/j.rser.2022.112279

[4] Kocak E., Ulug E.E., & Oralhan B. (2023). The impact of electricity from renewable and non-renewable sources on energy poverty and greenhouse gas emissions (GHGs): Empirical evidence and policy implications, *Energy*, 272, 127125. https://doi.org/10.1016/j.energy.2023.127125

[5] Sens, L., Neuling U., & Kaltschmitt M. (2022). Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines – Development by 2050, *Renewable Energy*, 185, 525–537. https://doi.org/10.1016/j.renene.2021.12.042

[6] Hernandez D.D., & Gencer E. (2021). Techno-economic analysis of balancing California's power system on a seasonal basis: Hydrogen vs. lithium-ion batteries, *Applied Energy*, 300, 117314. https://doi.org/10.1016/j.apenergy.2021.117314

share, accounting for 30.8% of the total installed capacity in the system. This reflects the historical, economic, and geographical conditions in the country, where rich coal deposits have led to the significant use of coal in both power generation and industry.[7,8] Accordingly, the generation assets of the Polish power system, particularly the long-standing ones, are predominantly based on coal fuel. Although these units are controllable and supply energy in a stable manner, thereby ensuring energy security and independence of supply, they are also a source of greenhouse gas emissions and harmful pollutants released into the atmosphere.[9]

In contrast to previous years, when lignite-fired power plants consistently held the second-largest share of installed capacity, 2024 saw photovoltaic installations surpass them in total capacity. The total capacity of solar power generation was 14.61 GW at the end of 2024, representing 23.9% of the total installed capacity in the system. Onshore wind power followed with 9.58 GW of installed capacity, representing 15.7% (Table 1.1). The observed increase in installed capacity from these sources reflects changing environmental and regulatory conditions that promote electricity production from low-emission energy sources. In this context, the capacity utilisation time of individual technologies plays a key role, and – because it depends on weather conditions – it is generally lower for renewable energy units than for conventional ones.

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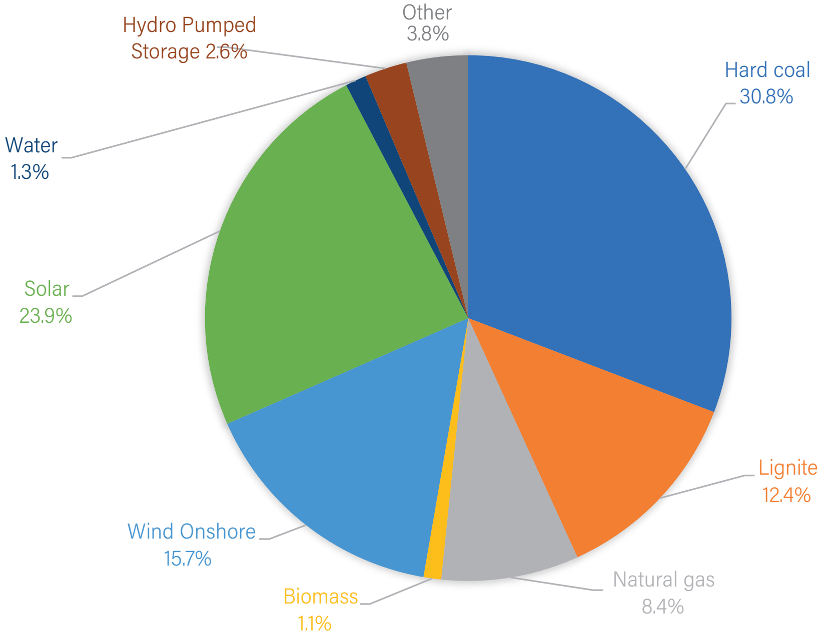
7 Rentier G., Lelieveldt H., & Kramer G.J. (2019). Varieties of coal-fired power phase-out across Europe, *Energy Policy*, 132, 620–632. https://doi.org/10.1016/j.enpol.2019.05.042.

8 Bórawski P., Bełdycka-Bórawska A., & Holden L. (2023). Changes in the Polish Coal Sector Economic Situation with the Background of the European Union Energy Security and Eco-Efficiency Policy, *Energies*, *16(2)*, 726. https://doi.org/10.3390/en16020726

9 Nyga-Łukaszewska, H., Aruga, K., & Stala-Szlugaj, K. (2020). Energy security of Poland and coal supply: Price analysis. *Sustainability*, *12(6)*, 2541. https://doi.org/10.3390/su12062541

Figure 1.1. Structure of installed capacity in the Polish power system in 2024



Source: Own study based on ENTSO-E 2024.[10]

Since 2015, significant changes have occurred in the structure of installed capacity in Poland, resulting primarily from international commitments to mitigate climate change and the ensuing domestic energy policies promoting renewable energy sources (Figure 1.2). One of the main differences compared to previous years is the considerable increase in the diversification of energy sources and the share of RES. In 2015, the share of installed capacity in wind units was 10.6%, and in photovoltaic systems – 0.04%, corresponding to values of 3.76 GW and 0.01 GW, respectively. By 2024, these shares had increased to 14.7% (wind) and 23.9% (PV), corresponding to installed capacities of 9.58 GW and 14.61 GW, respectively. While the growth of installed capacity in wind farms has been partially limited by the adoption of the so-called 'anti-wind turbine law', photovoltaic systems have shown a continuous increase in installed capacity, especially since 2021. This is primarily due to support systems designed for individual consumers, enabling them to purchase photovoltaic systems for installation on the roofs of private houses and public buildings, at preferential rates.[11]

[10] ENTSO-E. (2024). *Installed capacity per production type.* https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/

[11] Zdonek, I., Tokarski, S., Mularczyk, A., & Turek, M. (2022). Evaluation of the program subsidizing prosumer photovoltaic sources in Poland. *Energies*, *15(3)*, 846. https://doi.org/10.3390/en15030846

Table 1.1. Installed capacity in the Polish power system in 2024

Energy Carrier	Installed Capacity	Share of Total Installed Capacity
Hard Coal	18.83 GW	30.82%
Lignite	7.56 GW	12.37%
Natural Gas	5.16 GW	8.45%
Biomass	0.66 GW	1.08%
Onshore Wind	9.58 GW	15.69%
Solar Photovoltaics	14.61 GW	23.91%
Water	0.79 GW	1.29%
Hydro Pumped Storage	1.59 GW	2.61%
Other	2.31 GW	3.78%
Total	**61.09 GW**	**100.00%**

Source: Own study based on ENTSO-E 2024.[12]

The installed capacity in hard coal-fired power plants has remained relatively stable at around 19 GW for years. However, the share of these plants in the total installed capacity of the system decreased from 54.4% in 2015 to 30.8% in 2024. For lignite-fired generation units, capacity decreased by about 1 GW, with the share of total installed capacity falling from 23.7% to 12.4%. It should be noted that the relative stability in recent years is primarily due to the construction of new units, financed under the capacity market, replacing outdated generation units that are being decommissioned.[13] However, as this mechanism is no longer available for hard coal and lignite units, the installed capacity in the system is expected to decrease in the coming years due to the shutdown of further units, whose capacity will no longer be replaced by new coal-fired plants.

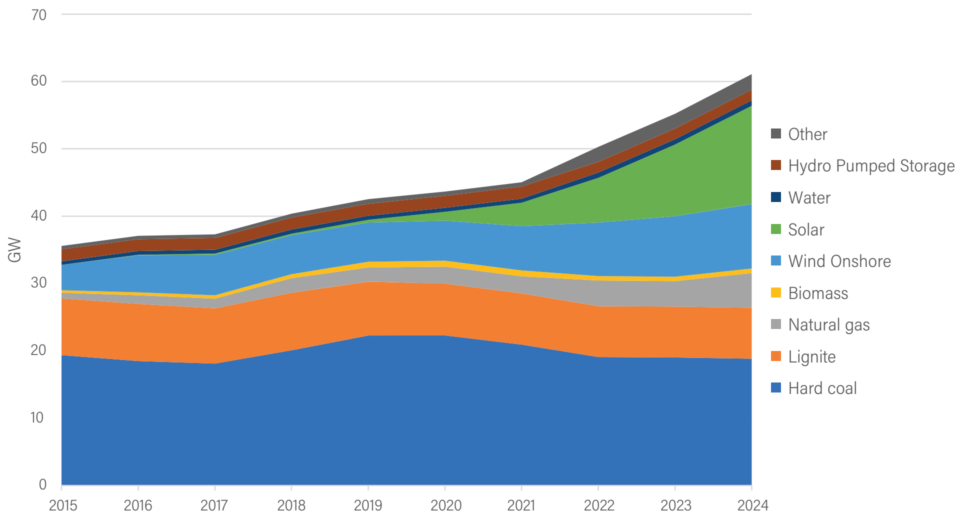
Recent changes indicate that among fossil fuel technologies, only natural gas-fired units have recorded an increase in both installed capacity and their share of the total capacity within the Polish power system. In 2015, the installed capacity of these units was 0.83 GW, representing 2.3% of the total system capacity. By 2024, this had increased to 5.16 GW and 8.4%, respectively. This is because natural gas is

12 ENTSO-E. (2024). *Installed capacity per production type.* https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/.

13 Kaszyński, P., Komorowska, A., Zamasz, K., Kinelski, G., & Kamiński, J. (2021). Capacity market and (the lack of) new investments: Evidence from Poland. *Energies*, *14(23)*, 7843. https://doi.org/10.3390/en14237843

considered a transitional fuel in the transformation of economies historically based primarily on coal-fired units. Furthermore, while coal-fired units can no longer be subsidised through support mechanisms without appropriate EU-level approval, natural gas-fired units can still benefit from additional financing instruments.[14]

Figure 1.2. Installed capacity in the Polish power system, 2015–2024



Source: Own study based on ENTSO-E 2024.[15]

Despite the significant increase in installed capacity in onshore wind and photovoltaic systems in the Polish power system in recent years, the specific characteristics of these technologies – particularly their strong dependence on weather conditions – mean that their impact on the structure of electricity production varies over time.[16] While the combined share of installed capacity for wind and photovoltaic units reached 27.2% in 2024, their contribution to total electricity generation averaged 26.0%, with hourly production fluctuating significantly throughout the day and across seasons.

For wind units, hourly electricity demand coverage ranged from 0.1% during windless periods to 55.4% during the windiest hours (Figure 1.3). The annual

[14] Leśniak, A., Surma, T., & Zamasz, K. (2023). Assessment of the support schemes for new high-efficiency cogeneration units in Poland. *Rynek Energii*, *5(168)*, 22–30.

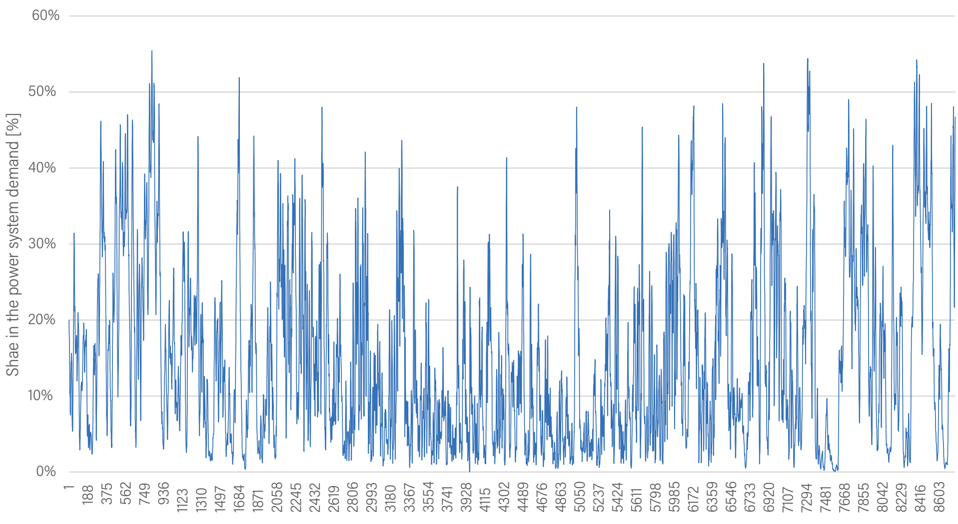
[15] ENTSO-E. (2024). *Installed capacity per production type.* https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/

[16] Jaworski, S., Chrzanowska, M., Zielińska-Sitkiewicz, M., Pietrzykowski, R., Jezierska-Thole, A., & Zielonka, P. (2023). Evaluating the progress of renewable energy sources in Poland: A multidimensional analysis. *Energies*, *16(18)*, 6431. https://doi.org/10.3390/en16186431

average was 14.9%, with a median of 11.5%. For photovoltaics, demand coverage ranged from zero at night to 67.7% during hours of high insolation (Figure 1.4). The annual average was 10.5%, with a median of 0.9%. In both wind and photovoltaic generation, the median is lower than the average, demonstrating an asymmetrical data distribution over the year. This indicates that higher values are observed less frequently but are sufficiently high to raise the average above the median.

Electricity production from wind farms is characterised by variability both daily and seasonally. Production is usually higher in the winter months, due to higher wind speeds than are observed in the summer months. Under conditions characteristic of Poland, higher winds are usually recorded at night.[17] Capacity factors of photovoltaic systems are usually lower than those of wind units, due to the limited amount of sunlight available during the day. Seasonal variability in photovoltaic production is evident, with higher volumes of energy produced in the summer, when the days are longer and insolation is higher compared to the winter months.[18]

Figure 1.3. Wind power contribution to power system demand in Poland, 2024



Source: Own study based on PSE (2024).[19,20]

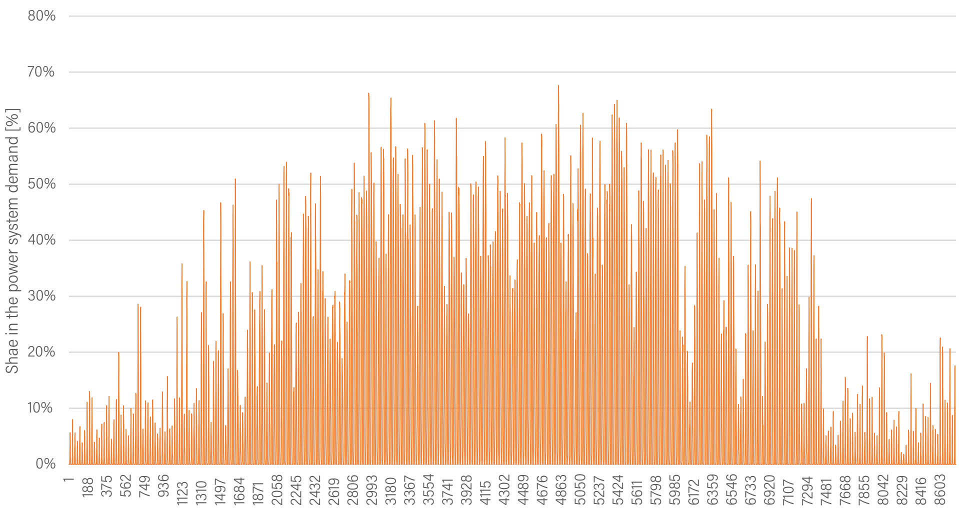
[17] Robak, S., Raczkowski, R., & Piekarz, M. (2023). Development of the wind generation sector and its effect on the grid operation: The case of Poland. *Energies*, *16(19)*, 6805. https://doi.org/10.3390/en16196805

[18] Pater, S. (2023). Increasing energy self-consumption in residential photovoltaic systems with heat pumps in Poland. *Energies*, *16(10)*, 4003. https://doi.org/10.3390/en16104003

[19] Polskie Sieci Elektroenergetyczne (PSE). (2023). *NPS operation – basic quantities*. https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-dobowe-z-pracy-kse/wielkosci-podstawowe

[20] Polskie Sieci Elektroenergetyczne (PSE). (2023). *NPS operation – generation from wind and photovoltaic sources*. https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-dobowe-z-pracy-kse/generacja-zrodel-wiatrowych

Figure 1.4. Solar photovoltaics contribution to the power system demand in 2024



Source: Own study based on PSE 2024[21,22]

Currently, the demand for electricity in Poland is still met mainly by production from conventional units. Power plants and combined heat and power (CHP) plants using hard coal and lignite for electricity production accounted for a total of 56.14% of the total electricity generated, which amounted to 158.46 TWh in 2024 (Table 1.2). Wind and photovoltaic units, in turn, accounted for 23.8% and 17.35% of total production, respectively. However, due to the seasonality of this generation and the low capacity factors of these plants, the changes in production are significantly lower than the increases in installed capacity within the system. As a result, although installed capacity may be the same over the selected period, production varies depending on the time of day and the season. Furthermore, the rapid development of RES technologies also generates challenges related to the availability of transmission infrastructure. Insufficient capacity of the transmission networks and accompanying infrastructure may lead to situations in which part of the energy produced cannot be utilised.[23]

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21 Polskie Sieci Elektroenergetyczne. (2023). *NPS operation – basic quantities*. https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-dobowe-z-pracy-kse/wielkosci-podstawowe

22 Polskie Sieci Elektroenergetyczne. (2023). *NPS operation – generation from wind and photovoltaic sources*. https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-dobowe-z-pracy-kse/generacja-zrodel-wiatrowych

23 Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*, *20*, 101621. https://doi.org/10.1016/j.rineng.2023.101621

Table 1.2. Electricity generation in the Polish power system in 2024

Energy carrier	Electricity generation	Share of Total Electricity Production
Hard Coal	56.06 TWh	35.38%
Lignite	32.90 TWh	20.76%
Natural Gas	16.66 TWh	10.51%
Biomass	2.36 TWh	1.49%
Onshore Wind	23.80 TWh	15.02%
Solar Photovoltaics	17.35 TWh	10.95%
Water	1.87 TWh	1.18%
Hydro Pumped Storage	1.14 TWh	0.72%
Other	6.33 TWh	4.00%
Total	**153.46 TWh**	**100.00%**

Source: Own study based on ENTSO-E (2024).[24]

The analysis of the current state of renewable energy in Poland indicates that although dynamic changes related to the construction of new generation capacity have been observed in recent years, the inherent characteristics of these technologies limit the potential for wind and photovoltaic units to meet electricity demand in the Polish power sector. Furthermore, electricity generation from these technologies is characterised by high daily and annual variability, which presents several challenges related to system balancing.

The national power system remains heavily dependent on fossil fuels, posing serious challenges related to its necessary transformation and the increased integration of renewable energy sources in the coming years. This transformation involves not only expanding installed capacity but also developing energy transmission and storage infrastructure to meet obligations arising from international agreements and strategic documents.

1.2. Strategic objectives for renewable energy

Renewable energy development is a key priority of climate and energy policy, aimed at mitigating climate change and promoting the sustainable use of resources. Increasing the share of renewable energy sources in total primary energy consumption – alongside reducing greenhouse gas emissions and improving energy efficiency – represents a fundamental goal in efforts to limit the impacts of climate change.

[24] ENTSO-E. (2024). *Actual generation per production type.* https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show

1.2.1. International climate commitments

The first official climate policy goals were formulated in 1997 in response to international negotiations on observed climate change and the Kyoto Protocol.[25] At that time, participating countries committed to reducing greenhouse gas emissions by an average of 5% compared to 1990 emission levels. The European Union and its then fifteen member states committed to an 8% reduction across the EU by 2012. Poland, as a country undergoing transformation to a market economy, committed to reducing greenhouse gas emissions by 6% compared to the base year.[26] The development of renewable energy sources, along with improvements in energy efficiency and the promotion of sustainable agriculture, was identified as a means to achieve these goals.

Following the provisions of the Kyoto Protocol, the European Union adopted a directive on the promotion of electricity produced from renewable energy sources in the internal electricity market (Directive 2001/77/EC); this was the first legislative act setting targets for increasing the share of renewable energy in the EU. Indicative targets related to the production of electricity from renewable energy sources were established at that time, formulated at 22% compared to 13.9% in 1997.[27]

In 2012, during the Doha climate conference, an amendment to the Kyoto Protocol, the *'Doha Amendment'*, was adopted. This amendment introduced a second period for commitments to reduce greenhouse gas emissions, valid from 2013 to 2020, obliging parties to reduce greenhouse gases by at least 18% below 1990 levels. Poland committed to a 20% reduction, similar to other Member States of the European Union.[28]

Regardless of this amendment, the European Union's 2009 climate and energy package[29] set a goal of reducing greenhouse gas emissions by 20% compared to 1990 levels. At that time, quantitative targets were also established to improve energy efficiency and increase the share of energy from renewable sources in the European Union's total energy consumption. The 2020 climate and energy package included the following objectives for the EU (known as the '20-20-20' targets):

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25 Eikleland P.O., & Sæverud I.A. (2007). Market diffusion of new renewable energy Europe, *Energy & Environment*, *18(1)*, 13–36.

26 Kyoto Protocol to the United Nations Framework Convention on Climate Change, Annex B. (1997, December 11). Published in *Journal of Laws of the Republic of Poland*, 2005, No. 203, item 1684.

27 Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market. *Official Journal of the European Communities*, L 283, 27/10/2001, 33–40.

28 United Nations Framework Convention on Climate Change (UNFCCC). (2012). *Doha Amendment to the Kyoto Protocol: Annex B to the Kyoto Protocol. Decision adopted at the 8th session of the Meeting of the Parties to the Kyoto Protocol, 26 November–8 December 2012*. Retrieved from https://unfccc.int/kyoto_protocol

29 Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union*, L 140, 5.6.2009, 16–62.

- A 20% reduction in greenhouse gas emissions,
- A 20% improvement in energy efficiency,
- A 20% share of renewable energy sources.

In promoting energy from renewable sources, a dedicated directive was adopted, obliging Member States to develop national action plans that outlined specific measures to achieve the objectives for the share of energy from renewable sources. This directive also set individual targets for individual Member States, depending on their share of renewable energy in total energy production at that time and their potential for growth. In Poland, the 2005 base level was 7.2%, and the target level for 2020 was set at 15%.[30]

The next milestone in climate and energy policy was the implementation of the Paris Agreement, signed in 2015 and established under the United Nations Framework Convention on Climate Change (UNFCCC). The agreement's primary objective was a commitment to actions aimed at limiting global warming to below 2°C above pre-industrial levels, while striving to limit the increase to 1.5°C.[31] Although the agreement did not specify quantitative targets for renewable energy, it required participating countries to establish nationally determined contributions (NDCs) outlining their climate commitments.

In response to the Paris Agreement, both the European Union and Poland developed new legislative and strategic documents to adapt climate policy. At the EU level, the 'Clean Energy for All Europeans Package' was adopted in 2018, containing legal acts aimed at:

- Further increasing the share of renewable energy sources in the EU,
- Improving energy efficiency,
- Ensuring a just transition.[32]

In Poland, however, the response to the Paris Agreement and other obligations arising from EU regulations was the development of the 'National Energy and Climate Plan for 2021–2030', which was published in 2019.[33]

In addition to the quantitative targets set under the previous phases of the European Union's climate and energy policy implementation, the 'Clean Energy for All Europeans' Package also aims to establish a balanced decision-making framework across three levels of governance:

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[30] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union*, L 140, 5.6.2009, 16–62.

[31] Paris Agreement to the United Nations Framework Convention on Climate Change, adopted December 12, 2015, Paris. *Journal of Laws*, 2017, item 36.

[32] European Commission. (2018). *Clean Energy for All Europeans package*. https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en?prefLang=pl

[33] Ministry of State Assets. (2019). *National Energy and Climate Plan for 2021–2030*.

- European,
- National,
- Local.

This package comprises eight legislative acts, designed to benefit the environment, economy, and consumers. These include four directives, which establish common rules for national regulatory frameworks and set shared objectives, and four regulations, which are binding legislative acts that must be applied in their entirety across all Member States.[34]

The directives adopted under the 'Clean Energy for All Europeans' Package include:

- Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. It establishes detailed requirements for improving the energy efficiency of buildings.[35]
- Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. It sets a target of achieving 32% renewable energy in the EU's energy mix by 2030 and includes provisions for integrating renewable energy sources (RES) in transport, heating, and cooling.[36]
- Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018, amending Directive 2012/27/EU on energy efficiency. It sets a target of achieving at least a 32.5% improvement in energy efficiency by 2030, relative to the 2007 baseline, and includes provisions extending the energy-saving obligation.[37]
- Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019, on common rules for the internal electricity market and amending Directive 2012/27/EU. It defines principles governing electricity generation, transmission, distribution, supply, and storage, while also addressing consumer empowerment and protection.[38]

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[34] Florence School of Regulation. (2020). *The Clean Energy for All Europeans Package*.

[35] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. *Official Journal of the European Union*, L 156, 19 June 2018, 75–91.

[36] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, L 328, 21 December 2018, 82–209.

[37] Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. *Official Journal of the European Union*, L 328, 21 December 2018, 210–230.

[38] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU. *Official Journal of the European Union*, L 158, 14 June 2019, 125–199.

The regulations adopted under the 'Clean Energy for All Europeans' Package are as follows:

- Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council. It establishes a new governance system for the Energy Union, obliging all Member States to formulate 10-year National Energy and Climate Plans (NECPs).[39]
- Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC; it requires Member States to prepare plans for dealing with potential future electricity crises.[40]
- Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 establishing a European Union Agency for the Cooperation of Energy Regulators (ACER). This regulation revises ACER's role and operational framework, expanding its competencies in cross-border energy regulation.[41]
- Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal electricity market. This regulation establishes regulatory principles for the EU's internal electricity market, with a particular focus on wholesale market operations and network management.[42]

In summary, the quantitative energy targets for 2030 set by the legislative documents within the 'Clean Energy for All Europeans' Package are as follows:

- At least a 40% reduction in greenhouse gas emissions,

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[39] Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No. 663/2009 and (EC) No. 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No. 525/2013 of the European Parliament and of the Council. *Official Journal of the European Union*, L 328, 21 December 2018, 1–77.

[40] Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC. *Official Journal of the European Union*, L 158, 14 June 2019, 1–21.

[41] Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 establishing a European Union Agency for the Cooperation of Energy Regulators. *Official Journal of the European Union*, L 158, 14 June 2019, 22–53.

[42] Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity. *Official Journal of the European Union*, L 158, 14 June 2019, 54–124.

- At least a 32% share of renewable energy in energy consumption,
- At least a 32.5% improvement in energy efficiency.

The next milestone for EU climate and energy policy was the European Commission's proposal of more ambitious measures for achieving EU climate neutrality by 2050. These measures were defined within the 'European Green Deal' action plan, aiming to transform the EU into a modern economy, reducing greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels) and achieving net-zero emissions by 2050.[43] Additionally, the European Green Deal assumes that:

- Economic growth will be decoupled from resource use,
- No region or individual will be left behind during the energy transition.

As part of the 'European Green Deal', the European Commission has adopted a package of legislative proposals concerning climate, energy, transport and taxation policies.

The European Commission has set out 10 priorities for the 'European Green Deal' initiative, covering the following areas[44]:

- Climate neutrality,
- Circular economy,
- Sustainable construction,
- Zero pollution,
- Biodiversity protection,
- Sustainable food systems,
- Sustainable transport,
- Support mechanisms,
- Research, development, and innovation,
- External representation of the European Union.

The climate neutrality of the European Union is a core priority of the 'European Green Deal', aiming to achieve net-zero emissions in the long term. To fulfil this objective, further actions are planned to:

- Enhance energy efficiency,
- Accelerate the development of energy sectors primarily based on renewable energy technologies,
- Establish a fully integrated, interconnected, and digitalised energy market at the EU level.

Additional key priorities relevant from the renewable energy perspective include:

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[43] European Commission. (2019). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal* (COM/2019/640 final).

[44] Simon, G. (2019, December 12). *EU Commission unveils 'European Green Deal': The key points*. Euractiv. https://www.euractiv.com/section/energy-environment/news/eu-commission-unveils-european-green-deal-the-key-points/

- Zero pollution,
- Sustainable transport,
- Support mechanisms,
- Research, development and innovation.

The Zero Pollution priority aims to achieve a significant reduction in various types of pollution, including air, soil, and water pollution, over the coming years, with the goal of eliminating pollution sources by 2050. The Sustainable Transport priority focuses on reducing transportation-related emissions by promoting the use of alternative and sustainable fuels in road[45], maritime, and air transport. Additionally, the electrification of transport and the expansion of vehicle charging infrastructure are actively encouraged, playing a crucial role in both renewable energy integration and business operations. From the perspective of renewable energy and energy companies operating RES generation units or planning their construction, a key priority is the financing of sustainable technologies, as well as research and innovation in this field through EU funding mechanisms. Furthermore, the financing of initiatives supporting the implementation of the 'European Green Deal' objectives remains a central priority of the European Commission.

In addition to the aforementioned goals and priorities of the 'European Green Deal', several other initiatives have been implemented at the EU level as integral components of its climate and energy policy. A key measure, adopted in 2020, is the 'Just Transition Mechanism', which aims to ensure that transition is fair.[46] Under this mechanism, additional support is provided to the regions and sectors most affected by decarbonisation processes to mitigate the social and economic consequences of the transition.

The 'Just Transition Mechanism' consists of three pillars:

- A new Just Transition Fund,[47]
- A Just Transition scheme under the InvestEU programme,[48]
- A new loan instrument for the public sector.[49]

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[45] Zamasz, K., Stęchły, J., Komorowska, A., & Kaszyński, P. (2021). The impact of fleet electrification on carbon emissions: A case study from Poland. *Energies*, *14(20)*, 6595. https://doi.org/10.3390/en14206595

[46] European Commission. (2020). *Just Transition Mechanism*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_pl

[47] Regulation (EU) 2021/1056 of the European Parliament and of the Council of 24 June 2021 establishing the Just Transition Fund. *Official Journal of the European Union*, L 231, 30 June 2021, 1–23. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1056

[48] Regulation (EU) 2021/523 of the European Parliament and of the Council of 24 March 2021 establishing the InvestEU Programme and amending Regulation (EU) 2015/1017. *Official Journal of the European Union*, L 107, 25 March 2021, 1–33. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R0523

[49] Regulation (EU) 2021/1229 of the European Parliament and of the Council of 14 July 2021 on the public sector loan facility under the Just Transition Mechanism. *Official Journal of the European Union*, L 279, 16 July 2021, 1–18. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1229

Additional financing is an instrument reducing the risk of investment and modernisation projects undertaken in the transition process.

Among the actions undertaken as part of the implementation of the 'European Green Deal', several additional documents have been adopted, outlining plans and defining objectives within specific strategic priorities. These include, among others, the 'European Industrial Strategy for a Green and Digital Europe', which focuses primarily on:

- Maintaining the competitiveness of European industry,
- Achieving Europe's climate neutrality by 2050,
- Shaping Europe's digital future.[50]

Another key document is the 'EU Strategy for Energy System Integration', which is structured around three main pillars:

- Creating a more circular energy system, in which improving energy efficiency and more effective use of local heat sources in buildings play a key role.
- Increasing electrification in end-use sectors, including the deployment of heat pumps in buildings, electric vehicles, and electric boilers in selected industries.
- Promoting clean fuels, such as hydrogen, sustainable biofuels and biogas, particularly in sectors that are difficult to electrify.[51]

In December 2020, the 'European Climate Pact' was adopted with the aim of raising awareness and encouraging public participation in climate action.[52] According to its foundational assumptions, the pact seeks to actively involve citizens in transformation processes.

As part of efforts to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, the European Commission published the 'Fit for 55' package of proposals in July 2021.[53] In the context of renewable energy, the following objectives were outlined:

Further increasing the share of renewable energy sources in the European Union's total electricity consumption.

[50] European Commission. (2020). *Industrial strategy for a green and digital Europe*. https://ec.europa.eu/commission/presscorner/detail/pl/ip_20_416

[51] European Commission. (2020). *European Union's strategy for the integration of the energy system*. https://ec.europa.eu/commission/presscorner/detail/pl/ip_20_1259.

[52] European Commission. (2020). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: European Climate Pact* (COM/2020/788 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0788

[53] European Commission. (2021). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: 'Fit for 55': Meeting the EU's 2030 climate target on the way to climate neutrality* (COM/2021/550 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550

Supporting the development of renewable energy technologies by expanding financial resources to encourage investment in these technologies and in transmission infrastructure that facilitates their effective integration.

Given the existing strategic and legislative documents on renewable energy, the current target for increasing the share of RES in total energy consumption in the European Union is set at 40% by 2030.[54]

1.2.2. National climate commitments

Poland, as a member of the EU, is obliged to:

- Implement EU climate and energy policies,
- Adopt internal strategic and legislative documents aimed at achieving the goals of reducing greenhouse gas emissions,
- Improve energy efficiency,
- Increase in the share of renewable energy sources in the overall structure of energy consumption.

In addition to the provisions arising directly from the implementation of EU objectives, national documents supporting sustainable economic development, environmental protection, and broader transformation processes are adopted in parallel.

The national strategic document that Poland, as a Member State of the European Union, was required to prepare is the 'National Energy and Climate Plan'. In response to these obligations, Poland developed an updated draft of the National Energy and Climate Plan for 2021–2030 (aKPEiK), which was submitted for public consultation in October 2024. The draft update of the National Energy and Climate Plan (aKPEiK) outlines two development scenarios for the energy sector up to 2040:

- A market and technology-based scenario (WEM – with existing measures).
- An intensified transition scenario (WAM – with additional measures), focusing on accelerating the deployment of renewable energy and low-emission technologies.

The main objectives outlined in this document are as follows:[55]

- Reduction of greenhouse gas emissions in non-ETS sectors by 14.1% by 2030, compared to 2005 levels.
- Achievement of a 29.8% share of renewable energy in gross final energy consumption by 2030.

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[54] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources and repealing Council Directive (EU) 2015/652. *Official Journal of the European Union*, L 2023/2413, 31 October 2023, 1–58. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413

[55] Ministry of Climate and Environment. (2024). *National Energy and Climate Plan until 2030.*

- Increase in energy efficiency by 5.9% by 2030, relative to the PRIMES 2020 projections for primary energy consumption.

The objective of increasing the share of RES in gross final energy consumption is to take into account total consumption in electricity, district heating, cooling, and transport. The planned RES share is 50.1% in electricity, 32.1% in district heating and cooling, and 17.7% in transport.

To achieve the planned targets, an increase in financing for renewable energy projects is anticipated through the continued application of existing support mechanisms and the development of new financial instruments to encourage investment in low- and zero-emission technologies for electricity, heating, and cooling production, as well as for transport applications. The document also outlines plans to expand small-scale renewable energy installations, increase use of advanced biofuels, and develop offshore wind energy.

Another national strategic document that defines energy and climate objectives is 'Energy Policy of Poland until 2040' (EPP2040),[56] published in February 2021, alongside the 'Assumptions for Updating the Energy Policy of Poland until 2040[57] released in March 2022. The latter was developed in response to the challenges posed by the COVID-19 pandemic and the war in Ukraine. These documents frame Poland's energy transition, taking into account the specific characteristics of the Polish energy sector and the challenges associated with aligning it with European climate and energy policy. The planned actions also prioritise ensuring energy security, maintaining the competitiveness of the national economy, improving energy efficiency, and reducing the environmental impact of the energy sector.

The 'Energy Policy of Poland until 2040' is structured around three key pillars:

- A just transition,
- A zero-emission energy system,
- High air quality.

These pillars serve as the foundation for the specific objectives outlined in this document, as well as for the strategic actions and projects designed to support their implementation. The specific objectives focus on:

- Optimal use of own energy resources,
- Expansion of electricity generation and grid infrastructure,
- Diversification of supply and development of network infrastructure for natural gas, crude oil and liquid fuels,
- Development of energy markets,

[56] Ministry of Climate and Environment. (2021). *Polish Energy Policy until 2040.*

[57] Ministry of Climate and Environment. (2022). *Assumptions for updating the Polish Energy Policy until 2040 of March 2022.*

- Implementation of nuclear energy,
- Development of renewable energy sources,
- Development of district heating and cogeneration,
- Improvement of energy efficiency.

The strategic projects planned for implementation under the specific objectives of Poland's Energy Policy are presented in Table 1.3. The listed areas of action encompass the entire energy supply chain, from acquiring raw materials through generating, transmitting, and distributing energy to its final use.

Table 1.3. Specific objectives and strategic projects of the Energy Policy of Poland

No.	Specific objective	No.	Strategic project
1.	Rational use of own energy raw materials.	1	Transition of coal regions.
2.	Expansion of electricity generation and network infrastructure.	2A	Capacity market.
		2B	Construction of a smart grid.
3.	Diversification of supply and development of network infrastructure for natural gas, crude oil and liquid fuels.	3A	Construction of the Baltic Pipe.
		3B	Construction of Line 2 of the Pomeranian Pipeline.
4	Development of energy markets.	4A	Implementation of the Action Plan for achieving the goal of 70% cross-border transmission capacity.
		4B	Gas hub.
		4C	Electromobility development programme.
5	Implementation of nuclear power.	5	Polish Nuclear Power Programme.
6	Development of renewable energy sources.	6	Implementation of offshore wind energy.
7	Development of district heating and cogeneration.	7	Development of district heating.
8	Improvement of energy efficiency.	8	Promoting of energy efficiency improvement.

Source: Ministry of Climate and Environment (2021).[58]

[58] Ministry of Climate and Environment. (2021). *Polish Energy Policy until 2040*.

In the context of renewable energy, the key elements of EP2040 include:

- An increase in the share of renewable energy sources across all sectors and technologies. The planned share of RES in gross final energy consumption is set at 23%, including:[59]
  - At least 32% in the power sector,
  - 28% in the heating sector,
  - 14% in the transport sector, including electromobility.
- Development of offshore wind energy, with a planned installed capacity of 5.9 GW by 2030 and 11 GW by 2040.
- Growth in installed capacity in photovoltaics, with a planned capacity of 5–7 GW by 2030 and 10–16 GW by 2040.
- Reduction in greenhouse gas emissions, with a planned reduction of approximately 30% by 2030, compared to 1990 levels.
- Measures to improve air quality in the heating and transport sectors, including the use of renewable energy technologies.
- Development of energy technologies and support for research, development and innovation in renewable energy, energy storage, electromobility, and hydrogen technologies.

The conclusions from the analyses undertaken to develop the EPP2040 include, among others, projected structure of net installed capacity, and structure of net electricity production.

These projections are provided for 2025, 2030, 2035, and 2040, disaggregated by energy source.

The forecasted installed capacity in the Polish power system is presented in Table 1.4. In this table, the projected values are shown with the current installed capacity. The figures representing the 2024 baseline differ from those reported by ENTSO-E (shown in Table 1.1), as only the technologies identified in Poland's Energy Policy 2040 strategic document are included here. This capacity is expected to increase to 56.4 GW by 2030 and 60.0 GW by 2040, although a temporary reduction in system capacity is anticipated in 2035 owing to the decommissioning of inefficient coal-fired units. Regarding renewable energy sources, PEP2040 projected an increase in installed capacity, primarily from offshore wind farms and photovoltaic systems. For this latter technology, the projected capacity for 2040 has already been achieved. At the end of 2024, the installed capacity in solar units amounted to 14,6 GW, compared to the initial targets of 5.1 GW by 2025 and 9.8 GW by 2040. This dynamic development is primarily a consequence of energy policy and implemented support mechanisms providing subsidies for the installation of photovoltaic panels. Government support programmes primarily contributed to the increase in installed capacity among households, public buildings, and enterprises.

[59] Ministry of Climate and Environment. (2021). *Polish Energy Policy until 2040.*

Table 1.4. Projected capacity in the Polish power system based on EPP2040 and as at the end of 2024

Technology	EPP2040 (MW)				Present capacity (MW)
	2025	2030	2035	2040	2024
Hard coal	18,304	17,615	11,561	8,530	18,831
Lignite	7,448	7,448	3,812	1,126	7,557
Natural gas	7,386	8,182	10,666	15,774	5,162
Biomass	1,115	1,302	1,442	1,423	662
Nuclear energy	0	0	2,200	4,400	0
Hydropower	2,419	2,419	2,419	2,419	2,378
Onshore wind	9,661	8,663	4,827	6,939	9,583
Offshore wind	0	5,900	9,590	9,590	0
Photovoltaics	5,114	5,114	5,114	9,814	14,609
Total	51,447	56,643	51,631	60,015	61,092

Source: Ministry of Climate and Environment (2021)[60] and ENTSO-E (2024).[61]

A direct consequence of the increase in installed capacity in photovoltaic systems is a dynamic growth in electricity generation from these sources. In 2024, these installations produced 17.3 TWh of electricity, compared to projections of 4.4 TWh for 2030 and 9.6 TWh for 2040 (Table 1.5). Projected trends also include the development of nuclear energy and offshore wind farms. Electricity production from these new sources is intended to cover system demand following the decommissioning of coal-fired units. It is also anticipated that, in the long term, electricity generation from hard coal and lignite-based units will become economically inefficient, owing to expected increases in the price of carbon dioxide emission allowances and environmental fees. The baseline figures presented in Table 1.5 also differ from those reported by ENTSO-E for 2024 (Table 1.2), as the table reflects only those technologies explicitly outlined in Poland's Energy Policy 2040 strategic document.

[60] Ministry of Climate and Environment. (2021). *Polish Energy Policy until 2040: Annex No. 2 – Conclusions from forecast analyses for the energy sector*.

[61] ENTSO-E (2024). *Installed capacity per production type*. https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/

Table 1.5. Projected electricity generation in the Polish power system based on PEP2040 and actual generation as of the end of 2024

Technology	PEP2040 (TWh)				Present generation (TWh)
	2025	2030	2035	2040	2023
Hard coal	35.9	26.9	21.8	18.2	56.1
Lignite	50.6	41.0	18.1	4.6	32.9
Natural gas	45.1	52.6	67.5	67.6	16.7
Biomass	6.6	7.4	8.0	7.5	2.4
Nuclear energy	0.0	0.0	16.7	33.4	0.0
Hydropower	1.8	1.8	1.9	1.8	1.9
Onshore wind	25.4	23.1	14.5	22.1	23.8
Offshore wind	0.0	24.0	39.2	39.4	0.0
Photovoltaics	4.6	4.4	4.3	9.6	17.3
Total	170.0	181.2	192.0	204.2	150.3

Source: Ministry of Climate and Environment (2021)[62] and ENTSO-E (2024).[63]

The development of renewable energy sources is a key element of climate and energy strategies aimed at achieving long-term climate neutrality, both globally and at the EU and national levels. In recent years, Poland has observed a dynamic increase in the share of renewable energy technologies, particularly photovoltaics and onshore wind energy. Although some previously planned renewable energy objectives have already been achieved, many strategic goals for increasing the share of RES in the electricity, district heating, and transport sectors remain to be met.

The development of the renewable energy sector is naturally associated with various uncertainties and challenges, including:

- The integration of new RES systems with transmission and distribution infrastructure,

[62] Ministry of Climate and Environment. (2021). *Polish Energy Policy until 2040*.

[63] ENTSO-E. (2024). *Actual generation per production type.* https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show

- Ensuring stability of supplies,
- The development of technologies enabling the balancing of variable production in wind farms and photovoltaic systems.

The above-mentioned factors imply technological and regulatory risks for energy companies implementing and planning investments in new renewable generation capacity.[64] Existing strategic and legislative documents highlight the key role of public funding in mitigating the investment risks associated with RES, particularly through support for relevant research and projects. Support systems dedicated to renewable energy technologies are expected to enable more efficient decarbonisation of energy systems and a 'just' transition, especially in regions historically reliant on coal-fired power plants.

1.3. Support mechanisms as a risk mitigation factor in renewable energy

Support mechanisms are widely used instruments to promote desired development directions across various economies and sectors, as well as to influence consumer behaviour.[65,66] In power systems, these mechanisms encourage investments in specific technologies by reducing investor risk.[67] Investment risk is one of the key challenges facing potential entrepreneurs. It stems from the dynamic development of the energy sector and the significant impact on project profitability from external factors, including both market conditions and legal and regulatory frameworks.[68] Currently, in the era of the energy transition and decarbonisation of global economies, effective risk management is essential for ensuring stable and sustainable business growth.[69]

The decarbonisation of the Polish power system, which is still largely based on fossil fuels, requires a reduction in capacity installed in coal-fired power plants

[64] Zamasz, K. (2020). Sources of uncertainty and investment risk in an energy company. In K. Zamasz, K. Szczepańska-Woszczyna, & G. Kinelski (Eds.), *Innovation in organisational management: Under conditions of sustainable development* (pp. 139–151). Dąbrowa Górnicza: Akademia WSB.

[65] Kamrat, W., Augusiak, A., & Jaskólski, M. (2007). Mechanizmy wspierania rozwoju wytwarzania energii elektrycznej ze źródeł odnawialnych [Support mechanisms for the development of renewable electricity generation]. *Polityka Energetyczna*, 10*(2)*, 53–69.

[66] Zamasz, K., Kapłan, R., Kaszyński, P., & Saługa, P.W. (2020). An analysis of support mechanisms for new CHPs: The case of Poland. *Energies*, 13*(21)*, 5635. https://doi.org/10.3390/en13215635

[67] Kozlova, M., & Overland, I. (2022). Combining capacity mechanisms and renewable energy support: A review of the international experience. *Renewable and Sustainable Energy Reviews*, *155*, 111878. https://doi.org/10.1016/j.rser.2021.111878

[68] Kamrat, W. (2004). *Metody oceny efektywności inwestowania w elektroenergetyce* [Methods for assessing investment effectiveness in the power sector]. Gdańsk: Wydawnictwo Politechniki Gdańskiej.

[69] Leśniak, A., Palacz, K., Surma, T., & Zamasz, K. (2024). Ewolucja (reforma) unijnego rynku energii elektrycznej. *Przegląd Elektrotechniczny, 100*(8), 52–56. https://doi.org/10.15199/48.2024.08.12

and an increase in capacity installed in renewable energy sources. However, owing to the operational characteristics of renewable energy units (primarily wind and photovoltaic installations), conventional generation capacity cannot be directly replaced on a one-to-one basis by renewable capacity. High capital expenditures required for investments in new RES sources, combined with their low capacity factors (compared to conventional units) and seasonal, weather-dependent production, make such investments highly risky.

Therefore, to meet decarbonisation commitments at both national and international levels, financial instruments have been introduced to reduce investor risk and create incentives for developing new renewable units. Programmes promoting RES implementation thus provide businesses with financial compensation in addition to revenues from electricity sales.[70]

In Poland, the support systems that provide additional remuneration for RES investors include:

- RES auctions,
- Capacity market,
- Contracts for Difference,
- Certificates of origin,
- Feed-in tariff systems,
- Mechanisms dedicated to small and medium individual producers.

The mechanisms and instruments supporting the generation of electricity in RES installations are the subject of the fourth chapter of the Renewable Energy Sources Act entitled 'Mechanisms and instruments supporting the generation of electricity from renewable energy sources, agricultural biogas and heat in renewable energy source plants' [Journal of Laws of 2015, item 478 (as amended)].[71]

Consistent with the research focus of this study, the following section examines support systems for RES targeted at energy companies. Systems designed for the agricultural sector or small consumers are excluded from this analysis. The emphasis is placed on RES auctions, the capacity market, and Contracts for Difference for offshore wind energy, as these mechanisms play a decisive role in shaping investment decisions of large-scale energy companies, secure substantial volumes of new capacity, and have a direct impact on both the cost structure and the pace of the energy transition in Poland.

[70] Kozlova, M., Huhta, K., & Loghrmann, A. (2023). The interface between support schemes for renewable energy and security of supply: Reviewing capacity mechanisms and support schemes for renewable energy in Europe. *Energy Policy, 181*, 113707. https://doi.org/10.1016/j.enpol.2023.113707

[71] Act of 20 February 2015 on renewable energy sources, *Journal of Laws 2015*, item 478.

1.3.1. RES auctions

RES auctions are a system introduced to promote the production of electricity from renewable energy sources and constitute a key element of Poland's climate and energy policy aimed at increasing the share of renewable energy and reducing greenhouse gas emissions. In these auctions, RES energy producers submit bids specifying the amount of energy they commit to generate and the price at which they are willing to sell it. The auctions are organised by the President of the Energy Regulatory Office and are conducted individually for different technology categories and installation sizes. The primary selection criterion for bids is price – the auction is won by the bids offering the lowest price per unit of electricity generated. Entities that win an RES auction sign long-term energy purchase agreements. These agreements guarantee a fixed energy price over the contract horizon (15 to 25 years), ensuring project financial stability. This stability minimises the risk related to price volatility in the electricity market, which itself is affected by numerous external conditions.

The functioning of the RES auction system is governed by the Renewable Energy Sources Act,[72] and further detailed in several regulations:

- The Ordinance of the Council of Ministers on the maximum quantity and value of electricity from renewable energy sources eligible for sale through auction,[73]
- The Ordinance of the Minister of Climate and Environment on the reference price of electricity from renewable energy sources,[74]
- The Auction Rules pertaining to the sale of electricity generated in RES installations.[75]

RES auctions are organised at least once a year by the President of the Energy Regulatory Office. These auctions are conducted separately for electricity generated in RES installations, categorised by the specific primary energy carrier used. In addition, auctions are also conducted separately for RES installations based on their total installed capacity:

- Installations with a capacity at or below a regulated threshold,
- Installations with a capacity exceeding that threshold.

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72 Ibid.

73 Ministry of Climate. (2022). *Ordinance of the Council of Ministers of 27 September 2022 on the maximum quantity and values of electricity from renewable energy sources that may be auctioned in individual consecutive calendar years 2022–2027* (Journal of Laws of 2022, item 2085).

74 Ministry of Climate and Environment. (2023). *Ordinance of 8 November 2023 on the reference price of electricity from renewable energy sources, periods applicable to producers that have won auctions, and reference electricity sales volumes* (Journal of Laws 2023, item 2440).

75 *Rules of the auction for the sale of electricity generated in renewable energy source systems* (ERO, 2020).

Typically, capacity thresholds are 500 kW or 1 MW, depending on the energy source used for electricity production. The main beneficiaries of RES auctions are units located in Poland. However, the law permits the participation of electricity produced outside Poland, although this is limited to 5% of the total quantity and value of electricity specified for sale in the relevant ordinance from the previous year.

Auctions are conducted separately based on the type of RES plant, which are classified into five categories, also referred to as technological groups (Figure 1.5). The first technological group contains sixteen types of plants described in the RES Act, which include:

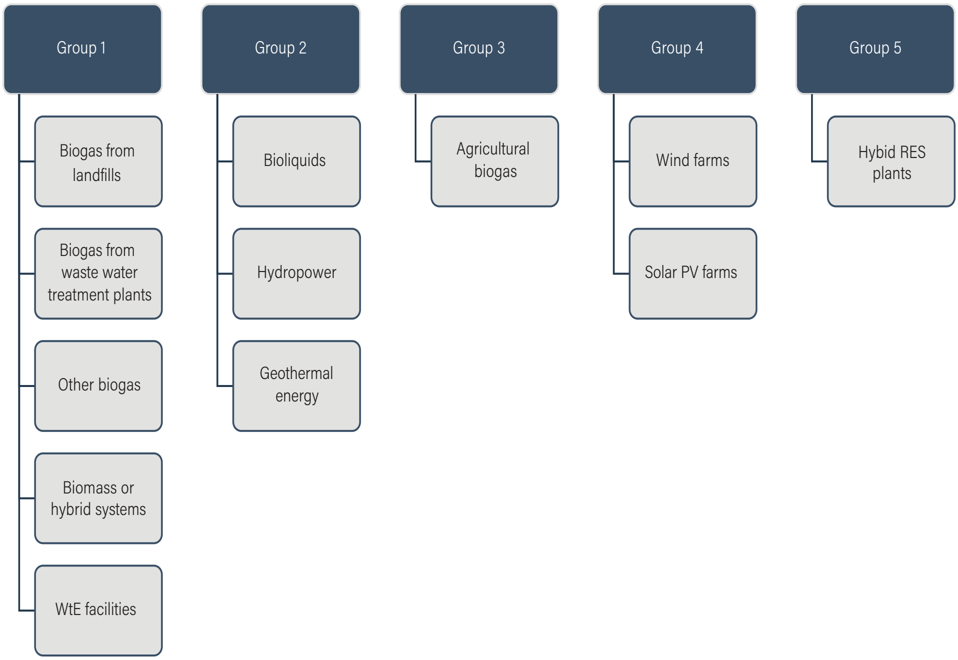
- Installations using non-agricultural biogas for electricity production, encompassing high-efficiency cogeneration units (representing twelve plant types varying by biogas source and total installed capacity),
- Dedicated biomass combustion installations or hybrid systems,
- Waste-to-energy (WtE) installations or dedicated multi-fuel combustion installations,
- Waste-to-energy installations within dedicated biomass combustion plants or high-efficiency cogeneration hybrid systems.

The second technological group contains plants using:

- Bioliquids,
- Geothermal energy,
- Hydropower for electricity production.

The third group includes installations using agricultural biogas. The fourth category consists of wind and photovoltaic units. The fifth group contains hybrid RES installations. These technological groups are one of the parameters for structuring the RES auctions.

Figure 1.5. RES auction technological groups



Source: Own study based on Journal of Laws of 2015, item 478.[76]

As previously noted, the quantity and value of electricity from renewable energy sources sold through the RES auction are determined by regulation. If these specified targets are not met in the initial auction within a calendar year, the President of the Energy Regulatory Office may organise additional tenders.

The maximum quantity of electricity from RES generation units that could be sold in 2022–2027, as determined by the relevant ordinance, was:[77]

- For units with a total installed capacity of up to 1 MW:
  - 11,250,000 MWh for wind and photovoltaic units, with a maximum value of PLN 3.825 billion,
  - 1,110,000 MWh for biogas units, with a maximum value of PLN 609.0 million,
  - 975,000 MWh for units using hydropower, bioliquids or geothermal energy, with a maximum value of PLN 508.5 million.
- For units with a total installed capacity of more than 1 MW:

[76] Act of 20 February 2015 on renewable energy sources (*Journal of Laws of 2015*, item 478).

[77] Ministry of Climate. (2022). *Ordinance of the Council of Ministers of 27 September 2022 on the maximum volumes and values of electricity from renewable energy sources that may be auctioned in individual consecutive calendar years 2022–2027* (Journal of Laws 2022, item 2085).

– 21,750,000 MWh for wind and photovoltaic units with a maximum value of PLN 6.225 billion,
– 45,000,000 MWh for biogas, biomass units or thermal waste treatment facilities with a maximum value of PLN 24.705 billion,
– 2,040,000 MWh for units using hydropower, bioliquids or geothermal energy with a maximum value of PLN 1,038 billion,
– 5,775,000 MWh for units using agricultural biogas with a maximum value of PLN 3,870 billion.

According to the current regulations, among installations with an installed capacity up to 1 MW, the largest volume and energy value were allocated to wind and photovoltaic units. For installations with a capacity exceeding 1 MW, the highest level of financial support was allocated to hydropower, geothermal, and bioliquid units. The presented amounts and values of energy apply to producers generating energy for the first time after the closing day of the auction session in RES plants. In other cases, i.e. for existing and modernised units, the regulation set the energy volume eligible for auction sales at zero.

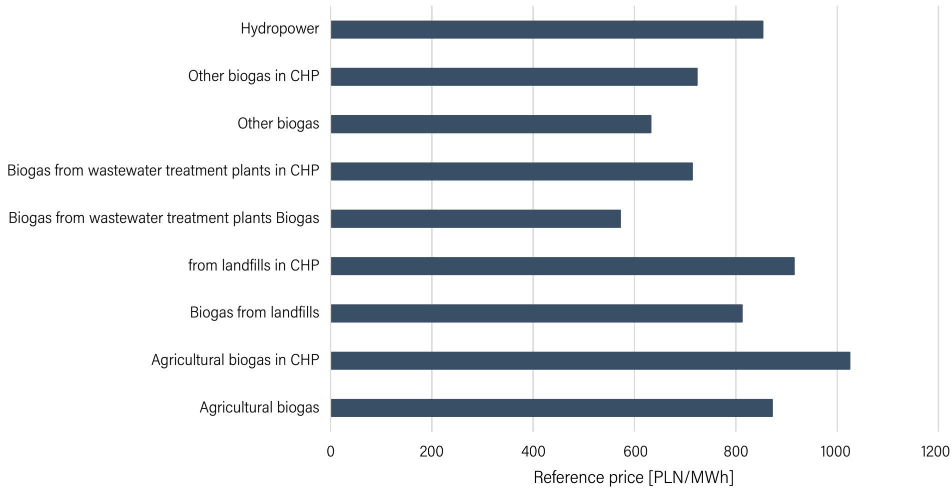
In addition to the presented parameters, a separate regulation defines the maximum unit price at which electricity can be sold by auction. The Minister competent for environmental affairs determines the reference price, taking into account a range of factors, including:

- Capital expenditures for the construction of RES installations together with the necessary infrastructure,
- Techno-economic parameters of individual RES installations,
- Operational costs,
- Forecasts for fuel prices and carbon dioxide emission allowances,
- Impact of the installation on the environment and water management,
- Economic and social objectives set out in national strategic documents.

The reference price is determined individually for each technology group and total installed capacity.

The reference prices for units up to 500 kW determined for the auction in 2024 ranged from PLN 572/MWh for units using biogas from wastewater treatment plants for electricity production to PLN 1025/MWh for cogeneration units using agricultural biogas for electricity production (Figure 1.6). In all units using biogas, regardless of its source, the reference price was set higher for cogeneration units to promote production from these sources.

Figure 1.6. Reference price for electricity from renewable energy sources with a total installed capacity of up to 500 kW

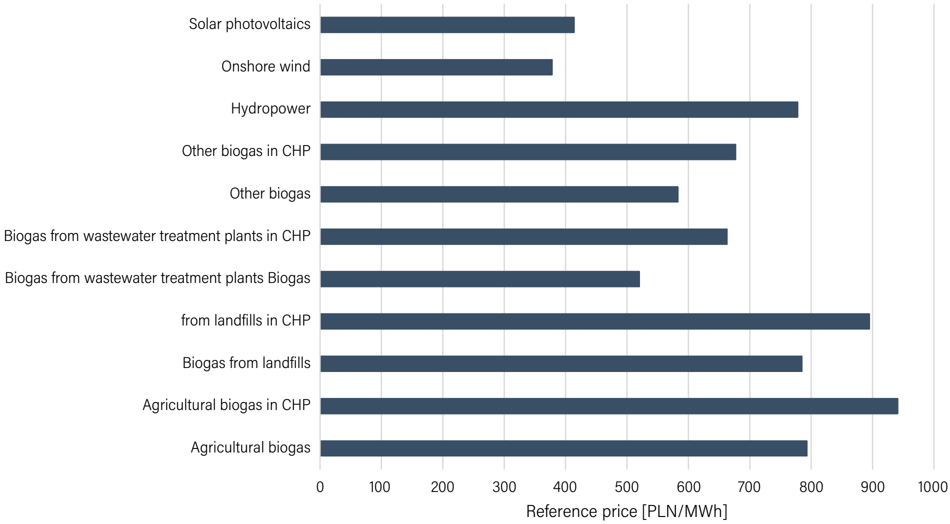


Source: Prepared on the basis of *Journal of Laws of 2023*, item 2440.[78]

For power generation units with a capacity up to 1 MW, the reference prices in 2024 ranged from 378 PLN/MWh for installations using wind energy for electricity generation to 941 PLN/MWh for cogeneration units using agricultural biogas for electricity production (For power generation units with a capacity up to 1 MW, the reference prices range from 378 PLN/MWh for installations using wind energy for electricity generation to 941 PLN/MWh for cogeneration units using agricultural biogas for electricity production (Figure 1.7). It is worth noting that the reference prices are higher for biogas units (regardless of the source of biogas) and hydropower units than for wind or photovoltaic units. Similarly, as in the case of units with a capacity of up to 500 kW, the reference prices set for cogeneration units are higher than those for operating in systems without high-efficiency cogeneration.

[78] Ministry of Climate and Environment. (2023). *Ordinance of 8 November 2023 on the reference price of electricity from renewable energy sources, periods applicable to producers that have won auctions, and reference electricity sales volumes* (Journal of Laws 2023, item 2440).

Figure 1.7. Reference price for electricity from renewable energy sources with a total installed capacity of up to 1 MW



Source: Prepared on the basis of *Journal of Laws of 2023*, item 2440.[79]

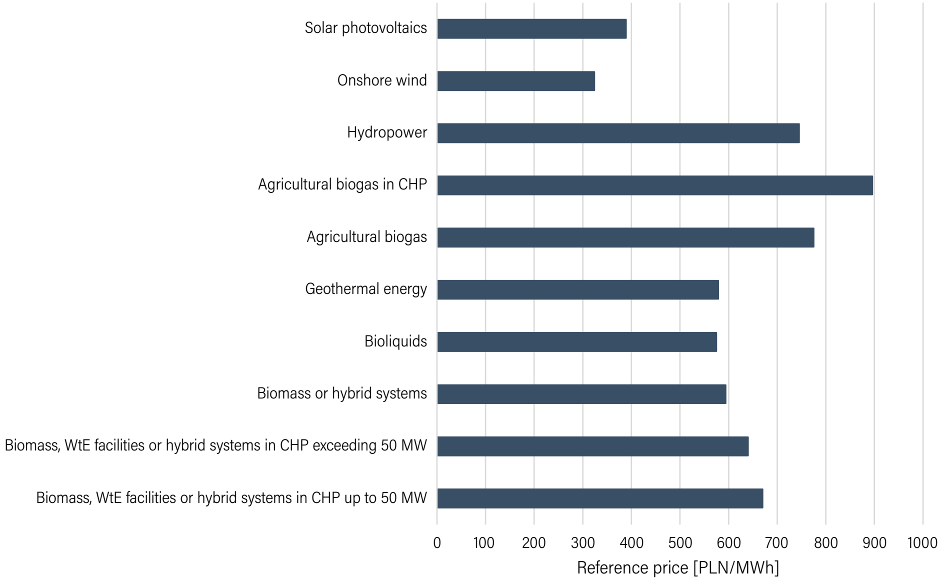
The ordinance of the Minister competent for the environment on the reference price of electricity from renewable energy sources also specifies reference prices for:

- Installations with a capacity exceeding 1 MW using agricultural biogas, hydropower, wind energy and solar energy for electricity generation,
- Waste-to-energy facilities, in dedicated biomass combustion installations or hybrid systems in high-efficiency cogeneration up to 50 MW and exceeding 50 MW,
- Dedicated biomass combustion installations or hybrid systems, as well as installations using bioliquids and geothermal energy, without restrictions on the installed capacity of these units (Figure 1.8).

As in the case of the previously analysed installed capacity ranges, the reference prices for electricity produced in the above-mentioned installations are highest for high-efficiency cogeneration units using agricultural biogas (PLN 896/MWh), and lowest for wind power plants (PLN 324/MWh) and photovoltaic installations (PLN 389/MWh).

[79] Ibid.

Figure 1.8. Reference price for electricity from renewable energy sources with a total installed capacity exceeding 1 MW



Source: Prepared on the basis of *Journal of Laws of 2023*, item 2440.[80]

To identify potential revenues for entities planning investments in RES and understand the impact of auction results on the risk level when assessing the economic efficiency of renewable energy projects, the results of RES auctions conducted in 2024 were analysed.

As part of the RES auctions announced by the President of the Energy Regulatory Office, the maximum amount of electricity that could be sold by auction in 2024 was 44.6 TWh, while the maximum value was set at PLN 17.0 billion (Table 1.6). The largest amount (33 TWh, 48.8% of the total announced for all RES tenders) was allocated to auctions for generators in onshore wind and solar photovoltaics installations exceeding 1 MW. In all cases, these maximum quantities and values coincide with those specified for 2023 in the Ordinance of the Council of Ministers on the maximum quantities and values of electricity from renewable energy sources that may be auctioned in individual consecutive calendar years from 2022 to 2027.[81]

[80] Ibid.

[81] Ministry of Climate. (2022). *Ordinance of the Council of Ministers of 27 September 2022 on the maximum volumes and values of electricity from renewable energy sources that may be auctioned in individual consecutive calendar years 2022–2027* (Journal of Laws 2022, item 2085).

Table 1.6. Parameters of RES auctions announced by the President of the Energy Regulatory Office in 2024

Technology/energy carrier	Capacity	Amount	Value
• Non-agricultural biogas • Biomass or hybrid systems • Thermal waste treatment facilities or multi-fuel firing combustion plants	≤ 1 MW	1.110 TWh	PLN 609 million
• Non-agricultural biogas • Biomass or hybrid systems • Thermal waste treatment facilities or multi-fuel firing combustion plants	> 1 MW	1.688 TWh	PLN 927 million
• Agricultural biogas	> 1 MW	5.775 TWh	PLN 3.870 million
• Hydropower ≤ 1 MW • Bioliquids • Geothermal energy	–	0.975 TWh	PLN 508.5 million
• Hydropower > 1 MW • Bioliquids • Geothermal energy	–	2.040 TWh	PLN 1.038 million
• Onshore wind • Photovoltaics	≤ 1 MW	11.250 TWh	PLN 3.825 million
• Onshore wind • Photovoltaics	> 1 MW	21.750 TWh	PLN 6.225 million
Total		**44.6 TWh**	**PLN 17.0 billion**

Source: Own study based on announcements of RES auctions in 2024.[82]

Although the total volume offered in all RES auctions planned for 2024 was 44.6 TWh, volume of 16.2 TWh was finally contracted, accounting for 36.2% of the maximum amount available (Table 1.7). Five of the seven auctions remained unresolved, namely those intended for:

[82] President of the Energy Regulatory Office. (2024). *Announcements of the President of the Energy Regulatory Office regarding ordinary auctions for the sale of electricity from renewable energy sources: AZ/1/2024, AZ/2/2024, AZ/3/2024, AZ/4/2024, AZ/5/2024, AZ/6/2024, AZ/7/2024.*

1) Installations using non-agricultural biogas or biomass,
2) Hybrid systems, waste-to-energy plants and multi-fuel combustion installations (regardless of the installed capacity),
3) Installations using agricultural biogas,
4-5) Installations using hydropower, bioliquids or geothermal energy for electricity generation – regardless of their capacities.

The above-mentioned auctions were unresolved due to an insufficient number of bids. According to the RES Act, an auction is settled only if at least three valid bids have been submitted.[83]

The auctions that were successfully concluded in 2024 included:

6) Auctions for wind and photovoltaic installations, with an installed capacity of no more than 1 MW,
7) Auctions for wind and photovoltaic installations with an installed capacity above 1 MW.

In the case of units with a capacity less than or equal to 1 MW, 0.74 TWh was contracted, which constituted 6.6% of the maximum amount that could be sold during the auction. Its value was PLN 254.7 million, i.e. 6.7% of the maximum possible value determined by the President of the Energy Regulatory Office for electricity sold during the auction. In the case of units with a capacity greater than 1 MW, 15.39 TWh of electricity was contracted (70.8% of the maximum amount) with a value of PLN 4.9 billion (78.0% of the maximum value).

In the auction for installations with a capacity of up to 1 MW, 174 bids were submitted, and 128 resulted in contracted electricity sales. The minimum contracted price was PLN 149.00/MWh, while the maximum was PLN 334.77/MWh. In the auction for installations with a capacity exceeding 1 MW, 96 bids were submitted, with 72 winning the auction. The minimum price was PLN 297.78/MWh, and the maximum price was PLN 388.00/MWh.

[83] *Act of 20 February 2015 on renewable energy sources*, Journal of Laws of 2015, item 478.

Table 1.7. Results of RES auctions conducted in 2024

Technology/energy carrier	System capacity	Amount of energy	Energy value
• Non-agricultural biogas • Biomass or hybrid systems • Thermal waste treatment facilities or multi-fuel firing combustion plants	≤ 1 MW	Unresolved	
• Non-agricultural biogas • Biomass or hybrid systems • Thermal waste treatment facilities or multi-fuel firing combustion plants	> 1 MW	Unresolved	
• Agricultural biogas	> 1 MW	Unresolved	
• Hydropower • Bioliquids • Geothermal energy	≤ 1 MW	Unresolved	
• Hydropower • Bioliquids • Geothermal energy	> 1 MW	Unresolved	
• Onshore wind • Photovoltaics	≤ 1 MW	0.74 TWh	PLN 254.7 million
• Onshore wind • Photovoltaics	> 1 MW	15.39 TWh	PLN 4,856.17 million
Total		**16.13 TWh**	**PLN 5,110.9 billion**

Source: Own study based on the decisions of the RES auction in 2024.[84]

The reason for the reduced interest in the auction support system is the availability of long-term *corporate Power Purchase Agreements* (cPPAs), which can be a more attractive solution for investors in renewable energy technologies. cPPAs are direct contracts between producers and consumers, typically concluded for 15–20 years, operating outside market transactions. This option can ensure stable energy prices long term and provide independence from energy sellers. Since these contracts can be concluded before the construction of RES plants begins, they offer an opportunity to secure project financing and are thus competitive with RES auctions.

[84] President of the Energy Regulatory Office. (2024) *Information of the President of the Energy Regulatory Office on ordinary auctions No. AZ/1/2024, AZ/2/2024, AZ/3/2024, AZ/4/2024, AZ/5/2024, AZ/6/2024, AZ/7/2024.*

1.3.2. Capacity market

The capacity market is a mechanism for remunerating capacity, introduced to ensure the long-term availability of generation capacity within the electricity system.[85,86] Poland uses a centralised form of this market,[87] and the product subject to trade transactions is dispatchable power.[88] Enterprises, after prior certification of their units, submit bids in which they specify the available capacity they submit for the auction and the corresponding price.[89] In this centralised market, the Transmission System Operator (TSO) acts as the sole buyer. After analysing the power system's current and projected state, the TSO announces the required capacity obligation to be procured through the capacity auction.[90] The capacity market framework includes main capacity auctions conducted five years before the supply period and additional auctions arranged one year prior. Units that win capacity market auctions are obliged, in return for remuneration, to remain available and to deliver their contracted capacity during periods of system stress.

The Capacity Market Act[91] and associated regulations govern the market in Poland, with detailed operations specified in the Capacity Market Rules.[92] These documents primarily determine the organisation of this market and the rules for providing the service of remaining ready to supply electrical power to the system and the service of supplying power during periods of emergency. The aim of these documents is not only to guarantee the security of electricity supply in the medium and long term, but also to ensure that these processes take place in a cost-effective and sustainable way.

Before proceeding to the main capacity auction, it is necessary to participate in two certifications:

1) General certification,
2) Certification for the main auction.

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[85] Spees, K., Newell, S. A., & Pfeifenberger, J. P. (2013). Capacity Markets – Lessons learned from the first decade. *Economics of Energy & Environmental Policy*, *2*(2), 1–6.

[86] De Vries, L., & Heijnen, P. (2008). The impact of electricity market design upon investment under uncertainty: The effectiveness of capacity mechanisms. *Utilities Policy*, *16*(3), 215–227.

[87] Act of 8 December 2017 on the capacity market, *Journal of Laws of 2018*, item 9.

[88] Cramton P., & Ockenfels A. (2012). Economics and Design of Capacity Markets for the Power Sector. *Zeitschrift für Energiewirtschaft*, *36*, 113–134.

[89] Zamasz, K. (2015). *Efektywność ekonomiczna przedsiębiorstwa energetycznego w warunkach wprowadzenia rynku mocy* [Effectiveness of the economic efficiency of the energy company in the conditions of introducing the power market]. Wydawnictwo Naukowe PWN.

[90] Bowring, J. E. (2013). Capacity markets in PJM. *Economics of Energy & Environmental Policy*, *2*(2), 51–53.

[91] *Act of 8 December 2017 on the capacity market,* Journal of Laws of 2018, item 9.

[92] Polskie Sieci Elektroenergetyczne (2023). *Capacity Market Rules.*

General certification is mandatory for all generating units in the system with a capacity exceeding 2 MW, irrespective of their plans for upcoming capacity auctions. Its purpose is for the operator to obtain information about physical units in the power system and to enter them into the capacity market register. Certification for the main auction is intended for units planning to participate in that auction, aiming to create capacity market units and admit them to the auction process.

Capacity market units can be both generation units and demand side response units. The following entities may participate in capacity auctions:

- Existing units,
- Units intended for modernisation,
- Planned units.

Different maximum contract durations apply depending on the status of the capacity market unit. Capacity contracts are therefore signed as follows:

- Existing units: 1 year,
- Units scheduled for modernisation: 5 or 7 years (depending on emissions profile),
- Planned units: 15 or 17 years.

Long-term contracts for units to be modernised and new generation units are crucial for ensuring the stability of the Polish power system, particularly considering the gradual phase-out of inefficient coal generation.

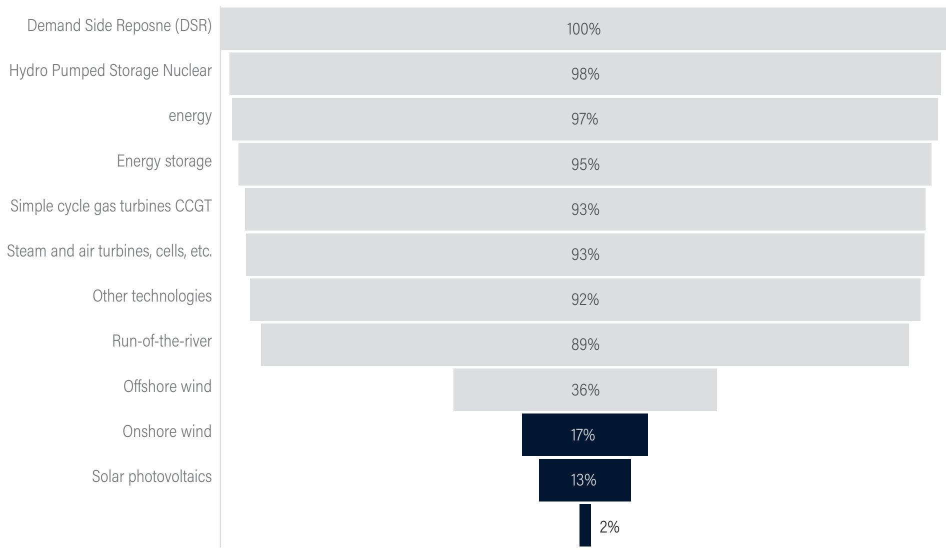
Besides domestic units, foreign companies (EU countries) whose electricity systems are directly connected to the Polish system may participate in capacity auctions. In accordance with applicable regulations, units located in three zones may participate in the capacity market:

1) The synchronous zone (Germany, Czech Republic, Slovakia transmission systems),
2) The Lithuanian transmission system zone,
3) The Swedish transmission system zone.

The maximum size of the capacity obligation that can be offered on the capacity market is the product of the unit power and the corrective availability factor. This factor, determined by ordinance individually for different technology groups, reflects the ability of individual technologies to produce electricity relative to their maximum theoretical potential and varies depending on the technology. Figure 1.9 presents the corrective availability factors for individual technology groups for the supply period in 2028. The 100% availability rate was determined only for demand side response units. Availability rates of 95% and more have been determined for reservoir and run-of-the-river hydroelectric power plants, reservoir hydroelectric power plants with a pumping unit, and reservoir and run-of-the-river hydroelectric power plants with a pumping unit, for nuclear units and electricity storage in the form of batteries, kinetic energy storage and supercapacitors. Rates exceeding 90% primarily apply to technologies such as simple-cycle gas turbines, gas-steam systems, steam turbines, steam turbine systems, air turbines, fuel cells, and the organic Rankine cycle.

Corrective availability factors for renewable energy technologies, specifically onshore and offshore wind farms, and for solar power plants, are the lowest among those determined by the ordinance. This reflects their specific operational characteristics and limited availability, which is dependent on system capacity demand. For offshore wind farms, this factor was set at 17.25%; for onshore wind farms, at 12.62%; and it was lowest for solar power plants, at 1.56%.

Figure 1.9. Corrective availability factors for individual technology groups for the supply period in 2028



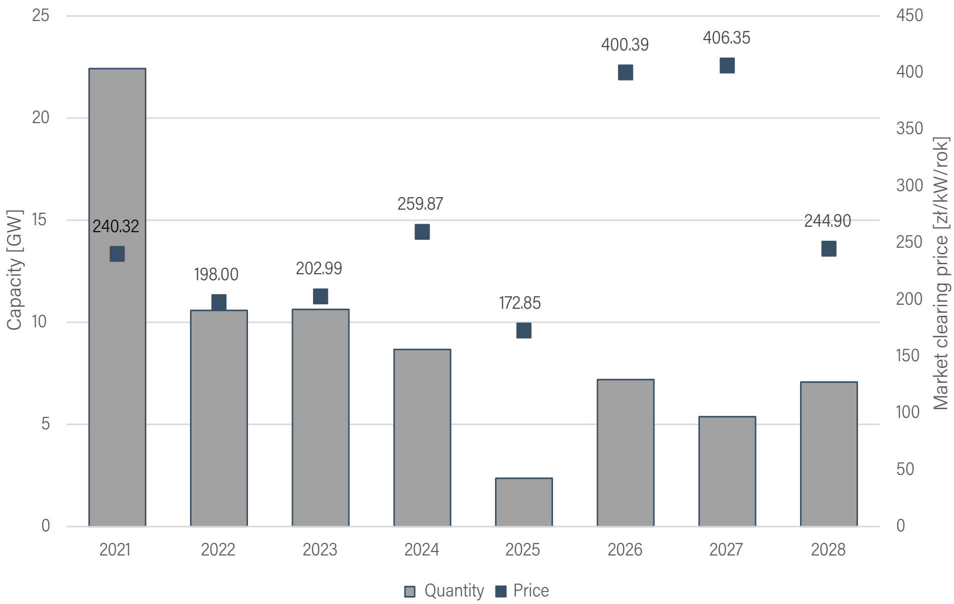
Source: Own study based on *Journal of Laws of 2023*, item 1561.[93]

To date, eight main capacity auctions have been conducted for the 2021–28 supply years. The market clearing price, dependent on the year of delivery, ranged from PLN 172.85/kW/year to PLN 406.35/kW/year (Figure 1.10). The highest market clearing prices occurred during the auctions for the 2026 and 2027 supply years, owing to the reduced availability of new generation capacities bid in those auctions

[93] Ministry of Climate and Environment. (2023). *Ordinance of the Minister of Climate and Environment of 4 August 2023 on the parameters of the main auction for the year of supply 2028 and the parameters of additional auctions for the year of supply 2025* (Journal of Laws 2023, item 1561).

compared to the announced capacity demand. During the most recent capacity auction, for the supply year 2028, the auction cleared in the sixth round, with a market clearing price of PLN 244.90/kW/year. This indicates a greater interest in participating compared to previous years, where auctions closed in the first round.

Figure 1.10. The contracted capacity obligation and the market clearing prices of the main capacity auctions carried out for the 2021–2028 supply period



Source: Own study based on the ERO.[94]

Of the 7.1 GW of capacity contracted for the 2028 supply year, approximately 30% was contracted by existing generating units belonging to the largest energy groups of the State Treasury, with one-year contracts in place. The beneficiaries of 17-year contracts were primarily energy storage facilities, which contracted a total of about 1.7 GW (14%). Among the modernised units, with 7-year contracts, there are about 1.3 GW of capacity, including 1 GW of units owned by Połaniec Power Plant in Enea Group, slated for adaptation to biomass co-firing to meet emission standards necessary for support within the capacity market. Additionally, 15.5% of the total capacity obligation was contracted by foreign generating units (1.1 GW), including 451 MW by units in Sweden, 438 MW by units located in Slovakia and

[94] President of the Energy Regulatory Office. (2021–2024). *Information from the President of the Energy Regulatory Office on the announcement of the final results of the main auction for the supply years 2021, 2022, 2023, 2024, 2025, 2026, 2027 and 2028.*

190 MW by units located in the Czech Republic. Demand reduction units contracted about 1 GW of capacity.

When analysing the results of the latest capacity auction from a renewable energy perspective, the primary beneficiaries of the tender procedure are capacity market units owned by PGE Energia Odnawialna SA, namely the Porąbka-Żar, Żarnowiec, Myczkowce, Dychów, and Smardzewice hydroelectric power plants. As in previous capacity auctions, no wind or solar power plants are among the winning capacity market units.

Consequently, although the capacity market is a non-discriminatory mechanism intended for all electricity generation technologies, non-controllable RES technologies have not benefited from the main capacity auctions conducted so far[95]. This is due to several factors:

- Their operational characteristics,
- The values of the established corrective availability factors,
- The potential penalties for failure to fulfil the capacity obligation.

In the context of risk analysis for assessing the economic efficiency of renewable energy projects in Poland, the capacity market as a support mechanism primarily reduces risk only for energy storage facilities accompanying RES plants.

1.3.3. Contracts for Differences

Contracts for Difference (CfD) represent a support mechanism specifically for offshore wind energy, designed to reduce the risk associated with electricity price volatility and reduce the dependence of investment profitability on changes in electricity markets over the long term.[96] This instrument guarantees energy producers a fixed price for a set period, enabling income stabilisation and predictable returns on investment.[97] Under a CfD, generators meeting the formal requirements can become entitled to negative balance coverage.

This entitlement allows generators to cover the difference between the market price of electricity and a predetermined reference price, thereby covering costs related to electricity production in offshore wind farms. If the market price falls below the reference price, the producer receives a subsidy covering the difference. Conversely, if the market price exceeds the reference price, the producer is obliged

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[95] Czarnecka, M., Ogłódek, T. (Eds.). (2023) *Odnawialne źródła energii. Rynek mocy: inwestycje w zakresie elektrowni wiatrowych. Promowanie energii w wysokosprawnej kogeneracji oraz w morskich farmach wiatrowych: komentarz.* [Renewable energy sources. Capacity market: Investments in wind power plants. Promotion of energy in high-efficiency cogeneration and offshore wind farms: Commentary]. Warszawa: Wydawnictwo C.H. Beck.

[96] Kell, N. P., Santibanez-Borda, E., Morstyn, T., Lazakis, I., & Pillai, A. C. (2023). Methodology to prepare for UK's offshore wind Contract for Difference auctions. *Applied Energy*, *365*, 120844. https://doi.org/10.1016/j.apenergy.2023.120844

[97] Welisch, M., & Poudineh, R. (2020). Auctions for allocation of offshore wind contracts for difference in the UK. *Renewable Energy*, *147*(1), 1266–1274. https://doi.org/10.1016/j.renene.2019.09.085

to reimburse the difference.[98] This provides financing for producers during periods of low electricity prices, without imposing additional costs on consumers when market prices are sufficient to cover production costs.[99]

Offshore wind energy holds a special place in strategic documents related to achieving climate neutrality and developing renewable energy.[100] Poland's potential for offshore wind stems from the favourable geographical and climatic conditions of the Baltic Sea, conducive to efficient electricity production.[101] The relatively high wind speeds recorded in the area of the Baltic Sea, combined with shallower sea depths compared to other basins, result in lower construction and maintenance costs of offshore wind farms.[102]

The primary document governing and supporting the development of offshore wind energy in Poland is the Act on the promotion of electricity generation in offshore wind farms.[103] It defines both the terms and conditions related to the preparation and implementation of investments in this technology, as well as the principles and conditions of support for electricity produced in offshore wind farms. The Act is therefore a key document governing the functioning of contracts for difference.

In accordance with applicable regulations, the amount of electricity for which a generator may receive coverage for the negative balance is calculated as the product of 100,000 hours and the installed capacity of the offshore wind farm (or relevant part thereof). The maximum support period is 25 years, starting either from the first day of electricity generation or the first day the generator applies to join the support scheme. Reference prices are determined by ordinance from the minister competent for the environment, based on technical and economic parameters of technologies for offshore wind farms and associated investment and operating costs related to plant construction and electricity generation. At the end of 2023, the maximum price for electricity produced in

98 Kell, N. P., van der Weijde, A. H., Li, L., Santibanez-Borda, E., & Pillai, A. C. (2023). Simulating offshore wind contract for difference auctions to prepare bid strategies. *Applied Energy*, *334*, 120645. https://doi.org/10.1016/j.apenergy.2023.120645

99 Nelson, T., & Dodd, T. (2023). Contracts-for-Difference: An assessment of social equity considerations in the renewable energy transition. *Energy Policy*, *183*, 113829. https://doi.org/10.1016/j.enpol.2023.113829

100 Sobotka, A., Rowicki, M., Badyda, K., & Sobotka, P. (2021). Regulatory aspects and electricity production analysis of an offshore wind farm in the Baltic Sea. *Renewable Energy*, *170*, 315–326. https://doi.org/10.1016/j.renene.2021.01.064

101 Caglayan, D. G., Ryberg, D. S., Heinrichs, H., Linssen, J., Stolten, D., & Robinius, M. (2019). The techno-economic potential of offshore wind energy with optimized future turbine designs in Europe. *Applied Energy*, *255*, 113794. https://doi.org/10.1016/j.apenergy.2019.113794

102 WindEurope. (2022). *Offshore wind in EU maritime spatial plans*. https://windeurope.org/intelligence-platform/product/offshore-wind-in-eu-maritime-spatial-plans/

103 *Act of 17 December 2020 on the promotion of electricity generation in offshore wind farms,* Journal of Laws of 2021, item 234.

an offshore wind farm, forming the basis for coverage for the negative balance, was PLN 319.6/MWh.[104]

The CfD support mechanism includes two phases. The first phase, a pre-auction phase, was in force until 31 March 2021, while the second phase, an auction phase, in 2025. In the first phase, the President of the Energy Regulatory Office granted support through individual administrative decisions. These decisions were based on an assessment of market conditions, the technical and economic parameters of the proposed plants (as submitted in investor applications), and the location conditions of the planned offshore wind farms. Under this phase, the right to cover the negative balance was granted to seven projects with a planned total installed capacity of 5.9 GW, including projects implemented by:

- RWE Offshore Wind Poland Ltd. (former Baltic Trade and Invest Ltd.):[105]
  - 100% of the shares owned by RWE Renewables International Participations B.V.,
  - Total installed capacity: 169–350 MW.
- Baltica Offshore Wind Farm 2 Ltd.:[106]
  - Joint venture: PGE and Ørsted,
  - Total installed capacity: 1,498 MW.
- Baltica Offshore Wind Farm 3 Ltd.:[107]
  - Joint venture: Equinor PGE and Ørsted,
  - Total installed capacity: 1,045.5 MW.
- MFW Bałtyk II Ltd.:[108]
  - Joint venture: Equinor Wind Power AS and Polenergia S.A.,
  - Total installed capacity: 720 MW.
- MFW Bałtyk II Ltd.:[109]
  - Joint venture: Equinor Wind Power AS and Polenergia S.A.,
  - Total installed capacity: 720 MW.

[104] Ministry of Climate. (2021). *Ordinance of the Minister of Climate and Environment of 30 March 2021 on the maximum price for electricity generated in an offshore wind farm and injected into the network in PLN for 1 MWh, which is the basis for settling the right to cover the negative balance.* (Journal of Laws 2021, item 587).

[105] RWE. (2023). *RWE Offshore Wind Poland Ltd. – Update of the supply chain plan.*

[106] PGE & Ørsted. (2023). *Elektrownia Wiatrowa Baltica 2 Sp. z o.o. – aktualizacja Planu łańcucha dostaw* [Baltica Offshore Wind Farm Ltd. – Update of the supply chain plan].

[107] PGE & Ørsted. (2023). *Elektrownia Wiatrowa Baltica 3 Sp. z o.o. – aktualizacja Planu łańcucha dostaw* [Baltica Offshore Wind Farm Ltd. – Update of the supply chain plan].

[108] Equinor Wind Power AS i Polenergia S.A. (2023) *MFW Bałtyk II Sp. z o.o. – aktualizacja Planu łańcucha dostaw* [MFW Bałtyk II Ltd. – Update of the Supply Chain Plan].

[109] Equinor Wind Power AS i Polenergia S.A. (2023) *MFW Bałtyk III Sp. z o.o. – aktualizacja Planu łańcucha dostaw* [MFW Bałtyk III Ltd. – Update of the Supply Chain Plan].

- Baltic Power Ltd.:[110]
  - Joint venture: PKN Orlen and NP Baltic Wind BV.,
  - Total installed capacity: 1,197 MW.
- BC – Wind Polska Ltd.:[111]
  - 100% of Ocean Winds shares resulting from the joint venture of EDP Renewables S.A. and Engie S.A.,
  - Total installed capacity: 400 MW.

The projects in question are to be launched and put into operation by 2030.

Phase II of the support system for offshore wind farms is auction-based, with operational rules designed similarly to those for RES auctions (as described in chapter 1.3.1). As with RES auctions, the auction is won by bidders submitting the lowest price for the electricity planned to be produced in their units. An auction will be concluded only if at least three valid bids are submitted.

So far, four auctions have been planned, for which the maximum installed capacity has been determined by law, allowing the right to coverage for the negative balance to be granted:

- In 2025, for a total installed capacity of 4 GW,
- In 2027, for a total installed capacity of 4 GW,
- In 2029, for a total installed capacity of 2 GW,
- In 2031, for a total installed capacity of 2 GW.

In summary, contracts for differences are a key element enabling the development of offshore wind energy in Poland. They provide investors with stable long-term revenues from sales of electricity, minimising financial risk related to the volatility of prices in the electricity market. The use of an auction mechanism in the second phase is expected to increase the transparency of transactions and contracts.

110 PKN Orlen & NP Baltic Wind BV. (2023) *Morska Farma Wiatrowa Baltic Power Sp. z o.o. – aktualizacja Planu łańcucha dostaw* [Offshore Wind Farm Baltic Power Ltd. – update of the Supply Chain Plan].

111 Ocean Winds. (2023) *Morska Farma Wiatrowa BC Wind Sp. z o.o. – aktualizacja Planu łańcucha dostaw* [Offshore Wind Farm BC Wind Ltd. – update of the Supply Chain Plan].

2.

Risks in the economic assessment of investment projects

This chapter presents theoretical and application-related considerations for risk analysis in project evaluations. The technique of discounted cash flows (chapter 2.1) is described, and the methods used to estimate the cost of equity (chapter 2.2) are analysed. Then, the following risk analysis methods analyses are presented:
- Sensitivity analysis (chapter 2.3),
- Scenario analysis (chapter 2.4),
- Monte Carlo simulation (chapter 2.5).

2.1. Discounted cash flow analysis

The discounted cash flow (DCF) analysis is a method commonly used to assess a project's value and financial viability; it is also commonly used in the energy sector.[112] According to the assumptions of DCF analysis, a project is rational if it is expected to provide an adequate return in the form of cash flows generated by it in the future.[113] This technique uses projected cash flows for the entire project lifetime, which are discounted to determine the present value of the investment venture.[114]

[112] Oosterom, J.-P., & Hall, C. A. S. (2022). Enhancing the evaluation of energy investments by supplementing traditional discounted cash flow with energy return on investment analysis. *Energy Policy*, *168*, 112953. https://doi.org/10.1016/j.enpol.2022.112953

[113] Lattanzi, C. R. (2001). *Discounted cash flow analysis input parameters and sensitivity*. Micon International Limited.

[114] Moro Visconti, R. (2022). DCF metrics and the cost of capital: ESG drivers and sustainability patterns. *SSRN*. https://doi.org/10.2139/ssrn.4132432

The use of DCF analysis enables the calculation and assessment of project feasibility indicators, which supports the decision-making process regarding whether to undertake or reject the project. The most commonly used feasibility indicators in the DCF method include net present value (NPV) and internal rate of return (IRR).[115]

Discounted cash flow analysis remains a fundamental method for assessing the effectiveness or functioning of enterprises.[116,117] In simple terms, it allows the calculation of the project's value or return by comparing the present value of its future gross cash flows with the present value of the capital expenditures required for its implementation.[118]

According to the definition, a cash flow is the annual balance of all income and expenses resulting from investment, operational, and financial activities that directly affect the company's cash balance.[119] Depending on the activities undertaken by the company in the settlement period, cash flows can be positive or negative. When anticipating future monetary revenues, adopting appropriate inflationary assumptions is crucial. A fundamental principle here is that the economic and financial parameters used as input for calculating project cash flows can be expressed in either:[120,121]

1) Nominal values,
2) Constant values.

These cannot be combined.

The main assumption of DCF analysis is that the considered project will be implemented according to a single, most probable operational scenario. The expected production and sales volumes, along with the economic and financial parameters used as input, are estimated based on the best knowledge available at the time of

[115] Cook, M. (2021). Economic indicators from the DCF. In *Development in Petroleum Science* (Vol. 71, pp. 207–229). Elsevier. https://doi.org/10.1016/B978-0-12-821190-8.00007-1

[116] Saługa, P. W., Szczepańska-Woszczyna, K., Miśkiewicz, R., & Chłąd, M. (2020). Cost of equity of Coal-Fired Power Generation Projects in Poland: Its Importance for the Management of Decision-Making Process. *Energies*, *13*(18), 4833. https://doi.org/10.3390/en13184833

[117] Dranka, G. G., Cunha, J., de Lima, J. D., & Ferreira, P. (2020). Economic evaluation methodologies for renewable energy projects. *AIMS Energy*, *8*(2), 339–364. https://doi.org/10.3934/energy.2020.2.339

[118] Christersson, M., Vimpari, J., & Junnila, S. (2015). Assessment of the financial potential of real estate energy efficiency investments – A discounted cash flow approach. *Sustainable Cities and Society*, *18*, 66–73. https://doi.org/10.1016/j.scs.2015.06.002

[119] Faulkender, M., Flannery, M. J., Hankins, K. W., & Smith, J. M. (2012). Cash flows and leverage adjustment. *Journal of Financial Economics*, *103*(3), 632–646. https://doi.org/10.1016/j.jfineco.2011.10.013

[120] Barth, M. E., Beaver, W. H., Hand, J. R. M., & Landsman, W. R. (1999). Accruals, cash flows, and equity values. *Review of Accounting Studies*, *4*(3–4), 205–229. https://doi.org/10.1023/A:1009630100586

[121] Leskinen, N., Vimpari, J., & Junnila, S. (2020). A review of the impact of green building certification on the cash flows and values of commercial properties. *Sustainability*, *12*(7), 2729. https://doi.org/10.3390/su12072729

evaluation.[122] Therefore, to obtain reliable results that enable decision-making, it is crucial to consider the broadest possible range of analyses concerning variables that shape the input parameters for the DCF analysis. This includes applicable technologies and economic and financial conditions. The quality and reliability of the evaluation depend on the accuracy of these individual input data estimates. Since all variables in the DCF calculation are expected values (representing the most likely outcomes based on knowledge at the assessment date), the sole parameter expressing the risk of the adopted scenario is the discount rate, which constitutes the investors' cost of capital (discussed further in chapter 3.2).[123]

Predictions of the future values of the various technical and economic-financial parameters used in DCF analysis are inherently uncertain – the levels of actual cash flows will differ from the expected ones; the level of this uncertainty also varies. Consequently, the scope of uncertainty (and thus the risk) will be assessed differently for projects using well-established technologies compared to those using technologies only just emerging on the market.[124] Uncertainty in technical parameters significantly affects the uncertainty regarding the project's operational horizon; this uncertainty increases with the assumed project lifetime.[125] In the case of energy projects, the level of uncertainty is also influenced by geopolitical aspects, including the expected availability of primary energy carriers, forecast costs of carbon dioxide emission allowances and other environmental charges, and the assumed directions of energy policies aimed at mitigating climate change.[126,127] R. Wiser and S. Pickle (1998) point to the significant impact of well-planned climate policy options on reducing the expected premium for risk.[128] Consequently, a well-designed energy policy, through predictable climate strategies and clear directions for the energy transition, can contribute to reducing the future costs of electricity generation while helping to ensure adequate revenues.

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[122] Blinski, P. (2013). Do Analysts Disclose Cash Flow Forecasts with Earnings Estimates when Earnings Quality is Low? *Journal of Business Finance & Accounting*, *41*(3–4), 401–434. https://doi.org/10.1111/jbfa.12056

[123] Konek, S., & Srilakshmi, D. (2021). Valuation of equity using discounted cash flow method. *Journal of University of Shanghai for Science and Technology*, *23*(3), 125–132. http://doi.org/10.51201/Jusst12658

[124] Kamrat, W. (2002). Investment risk forecasting in a local energy market. *Energy Conversion and Management*, *43*(4), 515–522.

[125] Saługa, P.W. (2017). Dobór stopy dyskontowej dla długoterminowych projektów sekwencyjnych z branży surowców mineralnych [Selection of the discount rate for long-term sequential projects in the mineral raw materials industry]. *Gospodarka Surowcami Mineralnymi – Mineral Resources Management*, *33*(3), 49–70. https://doi.org/10.1515/gospo-2017-0036

[126] Blyth, W., Bradley, R., Bunn, D., Clarke, C., Wilson, T., & Yang, M. (2007). Investment risks under uncertain climate change policy. *Energy Policy*, *35*(11), 5766–5773. https://doi.org/10.1016/j.enpol.2007.05.030

[127] Capasso, G., Gianfrate, G., & Spinelli, M. (2020). Climate change and credit risk. Journal of Cleaner Production, 266, 121634. https://doi.org/10.1016/j.jclepro.2020.121634

[128] Wiser, R. H., & Pickle, S. J. (1998). Financing investments in renewable energy: The impacts of policy design. *Renewable and Sustainable Energy Reviews*, *2*(4), 361–386. https://doi.org/10.1016/S1364-0321(98)00007-0

Considering the multitude of factors affecting project success[129], investors expect compensation for risk (a risk premium), the size of which depends on parameters influencing profitability, including the expected project implementation time.[130] S. Salm (2018) conducted a study analysing the expected level of risk premium for investing in renewable energy projects depending on the type of investor, considering two cases: an entity already operating in the market and an investor with no existing assets. The results indicate that – taking into account full exposure to the risk of electricity price volatility – established operators in the sector expect a risk premium of 3.04%, while new investors expect 6.61%.[131] The analysis also shows that although low-risk projects attract investors from both groups, riskier projects are undertaken primarily by enterprises with existing sector experience.

The relationship describing the discounted cash flow approach is presented in equation (1),[132] where it DCF_t represents the discounted cash flow in the year t, CF_t represents the balance of all cash inflows and outflows in this year, and the parameter R represents the discount rate, which expresses the risk of the expected cash flows.

$$DCF_t = \frac{CF_t}{(1+R)^t} \tag{1}$$

From an investor's perspective, the sum of discounted cash flows over the project's life is of primary interest. The final result (the total present value) is directly proportional to the sum of the cash flows over the analysed period and inversely proportional to the discount rate level and the number of years considered.[133] A summary including examples of discount rates is shown in Table 2.1.

The above-mentioned sum of discounted cash flows, which is a measure of value, is the basic indicator of economic efficiency in the DCF analysis. It is called *net present value* (NPV). It is complemented by the project return rate called

[129] Kamrat, W. (2013). Zastosowanie hierarchicznej analizy problemowej w badaniach efektywności inwestowania w elektroenergetyce [Analytic hierarchy process application for investment effectiveness studies in power engineering industry]. *Energetyka*, *10*, 721–728.

[130] Lipara, C., Aldea, A., & Ciobanu, A. (2011). Equity risk premium for investment projects in renewable resources. *Theoretical and Applied Economics*, *18*(12[565]), 115–124.

[131] Salm, S. (2018). The investor-specific price of renewable energy project risk – A choice experiment with incumbent utilities and institutional investors. *Renewable and Sustainable Energy Reviews*, *82*(1), 1364–1375. https://doi.org/10.1016/j.rser.2017.04.009

[132] Leporini, M., Marchetti, B., Corvaro, F., & Polonara, F. (2019). Reconversion of offshore oil and gas platforms into renewable energy sites production: Assessment of different scenarios. *Renewable Energy*, *135*, 1122–1132. https://doi.org/10.1016/j.renene.2018.12.073

[133] Xu, Y., Yang, Z., & Yuan, J. (2021). The economics of renewable energy power in China. *Clean Technologies and Environmental Policy*, *23*, 1341–1351. https://doi.org/10.1007/s10098-021-02031-0

discounted cash flow rate of return (DCFROR) although it is much more commonly referred to as the *internal rate of return* (IRR)[134,135], which is discussed further.

Table 2.1. Examples of rates of return used in economics and finance

Discount rate	Description
Opportunity cost of capital	Lost benefits that could be gained by investing capital in the best alternative investment.
Risk-free rate	Return on a risk-free instrument, estimated on the basis of treasury bills or short- or long-term treasury bonds.
Hurdle rate or minimal acceptable rate of return (MARR)	Any minimum rate of return applied internally (subjectively) by the enterprise.
Risk-adjusted discount rate (RADR) ≡ cost of equity	A rate, tuned to the project risk, usually calculated on the basis of the Capital Asset Pricing Model (CAPM).
Cost of debt	Interest rate on external funds.
Weighted average cost of capital (WACC)	A 'resultant' discount rate, weighting the cost of capital and the cost of debt, taking into account the relationship between the amount and interest rate of debt and equity.
Historical rate of return	Rate of return assumed on the basis of the cost of capital rates assumed in the calculations of the economic assessment of projects implemented in the past.
Time-varying discount rate[136]	Cost of capital reflecting changes in the level of risk over time; determined, for example, after obtaining the return on investment and achieving the minimum required rate of return on the project.
Varying discount rate adjusted to specific risk profile of the individual component of the cash flow [137]	Rate reflecting the differences in the level of risk between the different elements of the cash flow.
Social rate of return	Rate used to determine the value of social projects which, in addition to the financial aspects of the investment, also takes into account ethical issues and social justice.

Source: Own study.

134 Sgroi, F., Donia, E., & Alesi, D. R. (2018). Renewable energies, business models and local growth. *Land Use Policy*, *72*, 110–115. https://doi.org/10.1016/j.landusepol.2017.12.028

135 Sheikhi, A., Ranjbar, A. M., & Oraee, H. (2012). Financial analysis and optimal size and operation for a multicarrier energy system. *Energy and Buildings*, *48*, 71–78. https://doi.org/10.1016/j.enbuild.2012.01.011

136 Gormsen, N. J., & Huber, K. (2025). Corporate discount rates. *American Economic Review*, *115*(6), 2001–2049.

137 Awa, K. N., Nnametu, J., & Ogbuefi, J. U. (2020). Analysis of the use of discounted cash flow technique of appraisal under a changing discounted rate and cash flow condition. *International Journal of Scientific Engineering and Science*, *4*(6), 6–10.

The net present value (*NPV*) – as shown in equation (2) – is calculated as the difference between the sum of the gross discounted cash flows occurring in subsequent years and the sum of the discounted tranches of subsequent capital expenditures; the symbols in formula (2) mean as follows: GCF_t – gross cash flow in the year t, R – discount rate, t – year for which the cash flow is calculated, n – project lifetime (years), and I_t – capital expenditures implemented in year t.[138]

$$NPV = \sum_{t=0}^{n} \frac{GCF_t}{(1+R)^t} - \sum_{t=0}^{n} \frac{I_t}{(1+R)^t} \tag{2}$$

The 'decision-making' interpretation of NPV is as follows: if its value is positive (above zero), the project is acceptable; otherwise, it is not. The NPV measure (due to its versatility and common understanding) is widely used to assess various projects, including the valuation of projects aimed at building new generation capacities based on renewable energy sources. This indicator also allows direct comparison between different projects considered by investors, enabling them to select the project offering the highest expected value. However, using NPV also has limitations. These include the sensitivity of the results to the accuracy of predicted cash flows, the subjectivity inherent in selecting an appropriate discount rate, and the exclusion of qualitative factors from the analysis.[139,140]

Internal rate of return is the level of the discount rate at which the net present value of the project is equal to zero, as presented in equation (3);[141] thus, it is a limit parameter. Analogous to the equation describing the NPV, GCF_t means the (gross) cash flow in the year t, t – the year for which the cash flow is calculated, n – the project lifetime, calculated in years, and I_t – capital expenditures in year t.

$$NPV = \sum_{t=0}^{n} \frac{GCF_t}{(1+IRR)^t} - \sum_{t=0}^{n} \frac{I_t}{(1+IRR)^t} = 0 \tag{3}$$

IRR is an indicator completely independent of the discount rate adopted, which is one of the features that distinguish it from the net present value. Similarly

[138] Maric, B., & Grozdic, V. (2016). Monte Carlo simulation in valuation of investment projects. *Proceedings of the 27th DAAAM International Symposium*, 686–692. https://doi.org/10.2507/27th.daaam.proceedings.099

[139] Michalak, J. (2013). Wybrane metody wspomagające podejmowanie decyzji inwestycyjnych w energetyce [Selected methods supporting investment decisions in the energy sector]. *Polityka Energetyczna*, *16*(4), 1429–1439.

[140] Delapedra-Silva, V., Ferreira, P., Cuhna, J., & Kimura, H. (2021). Methods for Financial Assessment of Renewable Energy Projects: A Review. *Processes*, *10*(2), 184. https://doi.org/10.3390/pr10020184

[141] da Silva Pereira, E. J., Pinho, J. T., Barros Galhardo, M. A., & Macedo, W. N. (2014). Methodology of risk analysis by Monte Carlo method applied to power generation with renewable energy. *Renewable Energy*, *69*, 347–355. https://doi.org/10.1016/j.renene.2014.03.054

to NPV, IRR makes it possible to rank different projects. The higher the IRR value, the more economically efficient the project is, i.e. profitable from the perspective of investors' interests. The decision-making criterion in this case assumes that the investment should be implemented if the IRR reaches a value greater than the minimal acceptable rates of return (MARR) expected by investors, which is the usually assumed cost of capital.[142]

IRR is considered a more objective measure than MARR, as it is determined internally, unlike the latter, which is strictly subjective. Nevertheless, IRR is often criticised due to some well-known shortcomings. These are presented below. The first of these is the problem of reinvestment. The IRR value is determined solely on the basis of annual cash flows and initial investments, when NPV = 0. However, there is widely known controversy regarding the conditions under which the IRR may be considered analogous to the compound interest rate used for initial investments. Mathematically, two future values (FV) will only be equal if the annual dividends on the project's cash flows are reinvested at an interest rate equal to the IRR. Therefore, in order to interpret the IRR as analogous to the compound interest rate on initial investments, it is necessary to assume that the project's annual dividends will be reinvested at a rate equal to the IRR. If the IRR is high, it may be unreasonable to assume that dividends will be reinvested at such a high interest rate, as reinvesting at very high rates is rather rare.

Of course, a better rate than IRR is MIRR (*modified internal rate of return*), which takes into account the fact that the reinvestment rate is independent of the IRR generated based on cash flow and obtained over the period of the evaluated project. The reinvestment rate in the case of the MIRR method is therefore external to the assessed investment, and its level depends on market (external) investment conditions. These are very important observations, but for the purposes of this work they do not matter much. It has been assumed that money is not reinvested.

Second, is the multi-root problem. In cases where a project is characterised by large capital expenditures both at the start-up stage and in subsequent years, it is possible that more than one IRR value may exist for a given cash flow. Most textbooks incorrectly state that the multiple-root problem applies only to the IRR, making NPV a better metric. In practice, the MARR is arbitrary selected before determining the NPV. Depending on this, the NPV can be positive or negative. It may turn out that a 5% discount rate yields a negative NPV, while a 10% discount rate yields a positive NPV. Therefore, the NPV – like the IRR – depends on the

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[142] Fang, X., Guo, H., Zhang, D., & Chen, Q. (2021). Cost recovery and investment barriers for renewables under market manipulation of thermal collusion. *Applied Energy*, *285*, 116487. https://doi.org/10.1016/j.apenergy.2021.116487

discount rate (or MARR). In other words, the multiple-root problem does not only apply to IRR.

Nevertheless, the essence of this work is not to show which of the basic measures of the economic evaluation of energy projects is better or worse from the financial point of view – because the work deals with discount rates, IRR is used only as a parameter strictly related to the discount rate (more precisely: the cost of equity). Therefore, in the context of this work, the mentioned disadvantages of IRR are not of great importance. Typical projects discussed in the work are so compiled that they have only one IRR value, and the use of the MIRR rate would not be suitable here.

NPV and IRR are not the only measures of a project's economic efficiency. Other – but much less frequently used compared to NPV and IRR – are:

1) Discounted payback period (DPP),
2) External rate of return (ERR),
3) Growth rate of return (GRR),[143]
4) Present value ratio (PVR),[144]
5) Overall rate of return (ORR).[145]

In summary, DCF analysis provides information on a project's expected economic efficiency regarding both:

1) Value (NPV, at the assumed level of the discount rate),
2) Return (IRR).

Rational investors prefer the shortest possible periods of freezing their capital, because having ready-made money allows its optimal use by reinvesting in subsequent investment opportunities. However, in the expectation of significant profits in the future, investors may forgo quick profits in the hope of obtaining a rate of return on investment that compensates them for the sacrifices related to both waiting and dealing with uncertainty.[146] As previously mentioned, this expected rate of return is known as the cost of equity or discount rate. Depending on the context, it may be referred to using various terms (e.g., hurdle rate, minimum acceptable rate of return, MARR, required rate, expected rate, risk-adjusted discount rate, RADR).

143 Biezma, M. V., & San Cristobal, J. R. (2006). Investment criteria for the selection of cogeneration plants – A state of the art review. *Applied Thermal Engineering*, *26*(5–6), 583–588. https://doi.org/10.1016/j.applthermaleng.2005.07.006

144 Lee, B., Park, J., Lee, H., Buyn, M., Won Yoon, C., & Lim, H. (2019). Assessment of the economic potential: COx-free hydrogen production from renewables via ammonia decomposition for small-sized H_2 refueling stations. *Renewable and Sustainable Energy Reviews*, *113*, 109262. https://doi.org/10.1016/j.rser.2019.109262

145 Islam, M. T., Huda, N., & Saidur, R. (2019). Current energy mix and techno-economic analysis of concentrating solar power (CSP) technologies in Malaysia. *Renewable Energy*, *140*, 789–806. https://doi.org/10.1016/j.renene.2019.03.107

146 Zamasz, K. (2017). Discount rates for the evaluation of energy projects – Rules and problems. *Zeszyty Naukowe Politechniki Śląskiej*, *101*, 571–584.

2.2. Cost of equity and its choice

As mentioned, the cost of equity is the rate of return investors expect as compensation for deferring consumption and bearing the uncertainty associated with committing their own funds to a specific project. This cost therefore reflects compensation for the risks investors bear by committing equity to an investment, including the opportunity cost of forgoing alternative investments.[147] The term risk-adjusted discount rate (RADR) is also frequently used in literature to denote the cost of equity.

The cost of equity is a component of the weighted average cost of capital, WACC, which is commonly used as the discount rate in DCF analysis, as shown in equation (4).[148] The parameters used in the formula mean as follows: R_e – cost of equity, u_e – share of equity in total capital expenditures, R_d – cost of debt, u_d – share of debt capital within capital expenditures. This rate is called the pre-tax discount rate.

$$WACC = R_e u_e + R_d u_d \tag{4}$$

Equation (5), in turn, determines the formula for the after-tax cost of capital. This equation is more often used in finance since interest on debts incurred may be included in the costs by the company, which in turn reduces the tax base.[149] Then r_{tax}, means the income tax rate, and the formula (1 – *tax*) is the so-called tax shield.

$$WACC = R_e u_e + R_d (1 - r_{tax}) u_d \tag{5}$$

Both approaches to calculating the average cost of capital (equations (4) and (5)) – regardless of discounting cash flows with the pre-tax or after-tax rate[150,151] – should deliver the same results; however, calculations using the second model, i.e. after-tax[152] (as shown in equation (5)) are the recommended solution used in practice.

147 Saługa, P. W., & Kamiński, J. (2018). The cost of equity in the energy sector. *Polityka Energetyczna – Energy Policy Journal*, *21*(3), 81–96. https://doi.org/10.24425/124493

148 Harvey, L. D. D. (2020). Clarifications of and improvements to the equations used to calculate the levelized cost of electricity (LCOE), and comments on the weighted average cost of capital (WACC). *Energy*, *207*, 118340. https://doi.org/10.1016/j.energy.2020.118340

149 Vélez-Pareja, I., & Tham, J. (2009). Market value calculation and the solution of circularity between value and the weighted average cost of capital (WACC). *RAM. Revista de Administração Mackenzie*, *10*(6), 101–131. https://doi.org/10.1590/S1678-69712009000600007

150 Hall, M. (2011). Pre- and post-tax discount rates. *Journal of Applied Research in Accounting and Finance*, *5*(2), 6–9. https://ssrn.com/abstract=1755323

151 Jindra, J., & Voetmann, T. (2010). Discussion of the pre- and post-tax discount rates and cash flows: A technical note. *Journal of Applied Research in Accounting and Finance*, *5*(1), 16–20. https://ssrn.com/abstract=1655691

152 Davia, K. T. (2011). Why pre-tax discount rates should be avoided. *Journal of Applied Research in Accounting and Finance*, *5*(2), 2–5. https://ssrn.com/abstract=1755322

The cost of equity is usually higher than the cost of debt, which results from a greater risk associated with investing own funds (the bank diversifies its risk). In the case of debt capital, the bank already has guaranteed returns in the form of interest in the loan agreement and the repayment of the loan within the set deadline. Moreover, in the event of bankruptcy, it is the liabilities towards the bank that are fulfilled by the company in the first place. Private investors, by investing their own capital, agree to gain a profit at a later date. In addition, they receive their dividends only after all financial and tax liabilities have been fulfilled by the company implementing a given project. As a consequence, taking a greater risk, they expect higher returns on investment.[153]

The remainder of this chapter presents common methods for estimating the cost of equity (the risk-adjusted discount rate): the subjective estimation of the hurdle rate (chapter 2.2.1), the Gordon Dividend Growth Model (chapter 2.2.2), the Capital Asset Pricing Model (CAPM) (chapter 2.2.3), and other estimation methods (chapter 2.2.4).

2.2.1. Subjective estimation of the hurdle rate

As previously noted, the discount rate level critically impacts project economic efficiency assessments; its magnitude depends on the project's associated risks (particularly during the operational phase). As indicated earlier (in the discussion of NPV), the discount rate's impact on a project's present value increases with both the rate level and the project duration. For energy sector projects, which typically have long operational lifetimes, the appropriate choice of discount rate significantly affects the present value of future annual cash flows and, consequently, managerial decisions.

One method for selecting an appropriate project discount rate is *ad hoc* estimation based on subjective risk assessment.[154] This estimation is performed by industry analysts with extensive experience in project economic evaluation and deep knowledge of the specific industry sector where the project is planned. They typically use intra-sectoral benchmarks from comparable projects for this purpose.

Benchmarking involves, among other things, comparing a company's performance and assumptions (including those used for assessing project economic efficiency) with those of other enterprises in the same sector. This comparison helps verify the reasonableness of assumptions and their consistency with prevailing market practices.

[153] Shad, M. K., Lai, F. W., Shamin, A., & McShane, M. (2020). The efficacy of sustainability reporting towards cost of debt and equity reduction. *Environmental Science and Pollution Research*, *27*, 22511–22522. https://doi.org/10.1007/s11356-020-08398-9

[154] Zamasz, K. (2017). Discount rates for the evaluation of energy projects – rules and problems. *Zeszyty Naukowe Politechniki Śląskiej*, *101*, 571–584.

Selecting a discount rate this way involves identifying similar projects undertaken within the industry and, consequently, determining the assumptions used to assess their profitability. Analyst-practitioners play a key role here, providing cross-sectional understanding based on knowledge of the economic, financial, and production conditions relevant to similar projects. Their experience and expert knowledge are invaluable for developing assumptions for financial models, including setting hurdle rates for cash flow analyses. For example, J. Steinbach and D. Staniaszek have indicated that in the case of projects implemented in the electricity generation sector, discount rates may range from 6% to 15%.[155] However, this specialist knowledge often represents proprietary expertise ('hidden know-how') and is not widely publicised.

Due to its subjectivity, this approach is generally not preferred in financial theory and practice. The proportion of enterprises using subjective hurdle rate estimation is declining over time in favour of more advanced models.[156,157]

2.2.2. Gordon Dividend Growth Model

The Gordon Dividend Growth Model (DGM) is based on the assumption that dividends grow at a constant rate infinitely. As this assumption is unrealistic (forecasting dividends indefinitely is impossible), various discounted dividend models exist in finance. These models incorporate various constraints related to forecasting future growth.[158]

A prerequisite for using this model for company valuation is the assumption of stable growth and consistent dividend payments. A well-established dividend policy and a growth rate comparable to, or lower than, the overall economic growth rate are key factors supporting the applicability of the Gordon model.[159] This method posits that the value of a company's shares equals the present value of all expected future dividend payments. While expected growth rates vary by industry and company, the long-term dividend growth rate for many established

[155] Steinbach, J., & Staniaszek, D. (2015). Discount rates in energy system analysis – Discussion paper. Fraunhofer ISI. https://bpie.eu/wp-content/uploads/2015/10/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf

[156] Association for Financial Professionals. (2011). *Current trends in estimating and applying the costs of capital*. https://business.baylor.edu//don_cunningham/How_Firms_Estimate_Cost_of_Capital_(2011).pdf

[157] Mauboussin, M. J., & Callahan, D. (2023). *Cost of capital – A practical guide to measuring opportunity cost*. https://www.morganstanley.com/im/publication/insights/articles/article_costofcapital.pdf?1676472943960

[158] Nhleko, A. S., & Musingwini, C. (2015). Estimating cost of equity in project discount rates using the capital asset pricing model and Gordon's wealth growth model. *International Journal of Mining, Reclamation and Environment*, *30*(5), 390–404. https://doi.org/10.1080/17480930.2015.1093675

[159] Foerster, S. R., & Sapp, S. G. (2005). The Dividend Discount Model in the Long-Run: A Clinical Study. *Journal of Applied Finance*, *15*(2). https://ssrn.com/abstract=869545

companies is often assumed to approximate the nominal gross domestic product (GDP) growth rate.[160,161]

The expected rate of return, i.e. the cost of equity R (the required return investors expect for holding a company's stock, considering its risk) calculated according to the Gordon model, is presented in equation (6), where D_1 means the anticipated value of the dividend that the company plans to pay in the following year, P means the current market price at which the stock is trading, and g is the constant rate at which the company's dividends are expected to grow forever.

$$R = \frac{D_1}{P} + g \tag{6}$$

2.2.3. CAPM model

The most widely known and commonly used approach for estimating the risk-adjusted discount rate (cost of equity) is the Capital Asset Pricing Model (CAPM). This model was developed between 1964 and 1966 independently by W. Sharpe,[162] J. Lintner[163] and J. Mossin.[164] This model assumes investment risk comprises two components:

1) Systematic risk, arising from external factors affecting the entire market,
2) Sector-specific or company-specific risk.

Despite its limitations and many critical voices, this approach is still used by large companies, including those in the electricity and district heating sectors.

The CAPM posits that the expected return on a company's equity is the sum of:

1) Risk-free rate of return,
2) Market risk premium, which depends on the so-called beta factor.

These relationships were presented in equation (7), where it $\mathrm{E}(R)$ is the expected cost of equity (expected return on asset i), R_f – the risk-free interest rate, $\mathrm{E}(R_m)$ – the expected return of the market, and β – risk factor determined for the assets of interest (asset i).[165]

$$\mathrm{E}(R) = R_f + [\mathrm{E}(R_m) - R_f)]\beta \tag{7}$$

[160] Brealey, R. A., Myers, S. C., & Allen, F. (2020). *Principles of corporate finance*. McGraw Hill Education.

[161] Damodaran, A. (2012). *Investment valuation: Tools and techniques for determining the value of any asset*. Wiley.

[162] Sharpe, W. F. (1964). Capital asset prices: A theory of market equilibrium under conditions of risk. *Journal of Finance*, *19*(3), 425–442.

[163] Lintner, J. (1965). The valuation of risk assets and the selection of risky investments in stock portfolios and capital budgets. *The Review of Economics and Statistics*, *47*(1), 13–37.

[164] Mossin, J. (1966). Equilibrium in a capital asset market. *Econometrica*, *34*(4), 768–783.

[165] Faisol, A., Nidar, S. R., & Herwany, A. (2022). The analysis of risk and return using Sharia compliance assets pricing model with profit-sharing approach (Mudharabah) in energy sector company in Indonesia. *Journal of Risk and Financial Management*, *15*(10), 421. https://doi.org/10.3390/jrfm15100421

One of the key financial parameters, also used in the CAPM method, is the risk-free rate (R_f), which reflects the expected rate of return on securities, widely considered to be instruments with zero investment risk, such as treasury bills and short-term government bonds.[166,167] This rate reflects broad economic conditions (influenced by the economic situation and state monetary policy) and is generally considered independent of specific projects or industries.

In the second part of equation (7), in addition to the market risk premium (R_m – R_f), there is a measure of systematic risk – the above-mentioned beta factor, which expresses the volatility of the company stock return rates in relation to the volatility of the market return. According to the definition, the beta coefficient for a given value is determined by the quotient of the covariance between the return on a security in question and the return on the market ($cov(R_s, R_m)$) and the variance of market returns ($var(R_m)$), as presented in equation (8).[168]

$$\beta = \frac{cov(R_s, R_m)}{var(R_m)} \tag{8}$$

The interpretation of the beta factor indicates that the systematic risk associated with the assets increases as their value increases. If the beta is 1, it means that the assets in question are as risky as the market. Where the beta is greater than 1, the assets are riskier than the market, meaning that the rate of return on the analysed instrument is more variable than the market rate of return. If the beta is less than 1, the assets are less risky than the market, i.e. the rate of return on the security is less volatile than the rate of return on the entire market.[169]

It should be noted, however, that the classic beta factor calculated in the manner suggested in equation (8) (*levered beta*) does not take into account differences in the company's risk profile resulting from changes in its capital structure, i.e. it does not refer to the level of debt financing relative to equity capital; this factor will therefore be appropriate for investors for whom the company's financing structure is not important.

However, investors are often interested in the beta that would occur if the company was financed only with equity capital (*unlevered beta*). The relationship

166 Mukherji, S. (2011). The Capital Asset Pricing Model's Risk-Free Rate. *The International Journal of Business and Finance Research*, *5*(2), 75–83. https://ssrn.com/abstract=1876117

167 Franc-Dąbrowska, J., Mądra-Sawicka, M., & Bereżnicka, J. (2018). Cost of Agricultural Business Equity Capital – A Theoretical and Empirical Study for Poland. *Economies*, *6*(3), 37. https://doi.org/10.3390/economies6030037

168 Vergara-Fernandez, M., Heilmann, C., & Szymanowska, M. (2023). Describing model relations: The case of the capital asset pricing model (CAPM) family in financial economics. *Studies in History and Philosophy of Science*, *97*, 91–100. https://doi.org/10.1016/j.shpsa.2022.12.002

169 Wijaya, E., & Ferrati, A. (2020). Stock investment decision making capital asset pricing model (CAPM). *Journal Manajemen*, *24*(1), 93–108. http://dx.doi.org/10.24912/jm.v24i1.621

between the classic beta and the unlevered beta is shown in the formula (9).[170] The parameters used in the equation mean as follows: β – levered beta, β_u – unlevered beta, r_{tax} – corporate tax rate, V_d– amount of credit, V_e – amount of equity capital.

$$\beta = \beta_u[1 + (1 - r_{tax})\frac{V_d}{V_e}] \tag{9}$$

In summary, the capital asset pricing model allows the calculation of the cost of equity (risk-adjusted discount rate) for a company listed on the stock exchange, reflecting the relationship between the expected return on company shares and systematic risk, with the possibility of taking into account the risk related to the entire activity of a given company and the impact of debt financing on its total risk.

Although this model is widely used, it also has many limitations, among which are the assumptions that: the market is perfectly competitive; all investors have the same expectations regarding rates of return and risk; there are no transaction costs on the market; risk is one-dimensional and expressed by a single indicator; and investors have no restrictions on access to capital with a safe rate of return.[171,172] From the investors' viewpoint, a disadvantage of the model is also the high variability of beta factors over time and the fact that they allow for the calculation of the cost of equity of the company, and not specific projects, the risk of which may differ significantly from the 'resultant' risk calculated based on the company's beta.

2.2.4. Other methods of estimating the cost of equity

In addition to the methods listed in the previous subchapters, there are also a number of other, less commonly used methods for estimating the discount rate as the cost of equity. These models assume the existence of a larger number of risk factors (than in the Capital Asset Pricing Model (CAPM), for example) that should be taken into account when determining the discount rate. Such multi-factor models include, among others, the Fama-French model and the Arbitrage Pricing Theory (APT) model.

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170 Emhjellen, A., & Alaouze, C. M. (2003). A comparison of discounted cashflow and modern asset pricing methods – project selection and policy implications. *Energy Policy*, *31*(12), 1213–1220. https://doi.org/10.1016/S0301-4215(02)00181-7

171 Jajuga, K., & Jajuga, T. (2012). *Inwestycje, instrumenty finansowe, aktywa niefinansowe, ryzyko finansowe, inżynieria finansowa* [Investments, financial instruments, non-financial assets, financial risk, financial engineering]. PWN.

172 Michalak, A. (2012). Ograniczenia modelu CAPM i alternatywne propozycje w zakresie wyceny koszty kapitału własnego przedsiębiorstw górniczych [Limitations of the CAPM model and alternative suggestions in the scope of valuation of the cost of equity of mining enterprises]. *Zeszyty Naukowe Uniwersytetu Szczecińskiego – Finanse, Rynki Finansowe i Ubezpieczenia*, *51*, 583–593.

The Fama-French model extends the concept of the capital asset pricing model, CAPM, by considering additional indicators in the discount rate estimation.[173] This approach is based on three fundamental risk factors, hence it is often referred to in the literature as the Fama-French three-factor model. These factors, in addition to the overall market risk (also considered in the CAPM), include a factor based on company size (the degree to which small companies outperform large companies) and a factor based on the book-to-market ratio.

The Fama-French model was presented in equation (10), where R_f and R_m – by analogy to the CAPM – mean the risk-free rate and the market rate of return, *SMB* (Small /market capitalisation/ Minus Big) – the difference between the average rate of return of small-capitalisation companies and the average rate of return of large-capitalisation companies, *HML* (High /book-to-value/ Minus Low) – the difference between the average rates of return of high and low BV/MV companies, ε –the free component of the model, representing an extraordinary rate of return not related to three key risk factors, and β_{SMB}, β_M, β_{HML} – coefficients reflecting the sensitivity of the rate of return to changes in individual factors and ε – idiosyncratic risk or firm-specific risk of an asset that is not explained by the common macroeconomic factors included in the model.[174] It should be noted that the coefficient β_M is conceptually similar but numerically different from the CAPM β.[175]

$$R = R_f + (R_m - R_f)\beta_M + SMB \cdot \beta_{SMB} + HML \cdot \beta_{HML} + \varepsilon \quad (10)$$

The arbitrage pricing theory (APT) model[176] assumes that even more risk factors on the market should be considered in estimating the potential rate of return on investment than is presented in the CAPM and the Fama-French model. The APT model is represented by equation (11), where it R_f means the rate of return on risk-free assets, I_1, I_2 and I_n – further risk factors affecting the rate of return, β_1, β_2 and β_n – factors describing the sensitivity of the rate of return to changes in individual factors.[177]

$$R = R_f + I_1\beta_M + I_2\beta_2 + \ldots + I_n\beta_n + \varepsilon \quad (11)$$

[173] Fama, E. F., & French, K. (1992). The cross-section of expected stock returns. *Journal of Finance*, *47*, 427–465.

[174] Fama, E. F. (2014). Two pillars of asset pricing. *The American Economic Review*, *104*, 1467–1485.

[175] Redlicki, M., & Borowski, K. (2017). Wykorzystanie trzyczynnikowego modelu Famy-Frencha na GPW [Using the Fama-French three-factor model on the Warsaw Stock Exchange]. *Studia i Prace Kolegium Zarządzania i Finansów – Szkoła Główna Handlowa*, *153*, 81–102.

[176] Ross, S. A. (1976). The arbitrage theory of capital asset pricing. *Journal of Economic Theory*, *13*, 341–360.

[177] Kisman, Z., & Restiyanita, M. S. (2015). The validity of capital asset pricing model (CAPM) and arbitrage pricing theory (APT) in predicting the return of stocks in Indonesia stock exchange 2008–2010. *American Journal of Economics, Finance and Management*, *1*(3), 184–189.

However, due to their complexity and the challenges associated with identifying and measuring the relevant risk factors, the practical application of these multi-factor models is relatively limited.

2.3. Sensitivity analysis

Discounted cash flow analysis, in which risk, reflected through the discount rate, is a criterion in decision-making processes, and related methods represent one of the tools for the direct consideration of risk. In addition to direct methods, Leamer (1985)[178] also identifies indirect methods, the main goal of which is to provide additional information – generally not directly included in the decision-making criterion – about the analysed decision-making problem and the potential effects of the decisions made. These methods include, among others, the sensitivity analysis (which is the subject of this chapter), as well as scenario analysis and the Monte Carlo method, described later in this section.

Sensitivity analysis consists of introducing intended changes (relative to the base case or expected scenario) to the main input variables of the model developed for assessing a project's economic efficiency, conducting calculations, and analysing the impact of these changes on the values of output variables.[179] Sensitivity analysis makes it possible to determine the limit values (from the viewpoint of economic effects) of individual input variables for the considered project; it also helps to determine the related safety margins within a given time horizon. Wiśniewski (2007) classifies sensitivity analysis as one of the passive risk analysis methods.[180]

Sensitivity analysis helps answer questions about the direction and strength of the impact of individual input parameters on the project's economic efficiency, as well as the scope of permissible deviations for individual parameters that still allow the project to remain viable. Consequently, it is possible to identify the variables that have the greatest impact on the expected financial results (the so-called key parameters).

The method of sensitivity analysis uses the following concepts: explained variable, explanatory variable, and independent explanatory variable.

The explained variable (also referred to as the base or result parameter) is the output measure the analysis focuses on. In the economic assessment of project, the

[178] Leamer E. E. (1985) Sensitivity analyses would help. *American Economic Review*, *75*(3), 308–313.

[179] Pawlak, M. (2012). Metody analizy ryzyka w ocenie efektywności projektów inwestycyjnych [Methods of risk analysis in the assessment of the effectiveness of investment projects]. Zeszyty Naukowe Uniwersytetu Szczecińskiego. *Studia i Prace Wydziału Nauk Ekonomicznych i Zarządzania*, *30*, 207–217.

[180] Wiśniewski, T. (2007). Ryzyko projektu inwestycyjnego a ocena jego efektywności [The risk of an investment project and the assessment of its effectiveness]. Zeszyty Naukowe Uniwersytetu Szczecińskiego. *Prace Instytutu Ekonomiki i Organizacji Przedsiębiorstw*, *455*, 501–510.

explained variables are typically key efficiency measures such as net present value (NPV) and internal rate of return (IRR).

An explanatory variable is an input parameter whose value affects the explained variable. In the case of assessing the economic efficiency of energy projects, explanatory variables include, for example, fuel prices, electricity prices, production volume, environmental charges, and other operating costs.

In turn, independent explanatory variables are defined as parameters whose changes do not directly affect other variables, whereas dependent variables are those correlated with other parameters.

Although sensitivity analysis does not have a single universal mathematical equation, it can be simplified as the partial derivative of the output function $f(x)$ (equation (12) relative to x, where $\delta[]$ means a change in the explained variable (here, e.g.: NPV – then the notation δNPV or IRR can be used – using the notation δIRR), and δx means a change in the considered parameter, e.g. a change in the prices of fuels, electricity, production, environmental charges or other operating costs (δ is then the partial derivative symbol, indicating the change in y with respect to x while keeping all other elements constant – *ceteris paribus* assumption); SC represents the sensitivity coefficient of the tested efficiency measure to the determined change in the value of the explanatory variable. The greater this coefficient, the greater the variable's sensitivity explained to changes in the considered parameter x.

$$SC = \frac{\delta[f(x)]}{\delta x} = \frac{\delta y}{\delta x} \tag{12}$$

The practical application of sensitivity analysis involves defining specific deviations for individual explanatory variables; these can take the same percentage values for all variables (e.g., from -15% to +15%) or be defined individually for a given parameter based on its real-world variability (for example, electricity price variability might be assumed as -40% to +40%, while capital expenditures for a given technology might range from -20% to +20%). For each assumed deviation, the project efficiency measure (e.g., NPV or IRR) is calculated. Thus, the analysis involves systematically changing the base value of each explanatory parameter (e.g., in increments of 2%, 5%, or 10%) and recalculating the value of the explained variable in each iteration.

Interpreting the sensitivity analysis results enables decision-making aimed at mitigating risks resulting from the variability of parameters that have the greatest impact on the profitability of the investment. For example, if results indicate that electricity prices most significantly impact project profitability, the investor might explore mechanisms to hedge or secure prices. Similarly, if results depend heavily on fuel prices, the investor might consider long-term supply contracts to minimise exposure to fuel market volatility.

Although sensitivity analysis offers several advantages, including the rapid identification of key parameters affecting project profitability, it also has significant limitations. The primary limitation is the *ceteris paribus* assumption mentioned earlier: the analysis method typically changes only one explanatory variable at a time, holding all others at their base (expected) levels; therefore, it cannot assess the combined impact of simultaneous changes in multiple factors. Furthermore, standard (deterministic) sensitivity analysis typically ignores potential correlations or interdependencies between input parameters. The method also fails to incorporate the probability of occurrence for different values of the explanatory variables, information which can be crucial for decision-making.

This work focuses on the methodology for selecting the cost of capital of energy projects in relation to the risk involved, using sensitivity analysis. Other risk assessment methods commonly used in finance are presented below. Although they are not used further in this work, knowledge of them may – having once correctly determined the cost of capital – be useful in solving complex risk issues in energy project evaluations.

2.4. Scenario analysis

Scenario analysis is another indirect method used to assess risk within the Discounted Cash Flow (DCF) technique.[181,182] The scenario approach allows for the incorporation of different combinations of individual input parameters (explanatory variables) in the DCF model. Using this method can also reduce the arbitrariness of the assessment by considering various potential future states – the most likely, pessimistic, and optimistic scenarios, and potentially others (e.g., 'surprise' scenarios). Compared to sensitivity analysis, the main advantage of scenario analysis is its ability to incorporate simultaneous changes in multiple input parameters and examine their combined impact on the final result.

The scenario approach is widely used, notably also in energy research and development reports. The International Energy Agency (IEA) uses scenario analysis to present potential development paths for global fuel and energy markets. In its World Energy Outlook reports, the IEA presented three scenarios. Each scenario used different assumptions for key input parameters, reflecting distinct forecasts for the development of global markets. The first scenario reflected the assumptions aimed at achieving net zero carbon emissions by 2050; the second scenario assumed that governments would meet their climate commitments (similarly to the

[181] Kahn, H., & Wiener, A. (1967). The Next Thirty-Three Years: A Framework for Speculation. *Daedalus, 93*(6), 705–732.

[182] Schnaars, S. P. (1990). How to develop and use scenarios. In R. G. Dyson (Ed.), *Strategic planning: Models and analytical techniques* (pp. 153–167). John Wiley & Sons Ltd.

first scenario) and also make additional efforts to achieve objectives set out in other energy and climate strategies; while the third scenario reflected the actual actions taken by individual governments and their likely impact on emission reductions, rather than focusing solely on the objectives stated in strategy documents.[183]

Among other global energy agencies using scenario analyses, the International Renewable Energy Agency (IRENA) is worth mentioning. This agency develops analyses concerning the development of specific renewable technologies for electricity production, energy storage, and broader issues related to the energy transition in various national economies.

In assessing the economic efficiency of investment projects (including energy projects), three core scenarios are typically developed, reflecting different assumptions about the values of key input parameters:

1) Base scenario (also called reference, expected, or most likely): Assumes the most probable values for key input parameters,
2) Optimistic scenario: Assumes favourable values for parameters, leading to potentially higher financial outcomes for the project,
3) Pessimistic Scenario: Assumes distinctly unfavourable values for key input parameters.

Running the model calculations for these scenarios helps determine the potential range of outcomes (scope of uncertainty) by comparing the results from the pessimistic and optimistic cases.

In the energy sector, the popularity of scenario analysis stems from its affordability and relatively low computational complexity. As mentioned previously, this approach allows simultaneous changes in multiple input parameters to be reflected within a single computational procedure, which is why economists often prefer it over sensitivity analysis. However, this method considers only a limited number of variants, even when analysts expand beyond the typical baseline, optimistic, and pessimistic scenarios. Furthermore, it should be noted that scenario analysis typically assesses the probability of the entire scenario occurring, rather than considering the individual probabilities of the various input parameters within the financial model.

The scenario analysis was presented as an important tool for risk analysis. However, due to the purpose of the work, which is to evaluate the components of the discount rate, the presentation of the scenario analysis is of purely cognitive nature.

[183] International Energy Agency. (2023). *World energy outlook* (pp. 105–107). International Energy Agency.

2.5. Monte Carlo simulation

The Monte Carlo[184] method is an approach that allows for the consideration of the probability of occurrence for the values of individual input parameters within the calculation procedure, enabling the analysis of a vast number of potential scenarios. When applied to assessing the economic efficiency of projects (specifically here, energy sector projects), the procedure typically begins with developing a DCF spreadsheet for the project, following the principles described in Section 2.1. The next stage involves identifying the possible value ranges for key input parameters and defining appropriate probability distributions for them. These distributions can be based on historical data, expert judgements, market forecasts, or stochastic analysis, and should reflect expected future conditions. Determining any correlations between input variables and quantifying the degree of correlation is also a crucial step.

Unlike the deterministic risk analysis methods discussed previously (sensitivity and scenario analysis), the Monte Carlo method is a stochastic approach. It effectively extends classic scenario analysis by simulating hundreds or thousands of possible outcomes based on probabilistic inputs. Random sampling from the defined probability distributions of the input parameters is central to this approach.[185] The calculation procedure involves repeatedly and simultaneously drawing random values for each input variable from their defined (and potentially correlated) probability distributions. These drawn values are entered into the project's financial model (DCF spreadsheet), and the chosen financial metric (typically NPV or IRR is calculated for that specific set of inputs. This procedure is repeated hundreds or thousands of times (iterations), effectively simulating a vast number of different scenarios. Consequently, the final result is not a single value but a probability distribution for the output metric (e.g., the distribution of possible NPVs).

It should be emphasised that in the case of Monte Carlo simulations, the form of probability distributions of input data is crucial. However, experience with the application of algorithms of this method indicates that – *summa summarum* – the multidimensional stochastic process plays an overarching role in this method. It is clear that multidimensional trajectories are generated because projects (and the flows occurring within them) are considered in periods of at least several years – thus making it a dynamic process.

The method's widespread use, including in assessing the profitability of renewable energy investments, is documented in the literature. For example, S. Pereira et al. (2014) applied a Monte Carlo-based approach to analyse risk for a rooftop

[184] Eckhardt, R. (1987). Stan Ulam, John von Neumann, and the Monte Carlo Method. *Los Alamos Science*, 15 (Special Issue).

[185] Kroese, D. P., & Rubinstein, R. Y. (2011). Monte Carlo methods. *WIREs Computational Statistics*, *4*(1), 48–58. https://doi.org/10.1002/wics.194

photovoltaic plant project at a university, highlighting its utility in assessing how input parameter uncertainty affects the project's final economic outcome.[186]

The method is also applied to assess the economic efficiency and risk of wind projects. For instance, G. Caralis et al. (2014) used Monte Carlo simulation to evaluate the wind energy potential (expressed in PLN/MW) in four distinct regions of China, considering differences in wind resources, grid access, and economic conditions.[187] Their use of the Monte Carlo method provided valuable information for potential investors considering these regions. Although this case study focuses on China, the approach presented is universal and applicable to projects worldwide.

With the development of hybrid renewable systems, the Monte Carlo method also began to be used for analysing renewable energy projects combined with energy storage. For example, Uniwenza et al. (2021) employed this approach to assess the average cost of electricity from a hybrid system, taking into account the probability distributions of key technical and economic parameters described in the model.[188]

The Monte Carlo method is also applied to assess domestic investment projects in Poland, covering both conventional and renewable energy. D. Kryzia et al. (2020) used this approach to assess the potential for the development of gas microgeneration in Polish conditions, indicating the key elements of uncertainty and risk in such projects.[189] A. Dubel and P. Jastrzębski (2018) assessed the economic efficiency of a wind farm under Polish conditions, considering wind resources alongside technical and economic potential.[190] Similarly, a case study involving a photovoltaic plant in Poland was conducted by B. Ceran et al. (2021).[191] The authors analysed the probability distribution of the project's Net Present Value (NPV) as influenced by investment costs, projected electricity prices, the tariff system, and the discount rate, modelling these inputs using normal probability distributions.

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[186] da Silva Pereira, E. J., Pinho, J. T., Barros Galhardo, M. A., & Macedo, W. N. (2014). Methodology of risk analysis by Monte Carlo method applied to power generation with renewable energy. *Renewable Energy*, *69*, 347–355. https://doi.org/10.1016/j.renene.2014.03.054

[187] Caralis, G., Diakoulaki, D., Yang, P., Gao, Z., Zervos, A., & Rados, K. (2014). Profitability of wind energy investments in China using a Monte Carlo approach for the treatment of uncertainties. *Renewable and Sustainable Energy Reviews*, *40*, 224–236. https://doi.org/10.1016/j.rser.2014.07.189

[188] Uwineza, L., Kim, H. G., & Kim, C. K. (2021). Feasibility study of integrating the renewable energy system in Popova Island using the Monte Carlo model and HOMER. *Energy Strategy Reviews*, *33*, 100607. https://doi.org/10.1016/j.esr.2020.100607

[189] Kryzia, D., Kuta, M., Matuszewska, D., & Olczak, P. (2020). Analysis of the potential for gas micro-cogeneration development in Poland using the Monte Carlo method. *Energies*, *13*(12), 3140. https://doi.org/10.3390/en13123140

[190] Dubel, A., & Jastrzębski, P. (2018). Application of Monte Carlo simulations in economic analysis of a wind farm. *Central and Eastern European Journal of Management and Economics*, *6*(4), 35–45.

[191] Ceran, B., Jurasz, J., Mielcarek, A., & Campana, P. E. (2021). PV systems integrated with commercial buildings for local and national peak load shaving in Poland. *Journal of Cleaner Production*, *322*, 129076. https://doi.org/10.1016/j.jclepro.2021.129076

A key advantage of Monte Carlo simulation is its ability to analyse a vast number of potential project scenarios within a single integrated calculation procedure. By incorporating probability distributions for input parameters, the method yields a stochastic range of potential results (e.g., an NPV distribution) that reflects the likelihood of different outcomes.

Limitations of the Monte Carlo method include the difficulty in accurately defining reliable probability distributions for all input parameters. This stems mainly from limited data availability and the challenge of extrapolating historical data to reflect future conditions. A further challenge is that some parameters, like prices, are often modelled using static distributions within a standard Monte Carlo simulation, whereas their real-world behaviour may be dynamic over time. Accurately identifying correlated variables and determining the correct degree of correlation poses another problem. Finally, beyond requiring significant analyst expertise, this approach is computationally intensive and more time-consuming than deterministic methods like sensitivity analysis and scenario analysis.

Monte Carlo simulation is a comprehensive tool in the project risk analysis process; however, despite the widespread availability of applications for conducting it, it is not a widely used method for assessing project effectiveness. Given the assumption that the project risk is reflected in the probability distributions of the most important input data, the method uses the risk-free rate in the financial calculations. Therefore, the use of this method is of no practical relevance in the light of the research objectives.

The above-mentioned basic risk analysis methods are presented only as informational and cognitive content – merely to illustrate their advantages and disadvantages. Of course, as risk assessment tools, they are rated highly in financial science than sensitivity analysis. In this work, however, the focus will be on sensitivity analysis from another perspective – as a method enabling the assessment of the impact of individual uncertain key parameters of a project on the level of its risk and, as a result, on the level of the risk-adjusted discount rate.

3.

Economic assessment model of renewable energy projects under Polish conditions

To facilitate risk analysis within the evaluation process for renewable energy projects in Poland, a mathematical model was developed. This model reflects the relationships between the key elements that significantly affect the economic efficiency of such projects. The conceptual framework of this model, the identified parameters, and their interrelationships expressed as mathematical equations are detailed in Chapter 3.1.

Representative case study projects were developed for selected renewable energy technologies to evaluate the practical utility of this conceptual model and the corresponding discounted cash flow model implemented in a spreadsheet. Based on the specific characteristics of the Polish renewable energy sector and an analysis of expected market developments, the following RES technologies were selected for analysis:

- Photovoltaics,
- Wind energy,
  - Onshore,
  - Offshore,
- Biogas technology,
- Geothermal energy.

Detailed characteristics of these selected technologies are presented in Section 3.2.

The dynamic development of renewable energy necessitates careful consideration and development of assumptions for the input parameters used in economic assessment models for projects in this field, particularly those with a long-term perspective. Consequently, Chapter 3.3 presents the key assumptions and specific values adopted for the input data used in the subsequent calculations.

3.1. Concept of conducted research

Risk analysis within the assessment of economic efficiency for renewable energy projects is a multidimensional issue, integrating knowledge from economics, finance, and the energy sector.[192] Analysing these investments in the context of potential risk must therefore consider macroeconomic, political, technological, environmental, and other variables that can affect the expected costs and revenues associated with project implementation. Given this complexity, continuous monitoring of scientific literature and industry reports is necessary to obtain up-to-date data and stay informed about market trends. Furthermore, assessing the economic efficiency and risk of such projects requires advanced numerical tools. These tools should enable the integration of expert knowledge from energy and economics, the estimation of dynamically changing parameters characteristic of renewable energy technologies, and the simulation of typical projects to generate insights into their profitability.

Considering the research subject, a key element is the estimation of the cost of equity individually for each analysed technology, as this parameter reflects the risk associated with the specific investment opportunity. Currently, when assessing the economic efficiency of energy projects and comparing investment opportunities within energy companies, it is common practice to apply the same cost of equity (and consequently, the same Weighted Average Cost of Capital, WACC) to all projects undertaken by the entity, irrespective of the specific risks associated with the technologies involved. While this approach may be adequate for assessing conventional technology projects (e.g., investments in dispatchable coal or gas units characterised by relatively similar risk profiles),[193] it is less suitable for renewable energy. RES projects often involve less controllable production and exhibit more diverse risk profiles, which should be reflected in a technology-specific discount rate.[194]

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[192] Saługa, P. W., Zamasz, K., Dacko-Pikiewicz, Z., Szczepańska-Woszczyna, K., & Malec, M. (2021). Risk-Adjusted Discount Rate and Its Components for Onshore Wind Farms at the Feasibility Stage. *Energies*, *14*(20), 6840. https://doi.org/10.3390/en14206840

[193] Saługa, P. W., & Kamiński, J. (2018). The cost of equity in the energy sector. *Polityka Energetyczna – Energy Policy Journal*, *21*(3), 81–96. https://doi.org/10.24425/124493

[194] Egli, F. (2020). Renewable energy investment risk: An investigation of changes over time and the underlying drivers. *Energy Policy*, *140*, 111428. https://doi.org/10.1016/j.enpol.2020.111428

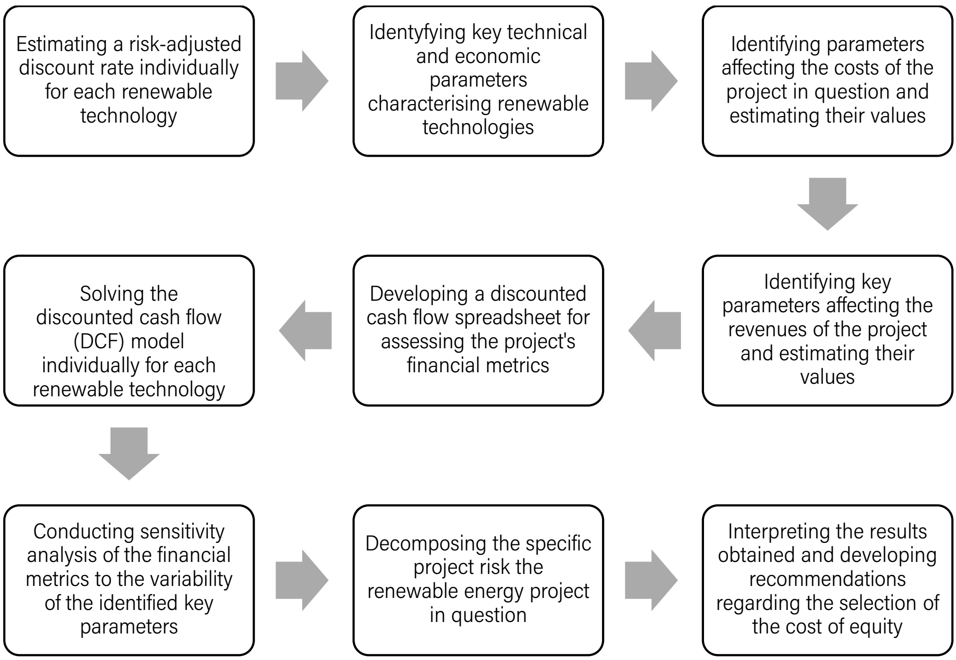
The work has been performed with an IRR sensitivity analysis. The calculations were made using the 'bare bones' assumption (on all the equity basis, constant money, after tax), which creates a good benchmark and starting point for comparing other investment alternatives and for future research. However, in fact, such a case will probably never exist, we can repeat the arguments for this – this approach provides a good reference scenario that helps in easily comparing investment opportunities.[195]

A diagram illustrating the concept of the research conducted on risk analysis in assessing the economic efficiency of renewable energy projects is presented in Figure 3.1. The research process involves the following stages:

- Estimating the cost of equity (risk-adjusted discount rate) individually for each selected technology (Stage 1).
- Identifying key parameters that describe the analysed technologies and significantly affect project costs and revenues (Stages 2–4).
- Developing a DCF model and solving it individually for each technology case study (Stages 5–6).
- Conducting a sensitivity analysis of the project's Internal Rate of Return, IRR, to changes in key parameters (Stage 7).
- Decomposing the specific risks associated with the analysed projects (Stage 8).
- Interpreting the results obtained and developing recommendations regarding the appropriate cost of equity to use when assessing the economic efficiency of projects employing each specific technology (Stage 9).

[195] Smith, L. D. (2000). *Discounted cash flow analysis and discount rates*. In Proceedings of the Special Session on Valuation of Mineral Properties, Mining Millennium 2000, Toronto, Ontario. Retrieved from https://www.cim.org/mes/pdf/VALDAYLarrySmith.pdf

Figure 3.1. Research concept for risk analysis in the economic efficiency assessment of renewable energy projects



Source: Own study

The concept for estimating the cost of equity (and its decomposition) used in evaluating energy projects is based primarily on the Capital Asset Pricing Model (CAPM), in which total investment risk is considered to consist of systematic risk (resulting from external market conditions) and specific risk (which varies depending on the sector or characteristics of the specific company). In this model, the expected rate of return on equity is assumed to be the sum of:

- Risk-free rate,
- Market risk premium,

as presented in equation (13),

$$R_e = RADR = R_f + (R_m - R_f)\beta \tag{13}$$

where:

- $R_e \equiv RADR$ – cost of equity.
- R_f – expected risk-free rate.
- R_m – expected market return, $(R_m - R_f)$ – market risk premium.
- β – beta factor.

The nominal risk-free rate is typically estimated based on the yield of financial instruments considered to have zero default risk, such as long-term government bonds. For Polish conditions, this often involves using the yield on long-term Polish government bonds or treasury bills, depending on the valuation horizon and specific assumptions.

The classic β factor – *levered beta* – does not adjust for differences between companies regarding their capital structure. In order to remove the component related to the impact of debt and isolate the underlying business risk from the total risk observed in the company's shares (represented by the classic levered beta), the beta should be 'unlevered' according to the Hamada equation:

$$\beta_u = \frac{\beta}{1 + (1 - r_{tax})\frac{V_d}{V_e}} \tag{14}$$

where:

- β_u – unlevered beta.
- $\beta \equiv \beta_L$ – classic beta factor (levered beta).
- r_{tax} – income tax.
- V_d – amount of debt capital.
- V_e – amount of equity capital.

The specific risk of the company is calculated as the product of the equity risk premium (*ERP*) and the unlevered beta (β_u), according to equation (15).

$$R_s = (R_m - R_f)\beta_u = ERP \cdot \beta_u \tag{15}$$

Another component taken into account in the estimation of the risk-adjusted real discount rate is the country risk premium (*CRP*), which increases the total investment risk, as presented in equation (16). In analyses assessing the economic efficiency of renewable energy projects, the country risk premium *RADR* is typically incorporated as a nominal value.

$$RADR = R_f + R_s + CRP \tag{16}$$

The Country Risk Premium (CRP) can be calculated based on the country rating provided by the Moody's rating agency [Damodaran online]. Moody's currently assigns Poland a long-term rating (LTR) of A2. Based on methodology referencing this rating [Damodaran online], this corresponds to: a *Sovereign Default Spread* (resulting from the assessment of Polish currency strength via bond return analysis) of 1.06%; an Adjusted Default Spread (adjusted default risk premium) of 0.92%; and a total *Equity Risk Premium* (ERP) for Poland of 5.84%. The CRP reflecting additional domestic investment risk is obtained by subtracting the ERP for the United States (used as a baseline mature market) from Poland's total ERP. Based on this data, Poland's resulting CRP is currently 1.24%.

In order to remove the effect of inflation, the nominal rate can be converted to a real rate according to the Fisher equation (17).[196] This relationship adjusts the nominal rate using the inflation rate (*i*), as shown below:

$$R_{real} = \frac{1 + R_{nominal}}{1 + i} - 1 \tag{17}$$

Consequently, for the developed capital asset pricing model, the equation for the risk-adjusted real discount rate, incorporating the country risk premium, is presented as follows:

$$RADR_{real} = \frac{1 + \left[R_f + \left(R_m - R_f\right)\beta_u + CRP\right]}{1 + i} - 1 \tag{18}$$

Estimating this risk-adjusted discount rate individually for each renewable technology, based on the equations presented and using relevant historical and current market data, constitutes the first stage of the research focused on risk analysis for assessing the economic efficiency of renewable energy source projects.

The second stage involves identifying key technical and economic parameters for renewable technologies. Depending on the specific technology, these parameters include:

- Installed power, in MW,
- Capacity factor, in percentage of the maximum possible output or in kWh of energy produced per 1 kW of installed capacity,
- Consumption of elements of the analysed project (e.g. panels in photovoltaic systems), as a percentage per year,
- Possibility of cogeneration (producing heat alongside electricity),
- Construction phase, in years,
- Project lifetime, in years,
- Capital expenditures, in million PLN/MW,
- Fixed operating costs, in PLN/MW,
- Variable operating costs, in PLN/MWh or PLN/GJ,
- Decommissioning costs, in PLN/MW.

The third stage of the research involves identifying parameters affecting project costs and estimating their values. In this respect, the primary components are costs related to project implementation, often listed among the economic parameters describing a given renewable technology. These include, among others, capital

[196] Fisher, L. (1990). *The Theory of Interest*. New York, MacMillan.

expenditures, operating costs and decommissioning costs. Information on the distribution of capital expenditures over time and data on the project's operational lifetime are also important in this context. In addition to technology-specific data, financial parameters such as the risk-free rate and corporate tax rate should also be considered.

The fourth stage involves identifying parameters affecting project revenues and estimating their values. For renewable energy projects, as with other energy ventures, the dominant component is typically revenue from the sale of electricity. Additionally, revenues from support mechanisms (e.g., RES auctions, the capacity market), heat sales (for cogeneration projects), and ancillary services provided to the transmission system operator can be taken into account. Relevant parameters in this context therefore include: unit prices for electricity sales (and heat sales, if applicable); remuneration levels from support mechanisms and ancillary services; and estimates of the quantities of energy sold, or the levels of power/energy associated with support mechanisms or ancillary services.

The fifth stage involves designing a Discounted Cash Flow model suitable for a standard economic efficiency assessment. This model must incorporate all relevant parameters describing the analysed renewable technology, as well as parameters affecting the costs and revenues expected over the project's lifetime.

Designing the discounted cash flow spreadsheet is an essential part of this research. In accordance with standard DCF analysis principles, the developed spreadsheet reflects the most likely (expected) project scenario. The basic parameters used as input data are estimated based on the best available knowledge at the time of preparation. The accuracy of the results obtained depends significantly on: the accuracy and quality of the model's formulae; the number of variables influencing the input parameters; the quality and reliability of the data and adopted values; and the estimation of the risk level as expressed by the risk-adjusted discount rate.

Developing the DCF model and preparing the input parameters for a typical project using a specific renewable energy technology, along with the corresponding technology-specific risk-adjusted discount rate, enables the sixth stage: solving the DCF model individually for each typical project case.

The primary results obtained at this stage are the NPV and IRR metrics, which are the focus of subsequent analysis. As already mentioned, NPV is the difference between the sums of discounted gross cash flows (GCF_t) generated by the project and discounted capital expenditures (I_t) in tranches in subsequent years, as presented in equation (2). IRR is the discount rate for which the NPV of the analysed project equals zero (equation (3)).

The seventh stage involves conducting a sensitivity analysis to determine the direction and magnitude of the impact key parameters have on the project's economic efficiency. As mentioned, the explained variable for this analysis is the IRR:

$$\sum_{t=0}^{n} \frac{CF_t}{(1+IRR)^t} = 0 \tag{19}$$

where CF_t represents the cash flow (balance of all revenues and costs) in year t, n – project lifetime.

The explanatory variables are key project parameters specific to the given technology, analysed over a range of +/- 30% from their base values, using 10% increments. The IRR was chosen as the explained variable because, being an interest rate itself, it allows for direct comparison with the discount rate (unlike NPV – expressed in monetary values – which does not align with the assumed goals of the work). It was found that, under the assumptions made, the IRR refers specifically to the return on equity. Within the scope of the research presented in this monograph, the sensitivity analysis focuses on the most uncertain assumptions:

- Capital expenditures (CAPEX),
- Capacity factor / productivity rate,
- Operational lifetime,
- Annual operating costs,
- Electricity prices,
- Fuel prices (specifically for biogas technology),

All the above-mentioned factors are widely recognised in the energy sector as crucial from the point of view of the economic efficiency of business activity in this industry; the appropriateness of this choice is confirmed by the results of sensitivity analyses.

The eighth stage involves decomposing the specific risk associated with the analysed renewable energy project. Based on the results of the sensitivity analysis of the IRR metric to the variability of selected key parameters, a spider diagram can be developed and the average tangents of the slopes of sensitivity curves of individual key parameter (determined). Then, following the practical but – unfortunately – forgotten today methodology proposed by Smith (1995)[197] (never used in the energy sector), which is based on the observation that risk (κ) is the product of uncertainty (α) and consequences (σ), as presented below:

$$\kappa = \alpha \cdot \sigma \tag{20}$$

the risk values for the analysed parameters were estimated.

[197] Smith, L. D. (1995). Discount rates and risk assessment in mineral project evaluations. *Canadian Institute of Mining and Metallurgical Bulletin*, *88*(989), 34–43.

The above equation is so clear and understandable that, due to its simplicity, it does not require any broader commentary. Nevertheless, within this quite simply and transparent framework, the accuracy of the estimation of individual key variables is the variable (which is determined as estimation accuracy parameter), while the tangent of the slope of the sensitivity curve of a typical project meaning represents the parameter. Multiplying these two values yields the value of the 'risk product' for a project (calculated at given inputs, including capital expenditures, capacity factor/productivity rate, project lifetime, annual operating costs, and electricity and fuel prices). The conducted research has shown that this adapted method is effective and efficient.

Transforming the obtained values into relative values (such that their total share is 100%) allows for the identification of relative risk. Subsequently, using the level of the cost of equity and the risk-free rate, the percentage portions of risk related to individual key parameters within the RADR can be determined in nominal terms. Once the nominal rate has been decomposed into individual risk components, the contribution of these elements to the total nominal risk value is calculated. These shares are then applied, in the same proportions, to the $RADR_{real}$ previously calculated in accordance with the Fisher equation (equation (17)), thereby yielding the portions of individual risk components within the cost of equity in real terms.

The last stage of the research includes the interpretation of the results obtained and the formulation of recommendations regarding:

- The selection of the cost of equity necessary for the economic evaluation of the project in the given technology,
- Decision-making.

The above-mentioned indicators: NPV and IRR are used as metrics for the economic viability of the renewable energy projects considered. In addition to the discussed measures, the results also include – as mentioned – the decomposition of the systematic risk of the project, the interpretation of which allows the ranking of risk factors for the planned project.

Implementing the discussed stages of the planned research methodology enables analogous risk analyses to be carried out for the economic assessment of various renewable energy projects. Estimating individual, technology-specific cost of equity rates, and determining the portions of risk associated with key factors within the specific risk of RES projects, is an interesting and useful undertaking from the sector's viewpoint. Furthermore, considering the production variability in these plants (dependent on regional weather conditions), the potential use of existing support mechanisms, and adaptation to other country-specific conditions represents a notable novelty in research on the profitability of renewable energy projects in Poland.

3.2. Technologies under consideration – case studies

To facilitate a risk analysis in assessing the economic efficiency of renewable energy projects in Poland, five typical case studies were developed, covering the following renewable technologies:

- Photovoltaic farm with a capacity of 50 MWp,
- Onshore wind farm with a capacity of 44.8 MW,
- Offshore wind farm with a capacity of 800 MW,
- 1 MW plant using biogas,
- Geothermal heating plant with a capacity of 50 MW_{th}.

It should be emphasised that, for the geothermal plant, only heat production for a specific district heating system is taken into account. The assumptions for the parameters describing individual technologies are characterised in Chapter 3.3.

3.3. Assumptions related to input data

This chapter presents the assumed values of key technical and economic parameters characteristic of typical investments implemented in individual renewable technologies. For this analysis, it is necessary to examine the sensitivity of a given project's internal rate of return (IRR) to changes in selected key assumptions (including capital expenditure size, capacity factors, electricity/heat prices, fuel prices, operating costs, and project lifetimes). This sensitivity analysis determines the IRR sensitivity curves resulting from changes in these parameters The averaged tangents of the slope of these curves relative to the X-axis are used to calculate risk, expressed as the product of the estimation uncertainty (α) for a given parameter and the effects of its impact on the project's economic efficiency [as shown in equation (20)].

This impact (the effect of → *consequences*, σ) is expressed as the averaged tangent of the slope of the relevant IRR sensitivity curve for the project. Using this methodology, relative risk portions for individual impact factors are obtained. These are then used to decompose the *project-specific risk* into individual components corresponding to the relative shares of the factors considered. These specific risk components, combined with the *risk-free rate* and the *country risk premium*, sum to the estimated risk-adjusted discount rate (RADR). The RADR (equivalent to the cost of equity) is characteristic of a given renewable technology under the theoretical assumption of 100% equity financing (*on an all-equity basis* – as per Smith (1995)[198]) the analysis focuses on the project's inherent value, not the owners' ability to secure preferential financing).

The economic efficiency assessment, combined with the IRR sensitivity analysis for a typical renewable energy project, relies on current and reliable assumptions.

[198] Ibid.

It aims to identify and quantitatively estimate the key risk components specific to investments in selected renewable technologies. Furthermore, comparing the results will enable these technologies to be ranked according to the investment risk associated with each under current conditions.

3.3.1. Risk-adjusted discount rate (RADR)

The estimation of the risk-adjusted discount rate (RADR), equivalent to the cost of equity, follows the adopted methodology and is based on the Capital Asset Pricing Model (CAPM). According to this methodology, estimating the asset beta coefficient (unlevered beta, reflecting the assumption of financing the project solely with equity) is required. This coefficient is typically derived from the average stock returns of comparable listed companies over a selected time horizon. However, compiling such objective data for a specific energy technology is challenging. This is due to the difficulty (linked to data availability) in identifying publicly listed companies that focus solely on that technology (e.g., generating electricity only from onshore wind farms) and also possess sufficient market liquidity. Consequently, due to the inability to collect objective market data of this type (particularly for the Polish market), the analysis relies on literature sources for asset beta factors specified for the analysed renewable technologies (specifically, variant with an electricity price guarantee) (Table 3.1) were used.

Table 3.1. Asset beta assumptions for selected renewable technologies

Parameter	Case study 1: Photovoltaic farm	Case study 2: Onshore wind farm	Case study 3: Offshore wind farm	Case study 4: Biogas power plant	Case study 5: Geothermal heating plant ***
Asset beta (unlevered, assuming electricity price guarantee)*	0.590	0.620	0.770	0.780	0.671
Asset beta volatility coefficient for the 'Green & Renewable Energy' sector (10-year average from 2015–23)**			14.17%		
Adjusted asset beta *(electricity price guarantee)*	**0.674**	**0.708**	**0.879**	**0.891**	**0.766**

* *Europe Economics 2018;*[199]
** *Own calculations based on the A. Damodaran 2015–23 database;*[200]
*** *Due to a lack of specific literature data, this value is assumed based on the 5-year average asset beta for the 'Green & Renewable Energy' sector (A. Damodaran database).*

Source: Own study.

Based on the adjusted asset beta and other CAPM model assumptions, the project-specific risk-adjusted discount rate (real), incorporating the country risk premium, was estimated (Table 3.2). The use of real (constant) values for comparison stems from the difficulty in reaching a consensus on inflation forecasts; consequently, comparing values using constant currencies is considered reasonable.

These results indicate that the lowest real RADR value is found for photovoltaic farms (5.73%) and onshore wind farms (5.94%). For offshore wind farms and biogas plants, on the other hand, the real cost of equity is higher, amounting to 7.01% and 7.08%, respectively, resulting from the higher initial unlevered beta levels for these technologies and signalling the greater risk associated with their implementation.

[199] Europe Economics. (2018). *Cost of capital update for electricity generation, storage and demand side response technologies*. Europe Economics.

[200] Damodaran, A. (n.d.). *Levered and unlevered betas by industry in Europe*. Retrieved July 31, 2025, from https://pages.stern.nyu.edu/~adamodar/

Table 3.2. Results of the calculation of the risk-adjusted discount rate, RADR

Parameter	Case study 1: Photovoltaic farm	Case study 2: Onshore wind farm	Case study 3: Offshore wind farm	Case study 4: Biogas power plant	Case study 5: Geothermal heating plant	*Source*
Assumptions – input parameters for calculations						
Nominal risk-free rate ($R_{f,nominal}$)			3.93%			*Average (15 years) profitability of 10-year Polish government bonds*
Average consumer inflation in Poland (*inflation; i*)			3.58%			*Average (15 years) core inflation in Poland according to NBP data*
Market risk premium (*ERP*)			6.47%			*Average (12 years), according to A. Damodaran 2024 data for Poland: Risk Premiums for Other Markets (pages.stern.nyu.edu/~adamodar/)*
Asset beta (β_u)	**0.674**	**0.708**	**0.879**	**0.891**	**0.766**	According to Table 3.1
Country risk premium (*CRP*)			1.22%			*Average (15 years), according to A. Damodaran 2024 data for Poland: Country Risk Premium (pages.stern.nyu.edu/~adamodar*
Calculation results						
Specific risk (κ_s)	4.36%	4.58%	5.69%	5.76%	4.95%	–
$RADR_{nominal,PL}$	9.51%	9.73%	10.84%	10.91%	10.11%	*Nominal risk-adjusted discount rate with country risk*
$\boldsymbol{RADR_{real,\ PL}}$	**5.73%**	**5.94%**	**7.01%**	**7.08%**	**6.30%**	*Real risk-adjusted discount rate with country risk (calculated using the Fisher formula according to equation 17)*

Source: Own study.

The following chapters present:

1) Technical and economic assumptions for typical projects implemented using selected renewable energy technologies, required for economic evaluations,
2) NPV and IRR calculations for the selected projects (case studies),
3) The results of the IRR sensitivity analysis to changes in key parameters (i.e., capital expenditures, operating costs, electricity/heat prices, fuel prices, and capacity factor/productivity rate).

It should be stated that the purpose of the analyses conducted is not to provide arguments, based on the obtained results, for decisions regarding whether to construct generating units. The adopted assumptions and calculations are mainly used to estimate the specific risk (expressed as the cost of equity), which varies across individual renewable energy technologies, and to indicate the extent to which individual key factors contribute to this risk. This is the reason for conducting the IRR sensitivity analysis of a typical project to changes in selected technical and economic assumptions. As mentioned, this approach is scientifically justified: the discount rate reflects the risk associated with a project (specifically, a project implemented using a specific renewable technology), and should be selected commensurate with this level of risk.

It should be noted that companies should avoid using a single cost of equity to evaluate projects with varying levels of risk (although this is a common practice in the sector) and should instead use different, project-specific rates. This change in approach would result in companies undertaking safe investments (which might currently be abandoned due to the negative effect of overstated corporate rates) and abandoning risky projects (which might sometimes be undertaken due to the positive effect of these same, but in this case understated, corporate rates).

3.3.2. Photovoltaic farm with a capacity of 50 MWp

A photovoltaic farm with a capacity of 50 MWp was selected as a representative project utilising photovoltaic technology. Table 3.3 presents the basic technical and economic assumptions for this type of installation. These assumed values draw upon data from the Institute of Renewable Energy's report *The Photovoltaic Market in Poland 2023*[201] and findings from research assessing renewable energy projects.

According to the presented data, for the photovoltaic farm in question, capital expenditures for construction were assumed to be PLN 3 million/MWp, and operational fixed costs were set at PLN 60,000/MWp. The investment period was set at 1 year, while the operational period (economic life) of the system was established as 25 years. It should be emphasised that for all analysed renewable technology

[201] Instytut Energetyki Odnawialnej. (2023). *Rynek fotowoltaiki w Polsce* [Photovoltaic market in Poland].

projects – including this PV project – decommissioning costs (incurred at the end of the operational period) were assumed to represent 2% of total capital expenditures.

An important indicator determining the electricity production volume from a given plant is its installed/available capacity factor, sometimes referred to as the productivity rate. For the analysed photovoltaic farm, this indicator was assumed to be 1,065 kWh of electricity produced per kWp of installed capacity. Furthermore, the degradation coefficient for the PV modules (which affects the reduction in overall plant productivity) was assumed to be 2% in the first year of operation and 0.5% in subsequent years.

The electricity price assumed for the analysed plant – PLN 389/MWh (constant throughout the operational period) – was based on the 2023 reference price for this type of unit (capacity >1 MW, using only solar energy). This reference price was specified in the relevant ordinance of the Minister of Climate and Environment[202] for the RES auction held that year.

Table 3.3. Technical and economic assumptions for the project construction of a photovoltaic farm – case study 1

Parameter	Unit	Value
Installed capacity	*MWp*	50.0
Capital expenditures	*million PLN/MW*	3.0
Productivity factor	*kWh/kWp*	1,065.0
Annual fixed operating costs	*PLN/MWp*	60,000.0
Electricity price	*PLN/MWh*	389.0
Construction phase	*years*	1
Economic life/operational period	*years*	25
Decommissioning costs at the end of the project lifetime	*%*	2% x CAPEX
Degradation of photovoltaic cells	*%/year*	2.0% in year 1, 0.5% in subsequent years
$RADR_{nominal,PL}$	**%**	**9.51%**
Corporate tax rate	%	19.0%

Source: Own study based on IEO 2023 and of the Ordinance of the Minister of Climate and Environment of 2023 (*Journal of Laws of 2023*, item 2440).

[202] Ministry of Climate and Environment. (2023). *Ordinance of 8 November 2023 on the reference price of electricity from renewable energy sources, periods applicable to producers that have won auctions, and reference electricity sales volumes* (Journal of Laws 2023, item 2440).

3.3.3. Onshore wind farm with a capacity of 44.8 MW

For the onshore wind technology, a characteristic project is assumed to be a farm consisting of 8 turbines, each with a capacity of 5.6 MW (totalling 44.8 MW). The basic technical and economic assumptions for this project are presented in Table 3.4. The assumed values are based on the data presented in the *Polish Wind Energy 4.0 Report*[203] and the results of research on the assessment of projects related to renewable energy.

According to the presented data, for the wind farm in question, capital expenditures for construction were assumed to be PLN 7.1 million/MW, and operational fixed costs were set at PLN 225,000/MW. The investment period is 2 years, while the operational period (economic life) is 20 years.

A capacity factor of 35% is assumed for modern high-power wind turbines. This equates to an annual electricity generation volume of approximately 3,070 MWh per MW of installed capacity.

The electricity price assumed for the analysed plant – PLN 324/MWh (constant throughout the operational period) – was based on the 2023 reference price for this type of unit (capacity >1 MW, using only onshore wind energy). This price was specified in the relevant ordinance of the Minister of Climate and Environment[204] for the RES auction held that year.

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[203] Polish Wind Energy Association. (2022). *Polish wind energy 4.0.*

[204] Ministry of Climate and Environment. (2023). *Ordinance of 8 November 2023 on the reference price of electricity from renewable energy sources, periods applicable to producers that have won auctions, and reference electricity sales volumes* (Journal of Laws 2023, item 2440).

Table 3.4. Technical and economic assumptions for the project construction of an onshore wind farm – case study 2

Parameter	Unit	Value
Installed capacity	*MW*	44.8
Capital expenditures	*million PLN/MW*	7.1
Capacity factor	*%*	35.0%
Annual fixed operating costs	*PLN/MW*	225,000.0
Electricity price	*PLN/MWh*	324.0
Construction phase	*years*	2
Economic life/operational period	*years*	20
Decommissioning costs at the end of the project lifetime	*%*	2% x CAPEX
$\boldsymbol{RADR_{nominal,PL}}$	**%**	**9.73%**
Corporate tax rate	*%*	19.00%

Source: Own study based on PWEA 2022 and of the ordinance of the Minister of Climate and Environment of 2023 (*Journal of Laws of 2023*, item 2440).

3.3.4. Offshore wind farm with a capacity of 800 MW

For offshore wind technology, a typical project is assumed to be a farm with a total installed capacity of 800 MW. The basic technical and economic assumptions for such an investment are presented in Table 3.5. The assumed values are based on the data presented in the *Wind Energy in Poland Report*[205] and the results of research on the assessment of projects related to renewable energy.

According to the presented data, for the offshore wind farm, capital expenditures for construction were assumed to be PLN 12.9 million/MW, and operational fixed costs were set at PLN 380,000/MW. The assumed investment period is 3 years, while the assumed operational period (economic life) is 25 years.

The capacity factor was assumed to be 46.3%, considering the weather conditions in Polish marine areas designated for wind farm construction (in accordance with the *Offshore Wind Farm Development Programme*). This equates to an annual electricity generation volume of approximately 4,060 MWh per MW of installed capacity.

The resulting electricity price assumed for the analysed plant – PLN 463/MWh (applied throughout the operational period) – was based on the maximum

[205] Polskie Stowarzyszenie Energetyki Wiatrowej, 2023. *Wind energy in Poland*.

price specified in the ordinance of the Minister of Climate and Environment[206] of 30 March 2021. This maximum price was subsequently indexed using the relevant inflation index, in accordance with the provisions of the ordinance.

Table 3.5. Technical and economic assumptions for the project construction of an offshore wind farm – case study 3

Parameter	Unit	Value
Installed capacity	*MW*	800.0
Capital expenditures	*million PLN/MW*	12.9
Capacity factor	*%*	46.3%
Annual fixed operating costs	*PLN/MW*	380,000.0
Electricity price	*PLN/MWh*	463.0
Construction phase	*years*	3
Economic life/operational period	*years*	25
Decommissioning costs at the end of the project lifetime	*%*	2% x CAPEX
$RADR_{nominal,PL}$	**%**	**10.84%**
Corporate tax rate	*%*	19.00%

Source: Own study based on PWEA 2023 and of the ordinance of the Minister of Climate and Environment of 2021 (*Journal of Laws of 2021*, item 587).

3.3.5. Biogas power plant with a capacity of 1 MW

The technical and economic assumptions for a typical (1 MW) project involving the construction of an agricultural biogas power plant are presented in Table 3.6.

Due to the high heterogeneity of the systems, differing in the substrates used in the biogas digester, the adopted numbers were processed on the basis of:

[206] Ordinance of the Minister of Climate and Environment of 30 March 2021 on the maximum price for electricity generated in an offshore wind farm and injected into the network in PLN for 1 MWh, which is the basis for settling the right to cover the negative balance (Journal of Laws of 2021, item 587).

- Literature data (including W. Gostomczyk 2020;[207] Biogaz Inwest;[208] Z. Ginalski 2011;[209] Romaniuk et al. 2022[210]),
- Actual data estimated for units of a similar scale in technology operating in Poland,
- Results from research assessing renewable energy projects.

According to the presented data, for the agricultural biogas plant in question, capital expenditures for construction were assumed to be PLN 18 million/MW, operational variable costs were set at PLN 14.6/MWh, and operational fixed costs were set at PLN 360,000/MW. The investment period was assumed to be 1 year, while the operational period (economic life) was assumed to be 25 years. Consistent with the other analysed renewable projects, decommissioning costs (incurred at the end of the operational period) were assumed to be 2% of total capital expenditures.

The operating characteristics of domestic biogas plants indicate high annual operating hours. An average installed capacity factor of approximately 90% (equivalent to over 7,880 hours per year) is assumed for the analysed system.

The electricity price for this plant (PLN 775/MWh throughout the operational period) is based on the reference price for this type of unit (>1 MW capacity, using only agricultural biogas), established in the ordinance of the Minister of Climate and Environment[211] for the 2024 RES auction.

Fuel purchase costs are an additional factor that was not present in the previously described technologies (PV and wind). For agricultural biogas plants, the fuel (substrate) for the biogas digester can include waste from animal husbandry (e.g., slurry), energy crops, waste from agricultural crops (e.g., straw, maize silage), or waste from food processing (e.g., fruit pomace). A significant part of these substrates can be obtained on the farm for free or for a small fee related to transport costs. For a 1 MW biogas plant operating continuously at the assumed capacity utilisation factor, the substrate demand may exceed the farm's own supply capabilities. Consequently, it is assumed that purchasing an additional volume of fuel/substrates from the market, equivalent to 50% of the total demand, will be

[207] Gostomczyk, W. (2020). *Efektywność substratów wykorzystywanych do produkcji biogazu* [Efficiency of substrates used for biogas production]. https://www.imp.gda.pl/bf2020/BF2012/prezentacje/p141.pdf

[208] Biogas Invest. (n.d.). *Calculation examples*. Biogas Invest.

[209] Ginalski, Z. (2011). *Substrates for agricultural biogas plants*. Agricultural Advisory Center in Brwinów, Radom Branch.

[210] Borusewicz, A., Skibko, Z., Romaniuk, W., Pietruszyńska, M., Milewska, A., Marczuk, A. (2024). Agricultural Micro Biogas Plants as a Factor in Farm Development – A Case Study. *Preprint*. https://doi.org/10.20944/preprints202405.0754.v1

[211] Ministry of Climate and Environment. (2023). *Ordinance of 8 November 2023 on the reference price of electricity from renewable energy sources, periods applicable to producers that have won auctions, and reference electricity sales volumes* (Journal of Laws 2023, item 2440).

necessary. Given the heterogeneity of potential substrates, maize silage was selected as the representative production fuel for this analysis. Based on the available commercial offers, the price of this fuel was estimated at PLN 300/Mg.

Table 3.6. Technical and economic assumptions for the project construction of a biogas power plant – case study 4

Parameter	Unit	Value
Installed capacity	*MW*	1.0
Capital expenditure	*million PLN/MW*	18.0
Capacity factor	*%*	90.0%
Annual fixed operating costs	*PLN/MW*	360,000.0
Annual variable operating costs	*PLN/MWh*	14.6
Fuel price	*PLN/Mg*	300.0
Electricity price	*PLN/MWh*	775.0
Construction phase	*years*	2
Economic life/operational period	*years*	25
Decommissioning costs at the end of the project lifetime	*%*	2% x CAPEX
$\boldsymbol{RADR_{nominal,PL}}$	**%**	**10.91%**
Corporate tax rate	*%*	19.00%

Source: Own study based on: Gostomczyk (2020); Biogaz Inwest; Ginalski (2011); Romaniuk et al. (2022); Euro-Most; and the Ordinance of the Ministry of Climate and Environment (2023, Journal of Laws of 2023, item 2440).

3.3.6. Geothermal heating plant with a capacity of 50 MW_{th}

For geothermal technology, a characteristic project adapted to Polish conditions is assumed to be a heating system using ground heat pumps with a total thermal capacity of 50 MW_{th}. For such a system, making six boreholes providing access to thermal water at 42°C is assumed to be necessary. The basic technical and economic parameters, based on business assumptions for a project of similar scale and configuration, are shown in Table 3.7.

According to the presented data, for the analysed geothermal heating plant, capital expenditures for construction (including necessary boreholes) were assumed to be approximately PLN 9.8 million/MW_{th}. Operational fixed costs (including heat pump service costs) were set at PLN 240,000/MW_{th}, and operational variable costs were set at PLN 6.5/GJ. The investment period was assumed to be approximately 3 years, and the operational period (economic life) was assumed to be 25 years.

In the case of the analysed geothermal system, a capacity factor of 60% was assumed. This equates to an annual heat generation volume of approximately 18.9 TJ per MW_{th} of installed capacity.

The heat sale price assumed for the analysed geothermal plant – PLN 103.1/GJ (constant throughout the operational period) – was based on the average 2023 sales price for heat from non-cogeneration RES units. This price was published by the President of the Energy Regulatory Office (ERO) in Information No. 16/2024, dated 28 March 2024[212]).

Table 3.7. Technical and economic assumptions for the project construction of a geothermal heating plant – case study 5

Parameter	Unit	Value
Installed thermal capacity	*MW_{th}*	50.0
Capital expenditures	*million PLN/MW_{th}*	9.8
Capacity factor	*%*	60.0%
Annual fixed operating costs	*PLN/MW*	240,000.0
Annual variable operating costs	*PLN/GJ*	6.5
Heat sale price*	*PLN/GJ*	103.1
Construction phase	*years*	3
Economic life/operational period		25
Decommissioning costs at the end of the project lifetime	*%*	5% x CAPEX
$RADR_{nominal,PL}$	**%**	**10.11%**
Corporate tax rate	*%*	19.00%

*Average heat sales prices for generating units constituting renewable energy sources that are not cogeneration units.[213]

Source: Own study based on data made available to the Author for a project of a similar scale and configuration.

[212] President of the Energy Regulatory Office. (2024). *Information No. 16/2024 on average sales prices of heat generated in generating units that are not cogeneration units in 2023*. Energy Regulatory Office.

[213] President of the Energy Regulatory Office. (2024). *Information No. 16/2024 on average sales prices of heat generated in generating units that are not cogeneration units in 2023*. Energy Regulatory Office.

Based on the adopted data and assumptions for the analysed renewable energy technologies, the next chapter presents the results of the economic efficiency analyses. This includes, in particular, the sensitivity analysis of the IRR to changes in the key parameters of the respective projects. Furthermore, for each technology, the chapter presents results decomposing the specific risk into individual factors that affect plant operation, considering both potential revenues and necessary costs.

4.

Risk in the assessment of economic efficiency of renewable energy projects – case study analysis

Using the methodology presented in the previous chapter, the assumed basic technical and economic parameters for selected projects (considered typical for individual renewable technologies), and the built discounted cash flow model, the net present value (NPV) and internal rate of return (IRR) of these case studies were estimated. The calculations were carried out at the end of 2024. Subsequently, to determine the risk portion within the cost of equity, a sensitivity analysis of the IRR (explained variable) was conducted concerning changes in selected parameters (explanatory variables), which constitute the key risk factors for a given project, namely:

- Capital expenditures,
- Capacity factor/productivity rate,
- Electricity prices,
- Heat prices (only for a geothermal heating plant),
- Annual operating fixed costs,
- Price of fuel (only for a biogas project),
- Project duration/lifetime.

Table 4.1. IRR value for the base parameters of the analysed case studies – results of the discounted cash flow model calculation

Parameter	Case study 1: Photovoltaic farm	Case study 2: Onshore wind farm	Case study 3: Offshore wind farm	Case study 4: Biogas power plant	Case study 5: Geothermal heating plant
$RADR_{nominal,PL}$	*9.51%*	*9.73%*	*10.84%*	*10.91%*	*10.11%*
$RADR_{real,PL}$	*5.73%*	*5.94%*	*7.01%*	*7.08%*	*6.30%*
IRR	**8.43%**	**8.85%**	**10.73%**	**12.64%**	**15.56%**

Source: Own study.

The changes in the aforementioned parameters for the sensitivity analysis ranged from -30% to +30% (in increments of 10%) relative to the assumed base values.

In the next step, based on the results of the IRR sensitivity analysis concerning the variability of key factors, *spider diagrams* were developed for each typical project, and the slopes of the individual sensitivity curves were determined. In addition to the slope indicators of the sensitivity curves, appropriate uncertainty values for the estimation accuracy of the base values of each parameter (based on literature research[214] and own experiences) were adopted:

- Capital expenditures – uncertainty (estimation accuracy): 15%,
- Capacity factor/productivity rate – uncertainty (estimation accuracy): 5%,
- Electricity price/heat price – uncertainty (estimation accuracy): 5%,
- Annual fixed operating costs – uncertainty (estimation accuracy): 15%,
- Price of fuel (only for a biogas project) – uncertainty (estimation accuracy): 15%,
- Project lifetime – uncertainty (estimation accuracy): 10%.

Using both the estimated slope indicators from the sensitivity curves and the assumed uncertainty surrounding the base value estimates for each key parameter, the specific project risk (expressed as the required cost of equity) was decomposed into components corresponding to the impact of key parameters on the IRR value. The results of this sensitivity analysis and the subsequent risk decomposition for each analysed project are presented later in this chapter.

The results of economic efficiency for the analysed case studies, i.e., investments in selected renewable energy technologies, are shown in Table 4.1. Due to very large differences in the scale of the analysed projects and the different

[214] McCarthy, P. (2025). *Why feasibility studies fail*. AMC Consultants. https://www.amcconsultants.com/feasibility-studies

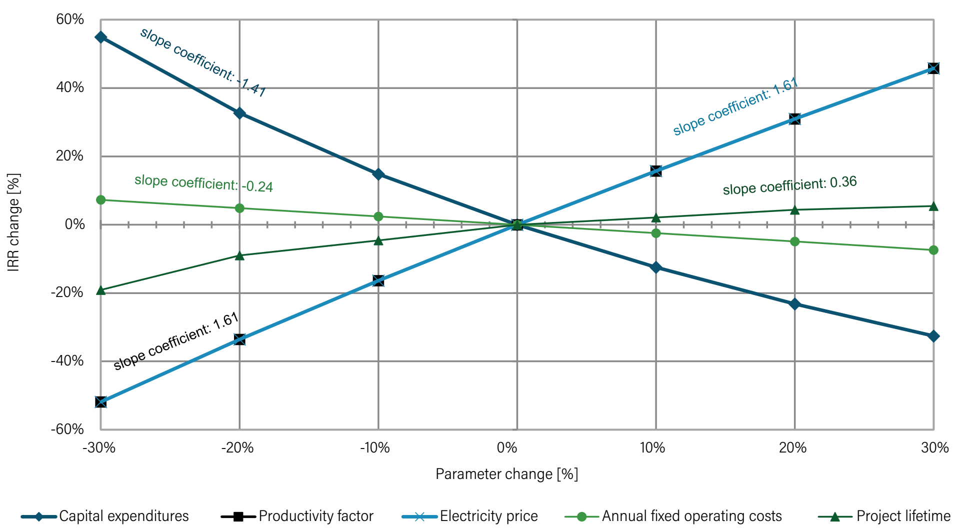
adopted values for the cost of equity (based on estimated risk-adjusted discount rates, including country risk – $RADR_{nominal,PL}$), comparing the obtained IRR values for the considered investments is reasonable. Notably, for all analysed renewable generation unit construction projects, the IRR exceeds the assumed real cost of equity (hurdle rate), meaning that each investment is profitable and generates value beyond the required return on invested capital. The highest IRR values are obtained for the geothermal heating plant project (15.56%), the biogas power plant (12.64%), and the offshore wind farm project (10.73%). For the other projects, the IRR is at a similar level: 8.85% for an onshore wind farm and 8.43% for a photovoltaic farm, respectively. This occurs despite adopting lower costs of equity for the latter projects; this primarily results from the much lower productivity of these two energy technologies.

4.1. Case study 1 – Photovoltaic farm with a capacity of 50 MWp

The results of the sensitivity analysis of the IRR for the photovoltaic farm construction project, concerning changes in its key parameters, are presented in the spider diagram – Figure 4.1. It should be noted that this investment shows the greatest sensitivity to:

- The amount of capital expenditures (inversely proportional relationship) – change in IRR in the range from -32.6% to +54.9%.

Figure 4.1. Results of the analysis of the sensitivity of the internal rate of return (IRR) to the change of selected parameters for case study 1: construction of a photovoltaic farm



Source: Own study.

- The level of electricity prices and the productivity index (directly proportional relationship) – change in the IRR for both parameters in the range from -51.9% to +45.8%.

Subsequently, the project of construction of a photovoltaic farm with a capacity of 50 MWp shows similar sensitivity to the following parameters:

- Fixed operating costs (inversely proportional relationship) – change in IRR in the range from -7.4% to +7.3%.
- Fixed operating costs (inversely proportional relationship) – change in IRR in the range from -7.4% to +7.3%.

Using equation (22), based on the estimated slope coefficients of individual sensitivity curves (values presented in Figure 4.1) and the assumed uncertainty indicators for the estimation of the base parameters, the specific risk for a typical photovoltaic farm construction project with a capacity of 1 MWp (at the feasibility study stage) was decomposed, expressed as the cost of equity in nominal terms ($RADR_{nominal,PL}$). The results obtained are presented in Table 4.2 and Figure 4.2.

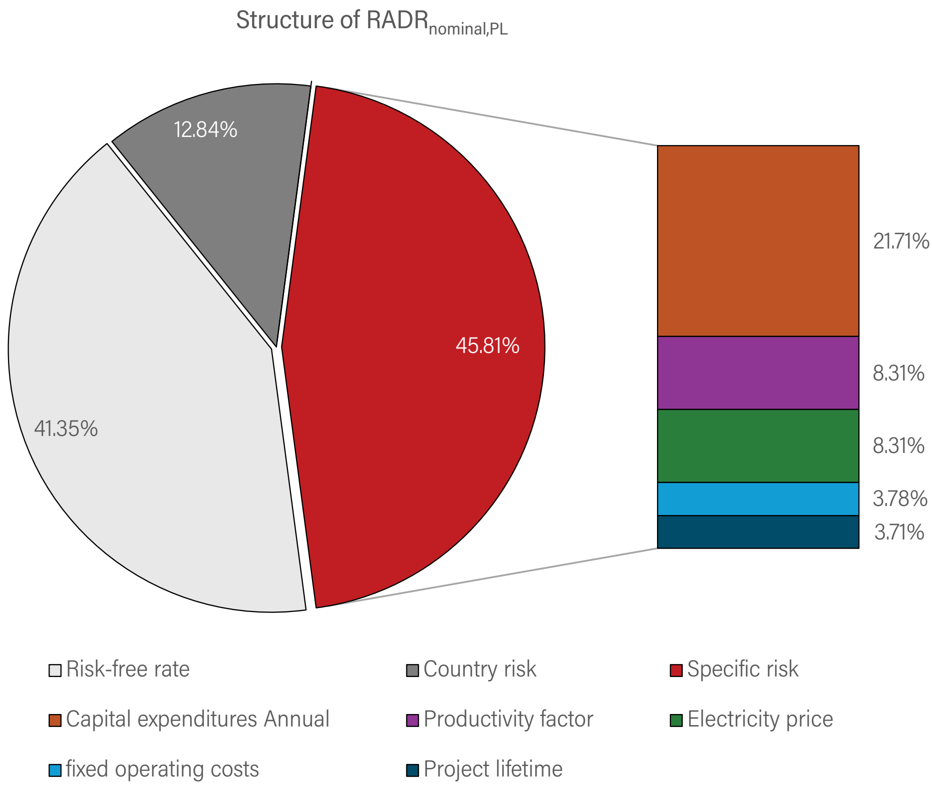
Then, based on the values obtained (risk portion) and the calculated value of the real cost of equity – RADR $_{real,PL}$ using the Fisher formula, in accordance with (17)), the values of risk components were determined in real terms. The results of the decomposition of the cost of equity in real terms (taking country risk into account, see Figure 4.3) in real terms were obtained assuming that risk portions within the real rate occur in the same proportions as within the nominal rate.

Table 4.2. Value of components and structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 1: construction of a photovoltaic farm

Risks component	Value, %	*Contribution, %*
Risk-free rate	**3.93%**	***41.35%***
Specific project risk, including:	**4.36%**	***45.81%***
Capital expenditures	*2.06%*	*21.71%*
Productivity factor	*0.79%*	*8.31%*
Electricity price	*0.79%*	*8.31%*
Annual fixed operating costs	*0.36%*	*3.78%*
Project lifetime	*0.35%*	*3.71%*
Country risk	**1.22%**	***12.84%***
$RADR_{nominal,PL}$	**9.51%**	***100.00%***

Source: Own study.

Figure 4.2. Structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 1: construction of a photovoltaic farm

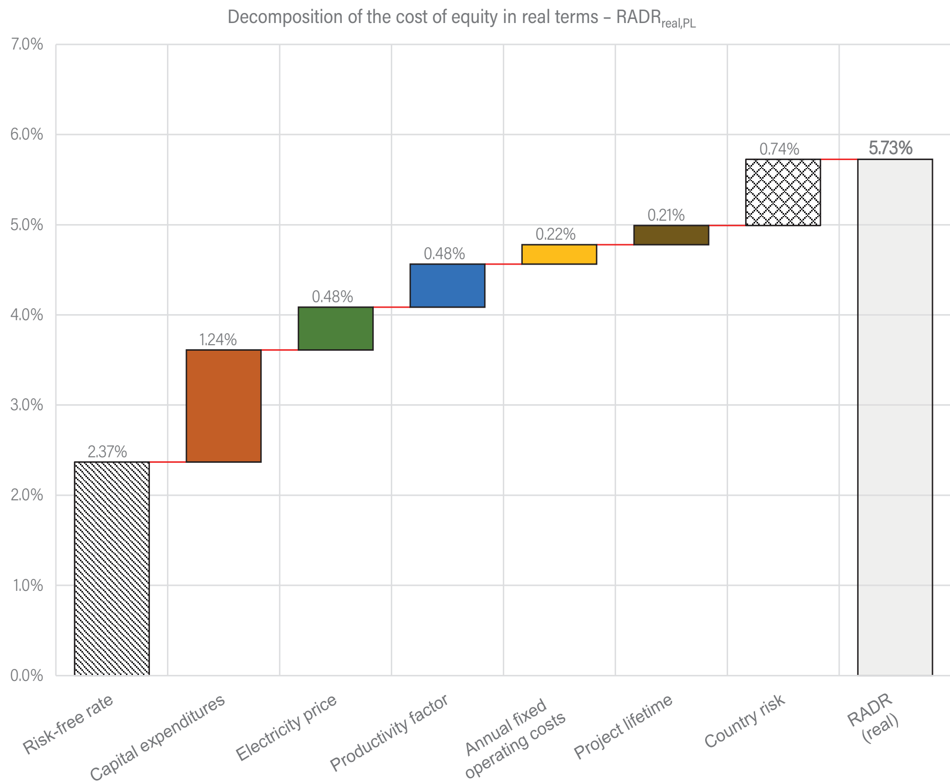


Source: Own study.

Bearing in mind the adopted assumption regarding the electricity price guarantee for renewable generation units construction projects in Poland, among the key factors within the specific project risk (expressed in real terms), the following provide the largest contribution:

- Capital expenditures (risk portion: 1.24%),
- Productivity coefficient and electricity prices (risk portion: 0.48% for both parameters),
- Fixed operating costs (risk portion: 0.22%),
- Project lifetime (risk portion: 0.21%).

Figure 4.3. Decomposition of the cost of equity – risk-adjusted discount rate (taking into account the national investment risk), specifying the specific project risk portion – case study 1: construction of a photovoltaic farm



Source: Own study.

4.2. Case study 2 – Onshore wind farm with a capacity of 44.8 MW

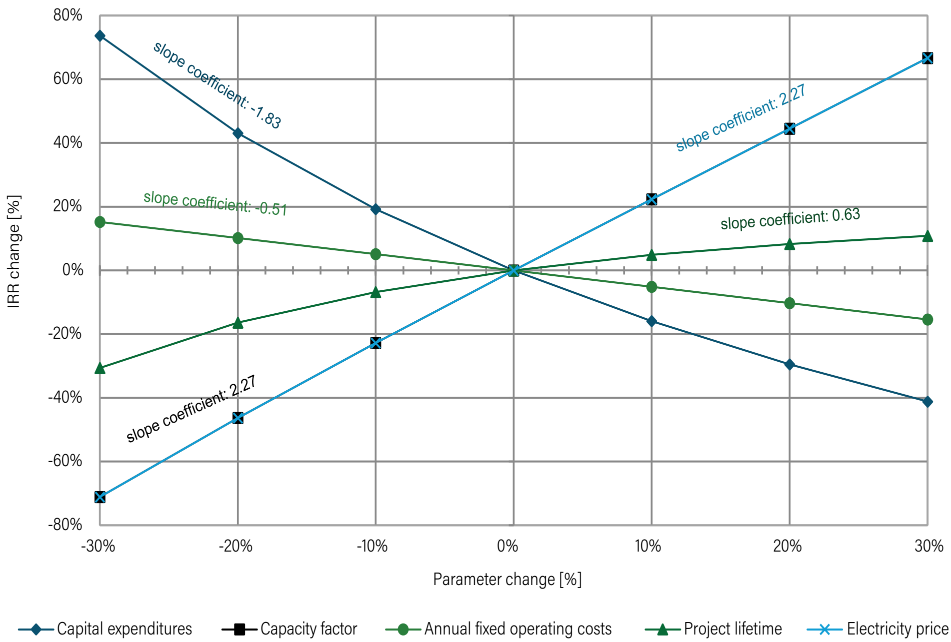
For the construction project of an onshore wind farm with a capacity of 44.8 MW, the results of the analysis of the IRR sensitivity to the change of selected key parameters are presented in Figure 4.4. It should be noted that the project in question shows the greatest sensitivity to changes:

- The amount of capital expenditure (inversely proportional relationship) – change in IRR in the range of -41.2% to +73.7%,
- The level of electricity prices and the productivity index/capacity factor (directly proportional relationship) – change in the IRR for both parameters in the range from -71.1% to +66.7%.

Subsequently, the project of construction of an onshore wind farm shows similar sensitivity to the following parameters:

- Project lifetime (directly proportional relationship) – change in IRR in the range from -30.6% to +10.9%,
- Fixed operating costs (inversely proportional dependence) – change in IRR in the range of -15.4% to +15.2%.

Figure 4.4. Results of the analysis of the sensitivity of the internal rate of return (IRR) to the change of selected parameters for case study 2: construction of an onshore wind farm



Source: Own study.

Similarly to the case study 1, the formula (22) was used to decompose the specific risk expressed in the nominal cost of equity ($RADR_{nominal,PL}$) for the construction project of an onshore wind farm with a capacity of 44.8 MW at the feasibility study stage; the calculation used the estimated values of the slope coefficients of the individual sensitivity curves, the values of which were presented in Figure 4.4, and the assumed uncertainty indicators for the estimation of the base parameters. The results obtained – shares of risk factors within the nominal rate – are presented in Table 4.3 and Figure 4.5.

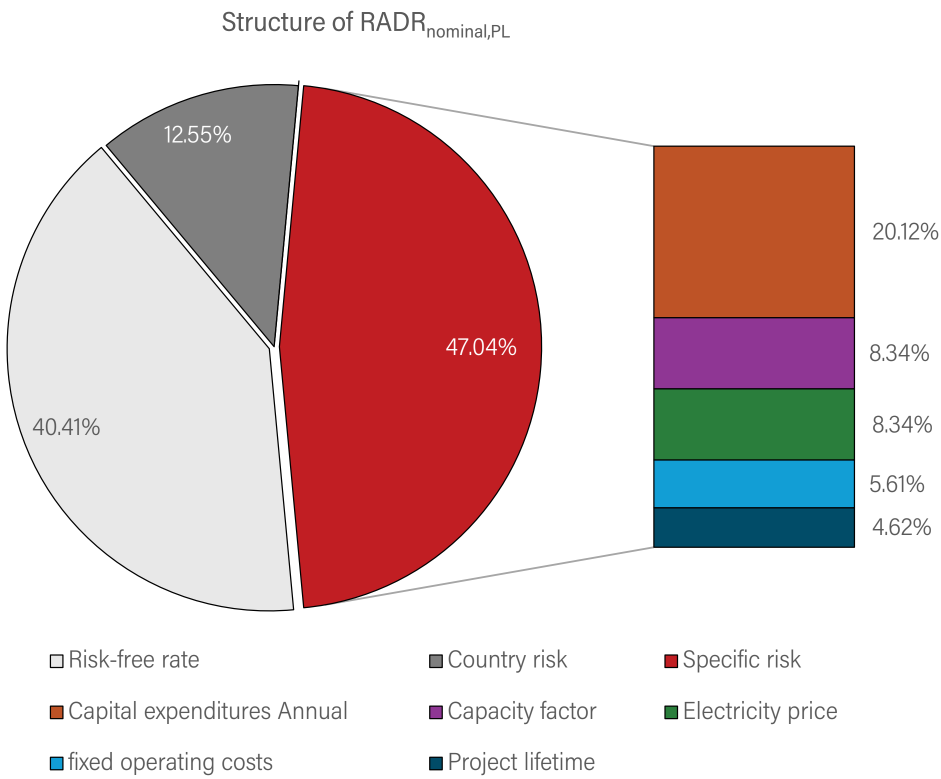
Then, based on the values obtained and the calculated value of the real cost of equity, $RADR_{real,PL}$ (using the Fisher formula, in accordance with (17)), the values of risk components were determined in real terms, assuming that the portions of these factors are arranged in the same proportions as in the nominal rate. The decomposition results are presented in Figure 4.6.

Table 4.3. Value of components and structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 2: construction of an onshore wind farm

Risks component	Value, %	*Contribution, %*
Risk-free rate	**3.93%**	***40.41%***
Specific project risk, including:	**4.58%**	***47.04%***
Capital expenditures	*1.96%*	*20.12%*
Capacity factor	*0.81%*	*8.34%*
Electricity price	*0.81%*	*8.34%*
Annual fixed operating costs	*0.55%*	*5.61%*
Project lifetime	*0.45%*	*4.62%*
Country risk	**1.22%**	***12.55%***
$RADR_{nominal,PL}$	**9.73%**	***100.00%***

Source: Own study.

Figure 4.5. Structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 2: construction of an onshore wind farm

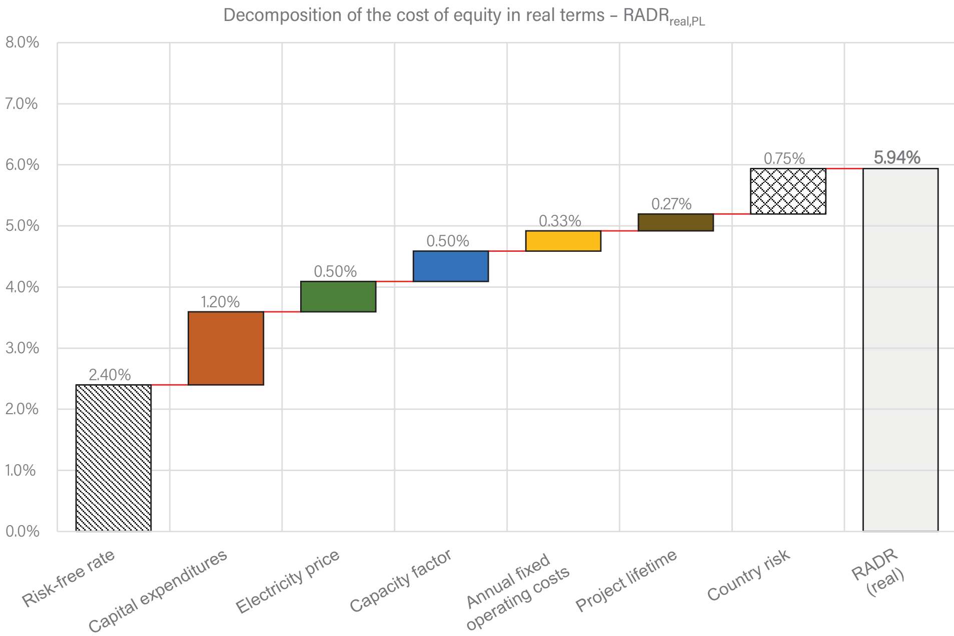


Source: Own study.

For the analysed case, it can therefore be concluded, subject to the previously described conditions regarding the electricity price guarantee for renewable generation unit construction projects in Poland, that within the specific risk of the wind farm – onshore project, among the key parameters, the following provide the largest share in the real cost of equity:

- Capital expenditures (risk portion: 1.20%),
- Utilisation rate of installed capacity (capacity factor) and electricity prices (risk portion: 0.50% for both parameters),
- Fixed operating costs (risk portion: 0.33%),
- Project lifetime (risk portion: 0.27%).

Figure 4.6. Decomposition of the cost of equity – risk-adjusted discount rate (taking into account the country risk), specifying the specific project risk portion – case study 2: construction of an onshore wind farm



Source: Own study.

4.3. Case study 3 – Offshore wind farm with a capacity of 800 MW

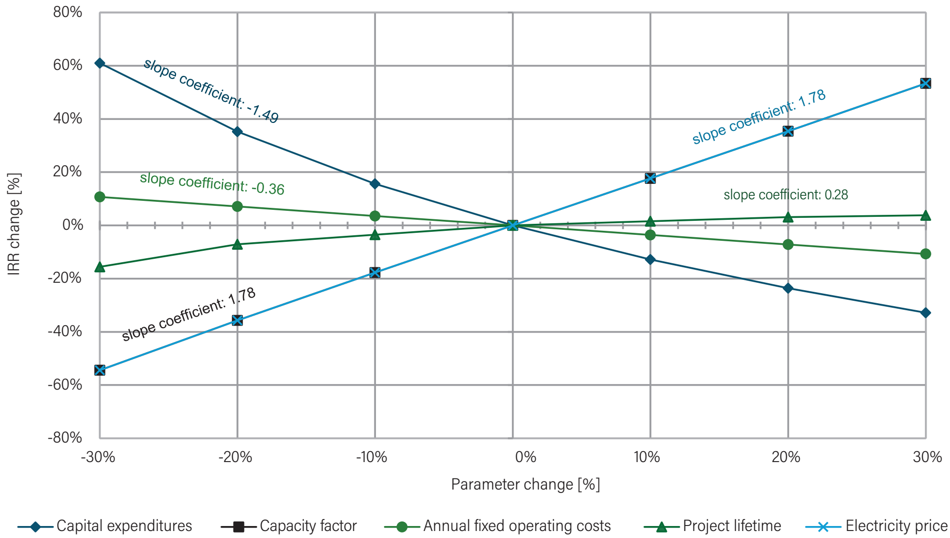
The results of the sensitivity analysis of the IRR for the 800 MW offshore wind farm construction project to changes in the key parameters of the project are presented in the spider diagram in Figure 4.7. It should be noted that the project in question shows the greatest sensitivity to:

- The amount of capital expenditures (inversely proportional relationship) – change in IRR in the range from -32.8% to +61.0%,
- The level of electricity prices and the productivity index/capacity factor (directly proportional relationship) – change in the IRR for both parameters in the range from -54.4% to +53.4%.

Subsequently, the project of construction of an 800 MW offshore wind farm shows similar sensitivity to the following parameters:

- Fixed operating costs (inversely proportional relationship) – change in IRR in the range from -15.6% to +10.7%,
- Project lifetime (directly proportional relationship) – change in IRR in the range from -19.1% to +3.8%.

Figure 4.7. Results of the analysis of the sensitivity of the internal rate of return (IRR) to the change of selected parameters for case study 3: construction of an offshore wind farm



Source: Own study.

Similarly to the previous case studies, equation (22) was employed to decompose the specific risk (expressed in the nominal cost of equity – RADR $_{nominal,PL}$) of the 800 MW offshore wind farm construction project at the stage of the feasibility study; the estimated slope coefficients of the individual sensitivity curves, (values presented in Figure 4.7), and the assumed uncertainty indicators for the estimation of the base parameters were used. The results obtained are presented in Table 4.4 and Figure 4.8.

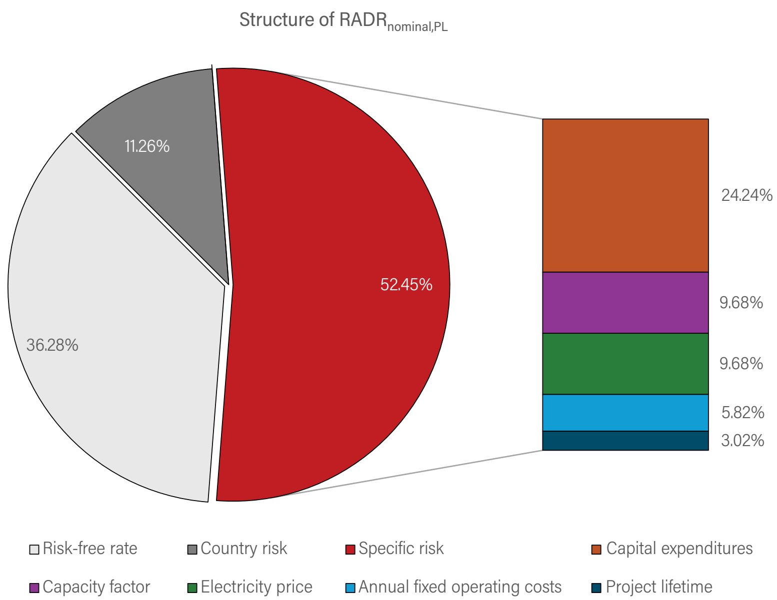
Then, based on the values of the shares of these risk factors and the calculated value of the cost of equity $RADR_{real,PL}$ (using the Fisher formula (17)), the portions of risk components in the real cost of equity were determined. This calculation assumed that the proportional shares of risk components are identical for both the nominal and real rates. The results are presented in Figure 4.9.

Table 4.4. Value of components and structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 3: construction of an offshore wind farm

Risks component	Value, %	*Contribution, %*
Risk-free rate	**3.93%**	***36.28%***
Specific project risk, including:	**5.69%**	***52.45%***
Capital expenditures	*2.63%*	*24.24%*
Capacity factor	*1.05%*	*9.68%*
Electricity price	*1.05%*	*9.68%*
Annual fixed operating costs	*0.63%*	*5.82%*
Project lifetime	*0.33%*	*3.02%*
Country risk	**1.22%**	***11.26%***
$RADR_{nominal,PL}$	**10.84%**	***100.00%***

Source: Own study.

Figure 4.8. Structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 3: construction of an offshore wind farm

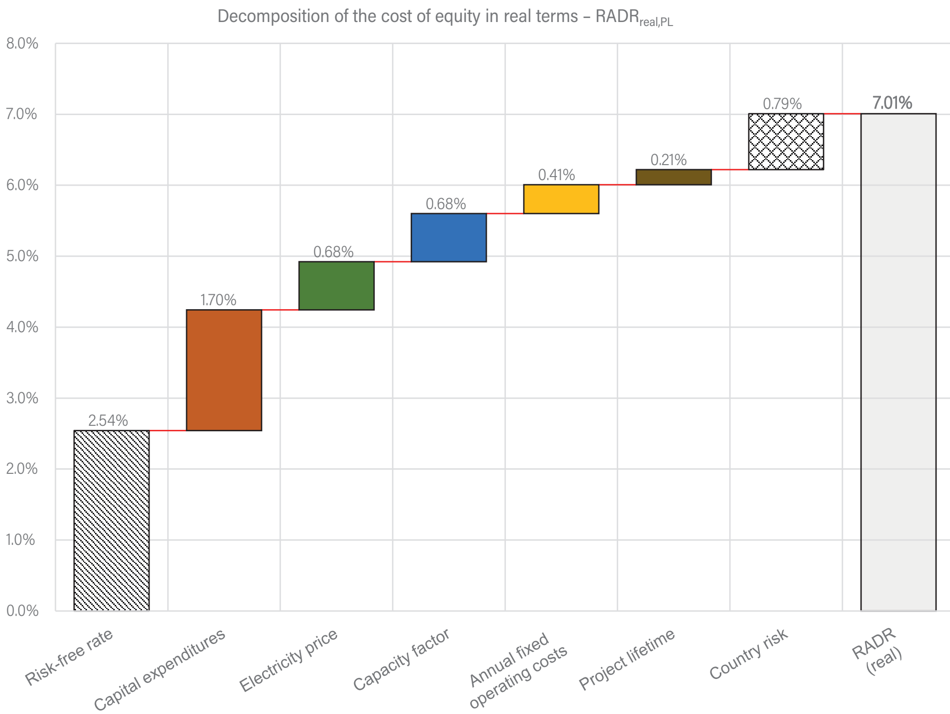


Source: Own study.

It should be stated that, even considering the assumption of electricity price guarantees for renewable generation projects in Poland, the following key parameters make the largest contribution to the specific project risk:

- Capital expenditures (risk portion: 1.70%),
- Utilisation rate of installed capacity (capacity factor) and electricity prices (risk portion: 0.68% for both parameters),
- Fixed operating costs (risk portion: 0.41%),
- Project lifetime (risk portion: 0.21%).

Figure 4.9. Decomposition of the cost of equity – risk-adjusted discount rate (taking into account the country risk), specifying the specific project risk portion – case study 3: construction of an offshore wind farm



Source: Own study.

4.4. Case study 4 – Biogas power plant with a capacity of 1 MW

In the case of the construction project of an agricultural biogas power plant with a capacity of 1 MW, the results of the analysis of the sensitivity of the IRR to the change of the key parameters of the project are presented in Figure 4.10. It should be noted that the investment in question shows the greatest sensitivity to changes:

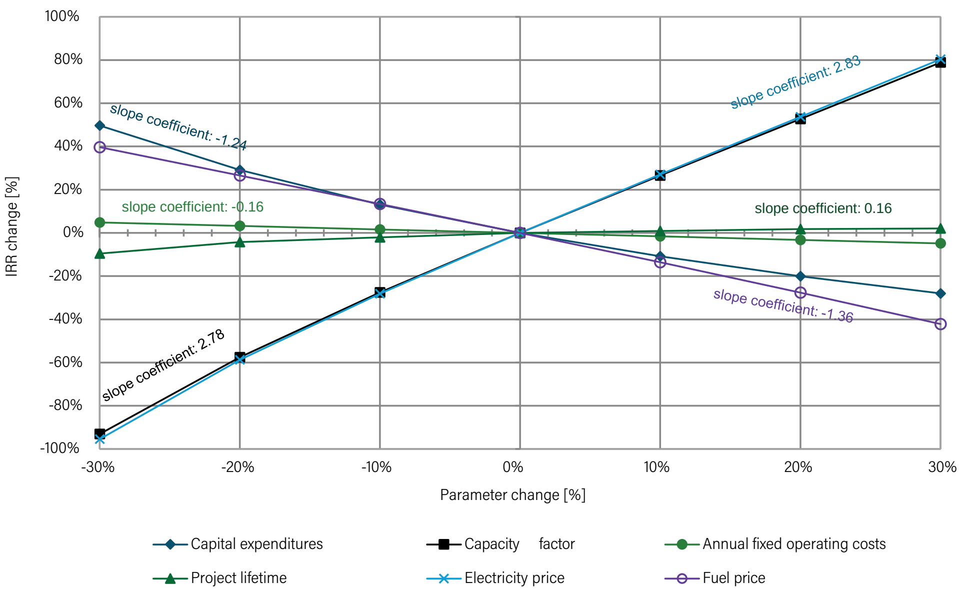
- Electricity prices and productivity index (capacity factor) (directly proportional dependence) – change in IRR for both parameters in the range of -95.5% (93.1%) to +80.4% (78.9%),

- The amount of capital expenditure (inversely proportional relationship) – change in IRR in the range of -28.0% to +49.7%,
- Fuel price level (inverse relationship) – IRR change ranging from -42.2% to +39.7%.

Subsequently, the project of construction of a biogas power plant with a capacity of 1 MW shows similar sensitivity to the following parameters:

- Project lifetime (directly proportional dependence) – change in IRR in the range of -9.6% to +2.1%,
- Fixed operating costs (inversely proportional relationship) – change in IRR in the range of -4.9% to +4.9%.

Figure 4.10. Results of the analysis of the sensitivity of the internal rate of return (IRR) to the change of selected parameters for case study 4: construction of a biogas power plant



Source: Own study.

For this case, equation (22) was used to decompose the specific risk (expressed in the cost of equity – $RADR_{nominal,PL}$) of a typical 1 MW agricultural biogas power plant construction project at the feasibility study stage, using the estimated values of the slope coefficients of individual sensitivity curves (values presented in Figure 4.10) and the assumed uncertainty indicators for the estimation of the base parameters. The results obtained – portions of key risk factors within the nominal rate – are presented in Table 4.5 and Figure 4.11.

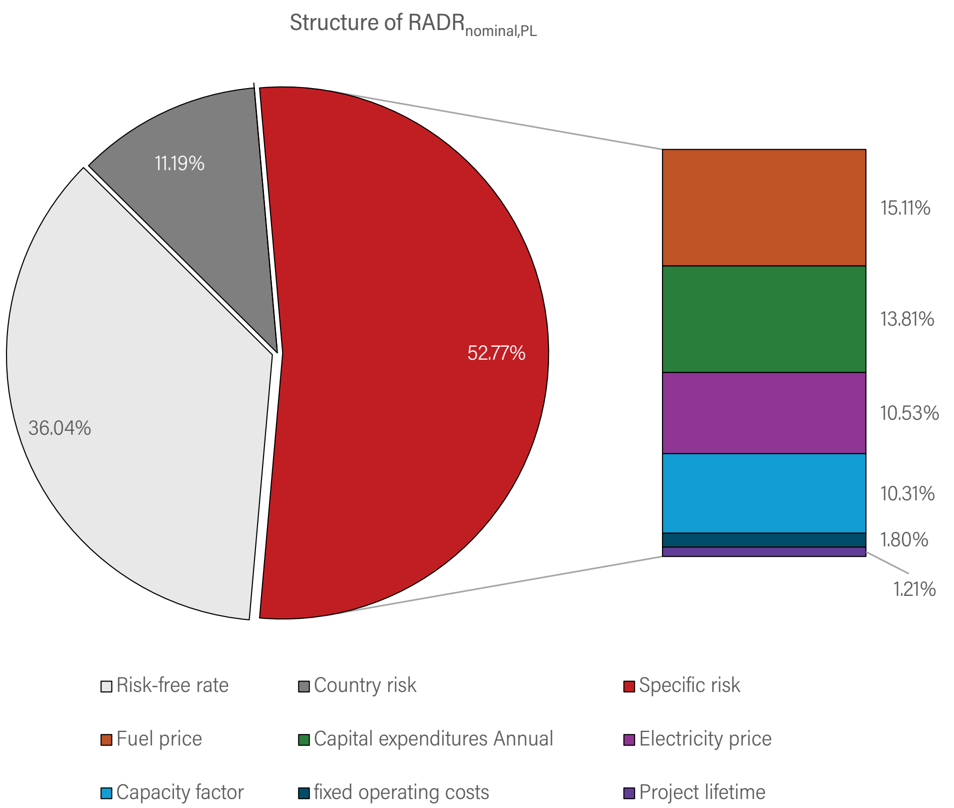
Based on the calculated values of the shares of risk factors and the calculated value of the cost of equity – RADR $_{real,PL}$ (using the Fisher formula, (17)), the values of risk components were determined in real terms, assuming that risk portions occur in the same proportions within the nominal and real rates. The results of this decomposition are presented in Figure 12.

Table 4.5. Value of components and structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 4: construction of a biogas power plant

Risks component	Value, %	*Contribution, %*
Risk-free rate	**3.93%**	***36.04%***
Specific project risk, including:	**5.76%**	***52.77%***
Fuel price	*1.65%*	*15.11%*
Capital expenditure	*1.51%*	*13.81%*
Capacity factor	*1.15%*	*10.53%*
Electricity price	*1.13%*	*10.31%*
Annual fixed operating costs	*0.20%*	*1.80%*
Project lifetime	*0.13%*	*1.21%*
Country risk	**1.22%**	***11.19%***
$RADR_{nominal,PL}$	**10.91%**	***100.00%***

Source: Own study.

Figure 4.11. Structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 4: construction of a biogas heating plant

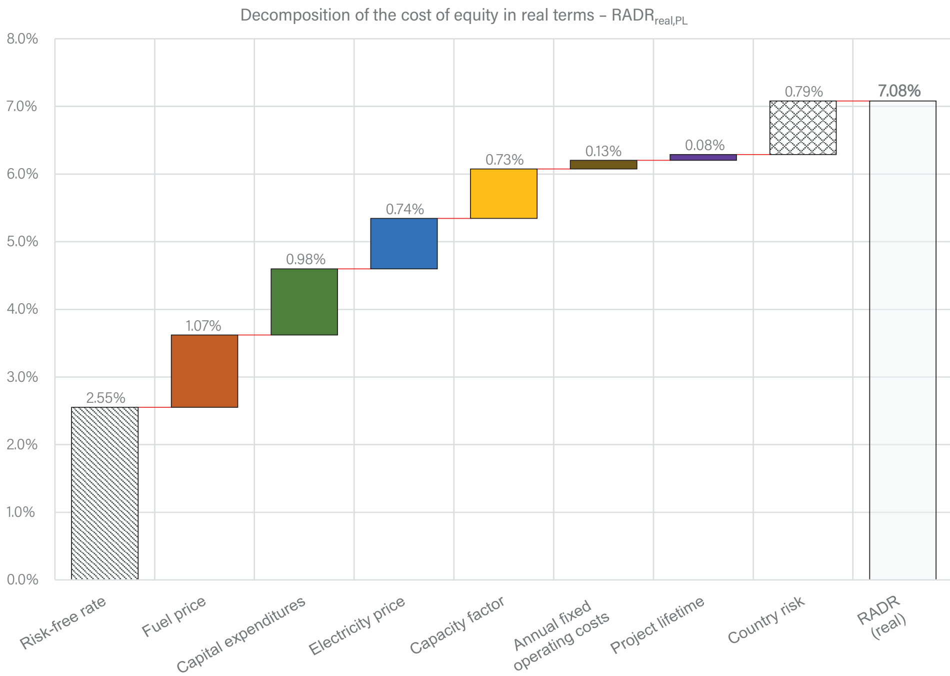


Source: Own study.

It should be emphasised, subject to the previously described assumptions regarding the electricity price guarantee for renewable generation unit construction projects in Poland, that within the specific risk of a typical biogas project, among the key parameters, the following provide the largest contribution:

- Fuel price (risk portion: 1.07%),
- Capital expenditures (risk portion: 0.98%),
- Electricity prices and utilisation rate of installed capacity/capacity factor (risk portion, respectively: 0.75% and 0.73%),
- Fixed operating costs (risk portion: 0.13%),
- Project lifetime (risk portion: 0.09%).

Figure 4.12. Decomposition of the cost of equity – risk-adjusted discount rate (taking into account the country risk), specifying the specific project risk portion – case study 4: construction of a biogas power plant



Source: Own study.

4.5. Case study 5 – Geothermal heating plant with a capacity of 50 MW_{th}

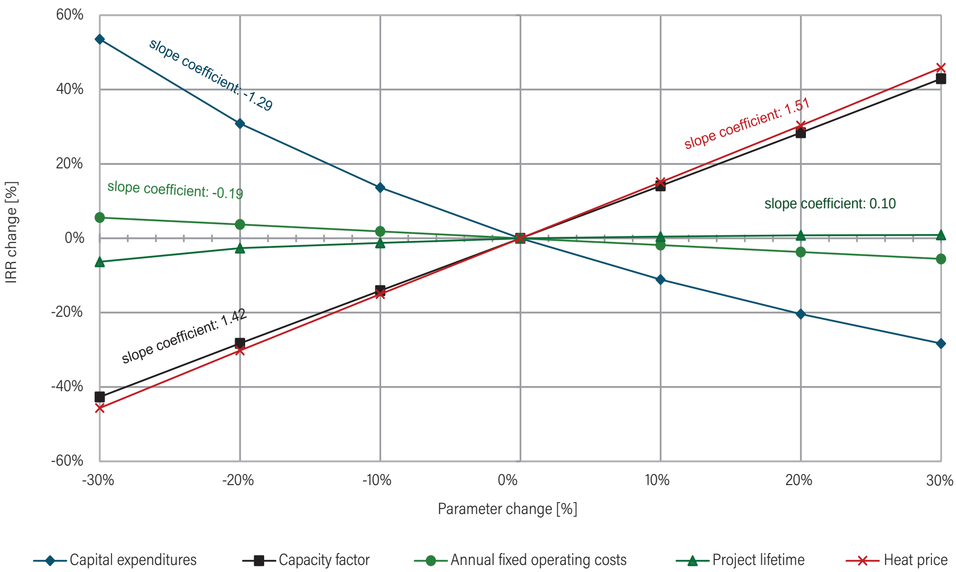
The results of the sensitivity analysis of the IRR for the geothermal heating plant construction project to changes in the key parameters of the project are presented in the spider diagram in Figure 4.13. It should be noted that the investment in question shows the greatest sensitivity to:

- Amount of capital expenditure (inversely proportional dependence) – change in IRR in the range of -28.3% to +53.4%,
- Level of heat prices (directly proportional relationship) – change in the IRR for both parameters in the range of -45.7% to +45.9%,
- Capacity factor (directly proportional dependence) – change in the IRR for the range of -42.7% to +42.9%.

Subsequently, the project of construction of a geothermal heating installation with a capacity of 50 MW_{th}, based on ground heat pumps, shows similar sensitivity to the following parameters:

- Fixed operating costs (inversely proportional dependence) – change in IRR in the range of -5.6% to +5.6%,
- Project lifetime (directly proportional dependence) – change in IRR in the range of -6.3% to +0.9%.

Figure 4.13. Results of the analysis of the sensitivity of the internal rate of return (IRR) to the change of selected parameters for case study 5: construction of a geothermal heating plant



Source: Own study.

Based on the estimated slope coefficients of individual sensitivity curves (the values of which are presented in Figure 4.13) and the assumed uncertainty indicators for the estimation of the base parameters, for a typical geothermal heating plant construction project with a capacity of 50 MW_{th} (at the feasibility study stage), the specific risk was decomposed, expressed as the cost of equity in nominal terms ($RADR_{nominal,PL}$). The results obtained are presented in Table 4.6 and Figure 4.14.

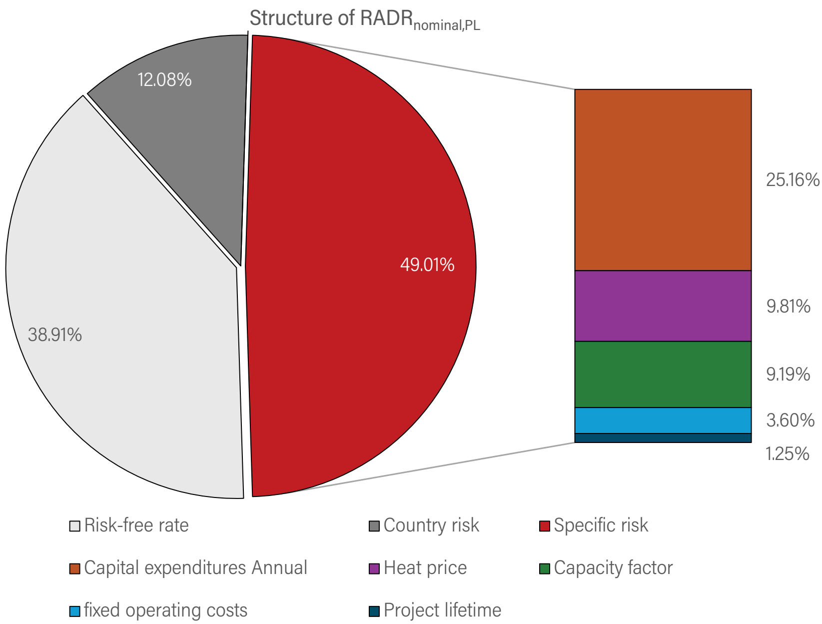
Then, based on the values obtained (risk portion) and the calculated value of the real cost of equity – RADR $_{real,PL}$ (using the Fisher formula, in accordance with equation (17)), the values of risk components were determined in real terms. The results of the decomposition of the cost of equity (taking into account the country risk Figure 4.15) in real terms () were obtained assuming that risk portions within the real rate occur in the same proportions as within the nominal rate.

Table 4.6. Value of components and structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 5: construction of a geothermal heating plant

Risks component	Value, %	*Contribution, %*
Risk-free rate	**3.93%**	***38.91%***
Specific project risk, including:	**4.95%**	***49.01%***
Capital expenditure	*2.54%*	*25.16%*
Heat price	*0.99%*	*9.81%*
Capacity factor	*0.93%*	*9.19%*
Annual fixed operating costs	*0.36%*	*3.60%*
Project lifetime	*0.13%*	*1.25%*
Country risk	**1.22%**	***12.08%***
$RADR_{nominal,PL}$	**10.11%**	***100.00%***

Source: Own study.

Figure 4.14. Structure of the cost of equity – risk-adjusted discount rate (taking into account the country risk) in nominal terms – case study 5: construction of a geothermal heating plant

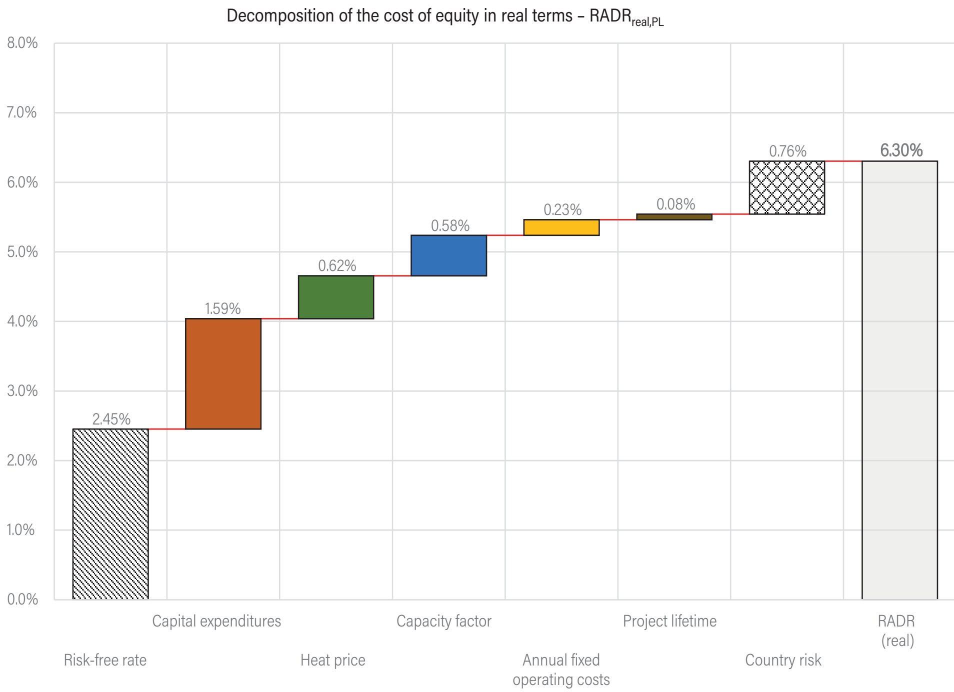


Source: Own study.

Bearing in mind the regulations regarding the determination and approval of heat sales prices within local heating systems (regulated activities), among the key parameters within the specific project risk (expressed in real terms), the following provide the largest contribution:

- Capital expenditures (risk portion: 1.59%),
- Heat sale price and capacity factor (risk portion, respectively: 0.62% and 0.58%),
- Fixed operating costs (risk portion: 0.23%),
- Project lifetime (risk portion: 0.08%).

Figure 4.15. Decomposition of the cost of equity – risk-adjusted discount rate (taking into account the national investment risk) in real terms, specifying the specific project risk portion – case study 5: construction of a geothermal heating plant



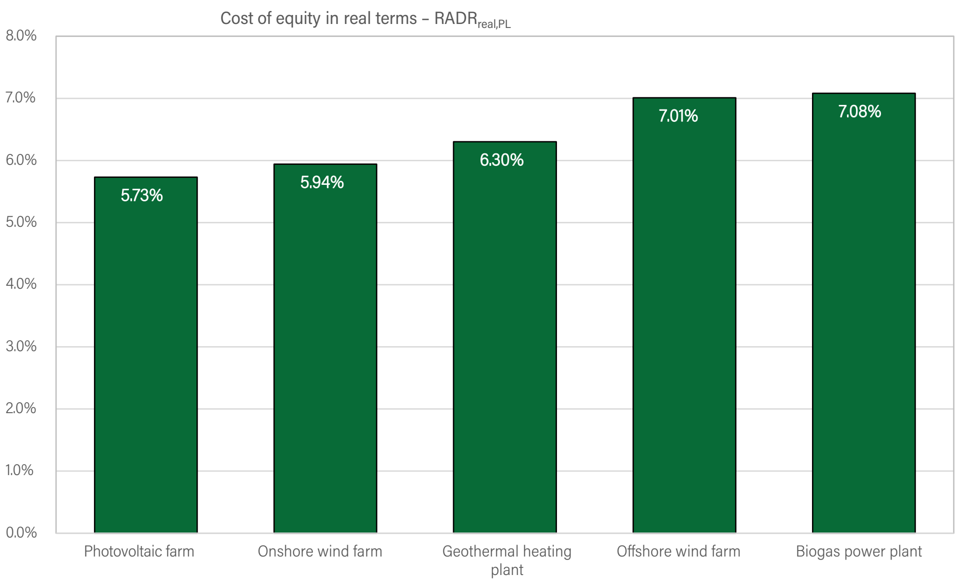
Source: Own study.

4.6. Benchmark analysis

Based on the assumptions, input data, and results obtained, a comparison of the estimated real cost of equity values is presented in Figure 4.16.

It should be emphasised that the purpose of the analyses was not to assess specific projects and support the process of making an investment decision regarding the construction of a new generation plant, but to assess the diversity of selected renewable energy technologies in terms of specific risk, reflected in the cost of equity, which should consequently translate into the weighted average cost of capital (WACC) used in the process of analysing the economic efficiency of projects. Only the results of these analyses, based on real data on the offer value of capital expenditures, as well as forecasts of energy prices and operating costs, can provide a reliable basis for making a specific investment decision.

Figure 4.16. Comparison of the cost of equity – risk-adjusted discount rate (taking into account the national investment risk) in real terms, for the analysed renewable energy technologies



Source: Own study.

Taking into account the results of the conducted research, it should be stated that among the renewable energy technologies analysed, the lowest values of the cost of equity (and thus the lowest investment risk) characterise projects for the construction of a photovoltaic farm ($RADR_{real,PL}$– 5.73%) and an onshore wind farm ($RADR_{real,PL}$ – 5.94%). On the other hand, the highest values of the risk-adjusted cost of equity (taking into account the national investment risk) in real terms were estimated for the project of construction of an offshore wind farm ($RADR_{real,PL}$ – 7.01%) and a biogas power plant ($RADR_{real,PL}$ – 7.08%). The result falling between the mentioned technology groups is that for a geothermal heating plant based on ground heat pumps ($RADR_{real,PL}$ – 6.30%). However, it should be emphasised that in the case of this technology, geological conditions related to the location of geothermal holes are particularly important (minimum depth of boreholes, access to water at a certain temperature, etc.), as well as the proximity of the district heating system to the off-take of the heat produced.

Given the results obtained, although due to the relatively homogeneous group of energy technologies analysed (market-mature renewable technologies) the range of variability in the cost of equity is not very wide, it can be clearly indicated that the risk associated with the implementation of individual projects varies, hence the recommended approach for selecting a risk-adjusted discount rate. Consequently, the weighted average cost of capital for a given investment is to move away from using the same corporate value of this indicator for each technology and to adopt an individually estimated cost of equity, taking into account the specific risk associated with the implementation of a particular project in a given energy technology.

Final conclusions

The consideration of risk in assessing the economic efficiency of renewable energy projects plays a key role throughout the decision-making process. Renewable energy sources, although characterised by significant potential for the decarbonisation of energy systems, possess limitations resulting from their specific nature. For wind and photovoltaic sources, the primary limitation is the variability of production dependent on weather conditions; for biogas units, challenges relate to the availability of the raw material; and for geothermal sources, difficulties arise concerning the temperature of the energy carrier. Furthermore, in all cases, the local context plays a crucial role, conditioning the production potential from these sources.

This monograph analyses the role and importance of risk in assessing the economic efficiency of renewable energy projects in Poland, specifically considering existing support instruments for RES projects. As the classic discounted cash flow (DCF) analysis is a commonly used method for project evaluation in the energy sector, this work focuses on the parameter within this technique that uniquely expresses project risk: the discount rate. This parameter typically takes the form of the weighted average cost of capital (WACC), a resultant rate representing the combined perception of equity owners and donors of foreign capital regarding the risk scope of the assessed project. Currently, there is a consensus within the energy sector that the capital asset pricing model (CAPM) is the only correct method for estimating the cost of equity. This model allows for the analytical calculation of the beta enterprise risk indicator and, consequently, the risk-adjusted discount rate (RADR). As this rate expresses the company's cost of equity, energy companies use it to assess all projects they are considering.

From the perspective of financial science, this approach is inappropriate because the projects under consideration differ, often significantly, in their level of risk. As a result, certain projects with a risk lower than that of the company may be rejected, whilst those with a risk higher than that of the enterprise may be accepted for implementation. The aim of this study was to differentiate the cost of equity by determining the discount rate corresponding to the specific risk scope of a given technology, in this case, renewable technology. Therefore, a mathematical model employing scenario analysis was developed to evaluate various electricity or heat production technologies, reflected in five case studies.

The case studies were developed as typical projects implemented in a given technology. These projects were calculated in fixed money; to enable comparisons between technologies, the focus was placed solely on the cost of equity, recognising that it objectively expresses the project's risk. This cost was calculated by identifying beta factors characteristic of each technology from literature sources. It was assumed that the measure of risk is a product of uncertainty (α) and consequences (σ). The uncertainty factor was represented by the scope of error or the estimation accuracy (*level of accuracy*) for key parameters of a typical project. The consequence factor, on the other hand, was determined using classic sensitivity analysis, which involved examining changes in the project's IRR (discount measure) in response to variations in key data assumptions. This consequence factor was expressed as the average tangent of the angle of the sensitivity curve for a given key parameter relative to the OX axis in a spider diagram. This process yielded the magnitude of the risk product, the relative risk, and – ultimately – the share of the risk component associated with each key parameter within the cost of equity characteristic of the specific technology.

The first case study concerns a photovoltaic farm with a capacity of 50 MWp, for which capital expenditures were assumed at 3 million PLN/MWp and operational fixed costs at 60,000 PLN/MWp. The investment period was set at 1 year, and the system's operating time, i.e., its economic life, was 25 years. Decommissioning costs, applicable to this and subsequent scenarios, were assumed to be 2% of total capital expenditures. The capacity factor was assumed at 1065 kWh/kWp; the module degradation rate was 2% in the first year of operation and 0.5% in subsequent operational years. Electricity prices used in the analysis were based on the results of the RES auction.

The second case study is an onshore wind farm, consisting of eight turbines with a capacity of 5.6 MW each (total of 44.8 MW). Capital expenditures were assumed to be PLN 7.1 million/MW, and operational fixed costs were set at PLN 225,000/MW. The investment period was set at 2 years, and the operational lifetime at 20 years. The capacity factor was assumed to be 35%, corresponding to an annual generation of 3,070 MWh per MW of installed capacity. Analogously to the photovoltaic case study, the electricity price for the analysis was based on RES auction results.

The third case study is an offshore wind farm with a capacity of 800 MW. Capital expenditures were assumed to be PLN 12.9 million/MW, and fixed operating costs were set at PLN 380,000/MW. The investment period is 3 years, and the operational lifetime is 25 years. The capacity factor was assumed to be 43.3%, corresponding to an annual electricity generation of 4,060 MWh per MW of installed capacity. In this case, the electricity price reflects the maximum price specified in the Ordinance of the Minister of Climate and Environment, indexed in subsequent years using the relevant inflation rate.

The fourth case study is a biogas power plant with a capacity of 1 MW. Capital expenditures were assumed to be PLN 18 million/MW, and operational fixed costs were set at PLN 14.6/MW. The investment period is 1 year, and the operational lifetime is 25 years. The capacity factor was assumed to be 90%. The electricity price was based on the RES auction reference price for plants using only agricultural biogas. For this technology, the fuel purchase cost was also considered, assumed to be PLN 300/Mg.

The fifth case study is a geothermal heating plant using ground heat pumps with a total power output of 50 MW_{th}. Capital expenditures were assumed to be PLN 9.8 million/MW_{th}, and fixed operating costs were set at PLN 240,000/MW. The scenario assumes the need for six boreholes providing access to thermal water at a temperature of 42°C. The investment period is 3 years, and the operational lifetime is 25 years. The heat sales price was based on the average sales price for heat from non-cogeneration RES generating units, as published by the President of the ERO.

For each of the aforementioned technologies, the net present value (NPV) the internal rate of return (IRR) were estimated using the developed discounted cash flow model. Subsequently, a sensitivity analysis was performed on the IRR relative to changes in the value of key project parameters to determine the risk component within the cost of equity. These parameters included: capital expenditures, capacity factor values, electricity or heat prices, fixed operating costs, fuel prices, and the operational period of the respective plants. The range of variation for these parameters was assumed as -30% to +30% relative to the base values, using 10% increments.

Then, using the sensitivity analysis results and the uncertainty (α) associated with estimating the base values of the analysed parameters, the project's specific risk (expressed as the cost of equity level) was decomposed into components corresponding to the impact of each key parameter on the IRR value.

The results obtained allow the following conclusions to be drawn:

1) The Internal Rate of Return (IRR) for all analysed projects exceeds the assumed real cost of equity (hurdle rate), meaning that all technologies considered are profitable, generating value beyond the required return on capital. The highest IRR value of 15.56% is achieved for the geothermal heating plant construction project, followed by the biogas power plant (IRR = 12.64%) and the offshore wind farm (IRR = 10.73%). This is due

to higher capacity factors in these units compared to the onshore wind farm and photovoltaic plant, for which the IRR is 8.85% and 8.43%, respectively.

2) The investment related to the construction of a photovoltaic farm with a capacity of 1 MWp shows the greatest sensitivity to changes in capital expenditures (change in IRR from -32.6% to +54.9%) and electricity prices and productivity index (from -51.9% to +45.8%). The IRR is less sensitive to changes observed in fixed operating costs (-7.4% to +7.3%) and the project lifetime (from -19.1% to +5.5%).
3) Decomposition of the cost of equity in real terms for the photovoltaic plant indicates the largest contributions to specific project risk (within the real cost of equity) come from capital expenditures (risk portion: 1.24%), productivity coefficient and electricity prices (0.48% for both parameters), fixed operating costs (0.22%), and the project lifetime (0.21%).
4) In the case of the onshore wind farm with a capacity of 44.8 MW, the project's economic efficiency is also most sensitive to changes in capital expenditures, electricity prices, and capacity factors. The change in IRR ranges from -41.2% to +73.7% for capital expenditure changes and from -71.1% to +66.7% for changes in electricity prices and capacity factor, respectively. Changes in project lifetime result in IRR changes ranging from -30.6% to +10.9%, while changes in fixed operating costs cause IRR changes ranging from -15.4% to +15.2%.
5) Within the specific risk of the onshore wind farm project, the same parameters as for the photovoltaic farm contribute most significantly to the real cost of equity. Nevertheless, the technology's specificity affects the differing risk portions: capital expenditures account for a risk portion of 1.20%; electricity prices and capacity factor account for 0.50%; fixed operating costs contribute 0.33%; and the project lifetime contributes 0.27%.
6) For offshore wind farms, the change in IRR in response to changes in individual parameters is as follows: for capital expenditures, IRR changes range from -32.8% to +61.0%; for electricity prices and capacity factor, from -54.4% to +53.4%; for fixed operating costs, from -15.6% to +10.7%; and for project lifetime, from -19.1% to +3.8%.
7) The shares in the specific risk of the offshore wind farm construction project are: capital expenditures – risk portion of 1.70%; electricity prices and capacity factor – 0.68%; operating costs – 0.41%; and project lifetime – 0.21%.
8) In contrast to the wind farm and photovoltaic projects, the biogas power plant construction project is most sensitive to electricity prices and capacity utilisation index – the change in IRR for both parameters ranges from -95.5% (93.1%) to +80.4% (78.9%). This project, on the other hand, is slightly less sensitive to changes in capital expenditures, where the observed change

in IRR ranges from -28.0% to +49.7%. Sensitivity to fuel price changes is also notable, resulting in IRR changes ranging from -42.2% to +39.7%. The project lifetime and fixed operating costs affect IRR changes ranging from -9.6% to +2.1% and -4.9% to +4.9%, respectively.

9) Fuel prices contribute the largest share to the specific risk of the analysed biogas project (risk portion: 1.07%), followed by capital expenditures (0.98%), electricity prices (0.75%), and capacity factor (0.74%). Fixed operating costs and the project lifetime in this case are responsible for risk portions of 0.13% and 0.09%, respectively.
10) The sensitivity analysis of the IRR for the geothermal heating plant construction project indicates the greatest sensitivity to changes in capital expenditures (IRR change from -28.3% to +53.4%), heat prices (from -45.7% to +45.9%), and capacity factor (from -42.7% to +42.9%). This project is least sensitive to changes in fixed operating costs (from -5.6% to +5.6%) and project lifetime (from -6.3% to +0.9%).
11) Decomposition of the cost of equity for the geothermal heating plant indicates the following shares of key parameters within the specific project risk: capital expenditures (risk portion: 1.59%), the sale price of heat (0.62%), capacity factor (0.58%), fixed operating costs (0.23%), and project lifetime (0.08%).
12) The study highlights the diversity among renewable energy technologies regarding their specific risk profiles, reflected in the cost of equity. This diversity should influence the weighted average cost of capital (WACC) used when analysing the economic efficiency of projects. The results concerning specific risk, when combined with actual data for a planned project, can support the decision to initiate or withdraw from constructing a unit using a particular renewable energy source.
13) Given that the risk associated with implementing individual projects varies, the recommended approach for selecting a risk-adjusted discount rate, and consequently the WACC for a given investment, involves moving away from using a single corporate rate regardless of technology. Instead, an individually estimated cost of equity should be adopted, taking into account the specific risk associated with implementing a particular project using a specific energy technology.

Summary (in Polish)

Rozwój odnawialnych źródeł energii (OZE) w krajowym sektorze wytwarzania energii elektrycznej i ciepła stanowi jeden z kluczowych kierunków transformacji energetycznej. Dynamiczny przyrost mocy zainstalowanej w instalacjach fotowoltaicznych i lądowych farmach wiatrowych sprzyja realizacji polityki klimatycznej, lecz jednocześnie niesie ze sobą wyzwania związane z ich zmienną, zależną od warunków pogodowych produkcją energii, co utrudnia stabilne bilansowanie systemu elektroenergetycznego i zwiększa poziom ryzyka inwestycyjnego. Efektywność ekonomiczna projektów OZE jest zatem narażona na niepewność związaną m.in. z wahaniami cen energii, kosztów kapitałowych, dostępnością surowców (np. biogaz) czy parametrami złożowymi (np. geotermia). Kluczowe znaczenie ma zatem rzetelna analiza ryzyka i właściwe oszacowanie kosztu kapitału.

Monografia koncentruje się na ocenie roli ryzyka w analizie ekonomicznej projektów OZE w Polsce, przy szczególnym uwzględnieniu mechanizmów wsparcia. Podstawą oceny jest metoda zdyskontowanych przepływów pieniężnych (DCF) oraz identyfikacja stopy dyskontowej odzwierciedlającej realne ryzyko technologiczne. W tym celu opracowany został model matematyczny do oceny różnych technologii wytwarzania energii elektrycznej lub ciepła, co zostało zilustrowane w pięciu studiach przypadku (farma fotowoltaiczna 50 MWp, lądowa farma wiatrowa 44,8 MW, morska farma wiatrowa 800 MW, biogazownia 1 MW oraz ciepłownia geotermalna 50 MW_{th}).

Dla każdej z wymienionych technologii oszacowano wartość bieżącą netto (NPV) oraz wewnętrzną stopę zwrotu (IRR), wykorzystując opracowany model zdyskontowanych przepływów pieniężnych. Następnie przeprowadzono analizę wrażliwości IRR względem zmian wartości kluczowych parametrów projektowych w celu określenia komponentu ryzyka w koszcie kapitału własnego. Do parametrów tych zaliczono: nakłady inwestycyjne, współczynnik wykorzystania mocy, ceny energii elektrycznej lub ciepła, stałe koszty operacyjne, ceny paliwa oraz okres eksploatacji poszczególnych instalacji. Zakres zmienności tych parametrów przyjęto na poziomie od –30% do +30% w stosunku do wartości bazowych, w krokach co 10%. Analiza wrażliwości wykazała, że głównymi źródłami ryzyka są nakłady inwestycyjne, ceny energii/ciepła oraz wskaźniki wykorzystania mocy, przy czym w biogazowniach istotną rolę odgrywa również cena paliwa.

Wyniki wskazują, że koszty kapitału i poziom ryzyka znacząco różnią się między technologiami OZE. Z tego względu stosowanie jednej stopy dyskontowej (WACC) dla całego przedsiębiorstwa może prowadzić do błędnych decyzji inwestycyjnych. Rekomendowane jest zatem odejście od jednolitej stopy korporacyjnej i wprowadzenie indywidualnie wyznaczanego kosztu kapitału własnego, odpowiadającego specyficznemu ryzyku danego projektu i technologii.

Monografia dostarcza narzędzi, wyników oraz wniosków, które mogą zostać wykorzystane przez inwestorów, decydentów oraz środowisko naukowe, ułatwiając ocenę efektywności ekonomicznej oraz zarządzanie ryzykiem w projektach OZE. Wyniki mogą wspierać podejmowanie trafniejszych decyzji inwestycyjnych i sprzyjać skuteczniejszemu planowaniu rozwoju zrównoważonej energetyki w Polsce.

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The topic of the book is important and relevant from the perspective of the development of science in the field of economics and energy economics. The book significantly fills a gap in the literature regarding studies presenting the methodology of decision analysis related to investing in renewable energy technologies. The main value of the monograph lies in the creative development of the current methods of risk analysis (especially the DCF model), based on classical methods of assessing economic efficiency and in the development of premises for the concept of a new method enabling a rational assessment of the efficiency of investing in renewable energy technologies.

Prof. Krzysztof Jajuga, PhD

The choice of the topic of the monograph is very pertinent. One of the biggest challenges in the coming years concerns the energy transformation towards renewable energy sources, which emphasizes the relevance and importance of this topic. The monograph comprehensively presents issues related to the significance of renewable energy in the Polish energy system. The author discusses tools for assessing the efficiency and risks of investment projects, including those related to renewable energy, and presents a proposal for a model framework that can be used to analyze the efficiency and risks of renewable energy projects.

Prof. Waldemar Kamrat, PhD

Akademia WSB
WSB University

WSB University
Cieplaka 1c, 41-300 Dabrowa Gornicza
Poland

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