

Janusz Zyśk

Opportunities for Adapting and Implementing Energy Solutions in Poland Based on International Experience:

Conditions, Barriers and Directions
of Green Transition Policy

SERIES: **GREEN TRANSFORMATION**
POLICY IN POLAND



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PREFACE

It is widely recognised that Poland's green transformation policy is centred on the shift away from fossil fuels, particularly coal, towards renewable energy sources (RES), with the overarching objective of achieving climate neutrality by 2050. This transition is being pursued through the *Energy Policy of Poland until 2040* (PEP2040), the *National Recovery and Resilience Plan* (NRRP) and European Union regulatory frameworks, including the European Green Deal. These measures encompass the development of renewable energy sources, the modernisation of the energy sector, including the development of nuclear power, improvements in the energy efficiency of buildings, the promotion of low-emission transport and support for innovation. Their implementation requires substantial investment, financed, inter alia, through European Union (EU) funding. Research indicates growing optimism among the Polish public

regarding the potential economic and social benefits of the transition. Nevertheless, the process requires significant levels of investment and entails considerable challenges, particularly for coal-mining regions. It also poses important theoretical, descriptive and practical challenges for the academic community.

The present series of publications, devoted to green transformation policy in Poland, provides an in-depth examination of the issues associated with this field of research. Spanning six volumes, the series enables a multifaceted exploration of the subject matter, integrating theoretical perspectives with practical considerations.

The publication series adopts an interdisciplinary approach, with the aforementioned subject matter providing a common thematic framework for the individual monographs. The authors address issues relating to public policy, management, environmental protection, law and public administration. By bringing these studies together within a single series, the research provides a comprehensive and multidimensional perspective on the issues under consideration.

The second volume in the series examines selected examples of energy transition initiatives implemented across European countries and regions and assesses the extent to which the experience gained from these initiatives may inform the planning of transition processes in

other geographical contexts. The scope of the research encompasses the principal infrastructural, organisational and technological dimensions of the energy transition. The projects analysed in the volume demonstrate considerable potential for adapting international experience to the Polish context, although the extent of their applicability varies. The author therefore emphasises that the adaptation of international experience should be preceded by a comprehensive technical, economic, environmental, social and institutional assessment, followed by the appropriate adjustment of the proposed solutions to the specific characteristics and conditions of the region concerned.

CHAPTER I

INTRODUCTION

The energy transition (also frequently referred to as the energy and climate transition) and adaptation to climate change are currently among the most important development challenges facing Poland. The two processes are closely interconnected. On the one hand, it is necessary to reduce greenhouse gas emissions by changing the way energy is produced and used (mitigation); on the other hand, it is necessary to prepare the economy and society for the impacts of climate change, which are already being observed and will intensify over the coming decades. This results from environmental considerations, international and EU commitments, as well as the need to ensure energy security and economic competitiveness. The transition is therefore not merely a response to the European Union's climate policy, but is becoming one of the key elements of the country's socio-economic development.

The importance of the transition also increased following the energy crisis triggered by Russia's aggression against Ukraine. These events highlighted the need to increase the resilience of energy systems to geopolitical disruptions and to reduce dependence on imported fossil fuels. As a result, energy security began to be understood not only as ensuring continuity of energy supply, but also as the capacity to utilise domestic renewable energy resources, develop nuclear power, energy storage and modern electricity networks. The contemporary energy transition therefore encompasses not only decarbonisation, but also the diversification of energy sources, the development of new technologies and increased flexibility across the entire energy system.

The social dimension of the energy transition is also of considerable importance. The process of moving away from fossil fuels should be carried out in accordance with the principles of a just transition, providing support to the regions and communities most dependent on mining and energy-intensive industries. Investment in new jobs, the development of professional skills and an active regional policy are necessary to enable these regions and communities to take advantage of new economic opportunities associated with the development of green technologies. It should be emphasised that the success of the energy and climate transition requires the engagement of society as a whole.

The transition encompasses all areas of the economy that use energy. This results from the need to achieve climate neutrality across the economy as a whole. In Poland, transport, buildings and industry account for the largest shares of final energy consumption, while agriculture and waste management also account for a significant proportion of greenhouse gas emissions. This means that achieving climate objectives requires parallel action across all sectors, including changes in the energy carriers used, improvements in energy efficiency and the deployment of new low-carbon technologies. Only coordinated action encompassing not only the electricity sector, but also district heating, buildings, industry, transport, agriculture and the land use, land-use change and forestry (LULUCF) sector can achieve lasting reductions in emissions while maintaining energy security and economic competitiveness.

Such a comprehensive approach to the transition is adopted in the National Energy and Climate Plan to 2030, with an outlook to 2040 (KPEiK), which currently constitutes the principal instrument for planning the energy transition in Poland and sets out the pathway towards achieving the climate and energy objectives arising from European Union law¹. The document adopts a comprehensive approach to the transition, identifying specific challenges and a set

¹ *National Energy and Climate Plan to 2030 (Update of the 2019 NECP)*, Warsaw 2025.

of measures aimed at reducing fossil fuel consumption, improving energy efficiency and reducing greenhouse gas emissions across all sectors.

The NECP envisages the gradual restructuring of the national energy system through the dynamic development of renewable energy sources, the introduction of nuclear power, the modernisation of electricity networks and the development of energy storage. At the same time, it provides for wide-ranging measures on the energy consumer side, including the thermal modernisation of buildings, the replacement of inefficient heat sources, the electrification of transport, improvements in the efficiency of industrial processes and the development of a circular economy.

An important element of the energy transition is the development of hydrogen technologies, which play a particularly significant role in the decarbonisation of sectors in which direct electrification is technically difficult or economically unjustified. Hydrogen is expected to be used primarily in energy-intensive industry and heavy transport. In the longer term, hydrogen is also expected to serve as an energy carrier enabling the seasonal storage of surplus electricity from renewable energy sources and supporting the balancing of the national electricity system. The development of the hydrogen economy includes the construction of production capacity and infrastructure for hydrogen

storage and transmission, as well as the deployment of technologies for its use in the energy sector and industry.

National energy and climate transition objectives and measures are further developed, specified and implemented at the regional level, taking into account local conditions, potential and challenges associated with the decarbonisation process. One of the most advanced examples of regional energy transition planning in Poland is the Eastern Wielkopolska region. This is due to the subregion's historically strong dependence on lignite mining and conventional power generation, which means that the process of moving away from fossil fuels presents economic, social and environmental challenges simultaneously.

In response to these circumstances, the Eastern Wielkopolska Development Strategy 2040 and the Eastern Wielkopolska Climate Neutrality Strategy 2040 were developed, setting out the directions for the region's just transition². These documents envisage a gradual shift away from a coal-based economy towards the development of renewable energy sources, improved energy efficiency, the development of the hydrogen economy and the circular economy, as well as the creation of new and innovative sectors of the economy.

² *Eastern Wielkopolska Development Strategy 2040*, Poznań 2022;
Eastern Wielkopolska Climate Neutrality Strategy 2040, Poznań 2021.

Particular emphasis is placed on ensuring a just socio-economic transition through the creation of new jobs, the improvement of workers' qualifications and support for entrepreneurship, in order to mitigate the negative effects of the phasing-out of the mining and energy sector. The strategy also emphasises the need to pursue the transition across all sectors of the economy and to actively involve local authorities, businesses, the research community and residents in achieving the established objectives, with the aim of achieving climate neutrality in the region by 2040.

At the same time, Poland is increasingly experiencing the effects of climate change. In recent years, an increase in average air temperature has been observed (it is worth noting that record temperatures were recorded in Poland at the end of June 2026, the highest in the country's measurement history), along with more frequent heatwaves, periods of drought, intense rainfall leading to local flash floods and increasingly frequent extreme weather events, such as strong winds and hailstorms. These changes affect the functioning of almost all sectors of the economy, from agriculture and water management, through transport and the energy sector, to public health. Energy infrastructure is particularly vulnerable, as its operation depends on the availability of water resources, ambient temperatures and the resilience of transmission networks to extreme weather

conditions. This means that adaptation measures must be implemented in parallel with the energy transition.

The energy transition is a complex, long-term process encompassing technological, economic, social and environmental aspects. Given the scale of the challenges and the high investment costs involved, particular importance should be attached to drawing on the experience of countries and regions that began the process of moving away from fossil fuels at an earlier stage. The analysis of international examples makes it possible to better understand the mechanisms underlying the changes taking place, identify success factors and avoid mistakes that have occurred at different stages of the transition. The exchange of experience also constitutes an important element in building institutional capacity and supports the development of more realistic strategies and development scenarios.

Drawing on good practices does not mean directly replicating solutions applied in other countries. Each region is characterised by different conditions arising from the availability of natural resources, the structure of the economy, the state of energy infrastructure, climatic conditions and the social situation. International experience should therefore be treated as a source of inspiration and knowledge about possible directions of development, which should subsequently be adapted to local conditions. Such an approach makes it possible to reduce investment

risk, increase the efficiency of the use of public funds and better prepare regions for changing technological and economic conditions.

One of the most important conclusions drawn from experience to date is the need to pursue the transition in a comprehensive manner. This process cannot be limited solely to replacing fossil fuel-based power plants with new energy sources. Equally important is the development of transmission and distribution infrastructure, energy storage facilities, demand-side management systems and technologies enabling the integration of large amounts of renewable energy into the national electricity system. In many cases, the development of new generation capacity became possible only after the prior modernisation of electricity networks and the implementation of modern digital energy management systems.

Hydrogen technologies, large-scale energy storage and sector coupling, which enable the integration of the electricity sector with district heating, transport and industry, are also playing an increasingly important role in the transition process. In many development strategies, hydrogen is regarded as an important energy carrier supporting the decarbonisation of sectors that are difficult to electrify, while energy storage is becoming an essential element in ensuring the stable operation of systems based on renewable energy sources. The development of these technologies

demonstrates that an effective transition requires the simultaneous implementation of multiple interconnected technical solutions.

International experience also highlights the importance of the appropriate redevelopment of post-industrial and post-mining areas. These areas are increasingly being used as locations for new renewable energy installations, energy storage facilities, production plants and research and development centres. Such an approach not only reduces pressure to use new land for investment purposes, but also contributes to the regeneration of areas affected by industrial restructuring and to the creation of new jobs.

The social dimension of the transition is equally important. The experience of many countries shows that the success of the overall process depends not only on the availability of technology and financing, but also on public acceptance and the appropriate preparation of local communities for the changes taking place. Investment measures are therefore increasingly complemented by worker retraining programmes, support for entrepreneurship, the development of education and the creation of new areas of economic specialisation. This approach is consistent with the concept of a just transition, which aims to mitigate the negative social impacts associated with moving away from fossil fuels.

It is worth emphasising that analysing the experience of other countries and regions is important not only from the perspective of energy policy, but also for the development planning process. It makes it possible to verify the assumptions adopted, assess the feasibility of scenarios and identify technologies that have proved most effective in practice. As a result, the strategies developed can be based not only on theoretical projections, but also on experience gained from transition processes that have actually been implemented.

It can therefore be concluded that drawing on international experience constitutes one of the key elements of effective energy transition planning. It enables the development of better-prepared strategies, reduces the risks associated with decision-making and increases the efficiency of the use of financial resources. At the same time, it demonstrates that the energy transition is not merely a technological process, but a comprehensive change encompassing the economy, society and the environment, requiring a long-term and integrated approach.

The aim of this study is to present and analyse examples of energy transition implemented in selected European countries and regions. Comparing the experience of different areas makes it possible to demonstrate the diversity of the solutions applied and to identify measures that may serve as a source of good practice for other regions

at different stages of the transition. The analysis covers both countries and regions with long-standing traditions of fossil fuel extraction and use, as well as areas actively developing modern energy technologies. This makes it possible to identify effective instruments that support the achievement of climate objectives and enhance energy security while maintaining economic competitiveness.

An important area of the transition is the modernisation of district heating systems. The decarbonisation of heat production requires the development of low-temperature networks and heat pumps, the use of waste heat and local energy resources, and the integration of district heating systems with electricity generation and energy storage. These solutions make it possible to reduce the use of fossil fuels and increase the efficiency of the energy system as a whole.

The development of the hydrogen economy is another important direction of the transition. Hydrogen can be used as a feedstock, fuel and energy carrier supporting the decarbonisation of sectors that are difficult to electrify directly. The development of hydrogen technologies requires the construction of infrastructure for hydrogen production, storage, transport and end use, as well as the integration of hydrogen installations with renewable energy sources.

The growing share of wind and photovoltaic power increases the importance of energy storage. The integration

of renewable energy sources with energy storage systems makes it possible to reduce imbalances between generation and demand, alleviate grid congestion and increase the use of locally generated energy. The development of hybrid systems therefore constitutes an important element in increasing the flexibility of electricity systems.

Biomass, biogas and biomethane also play an important role in the energy transition. Their ability to be stored and transported enables their use in the energy sector, district heating, transport and industry. The development of this area requires the establishment of efficient biomass supply chains, the utilisation of waste and by-products, and the development of regional bioeconomy structures.

The development of distributed energy requires the simultaneous modernisation of electricity networks. The growing number of renewable energy sources, energy storage systems, prosumers and active consumers necessitates the development of automation, digitalisation, smart metering systems and energy flow management. Modern electricity networks are becoming a fundamental prerequisite for the safe integration of a growing number of distributed energy sources.

Another important area of action is improving energy efficiency, which makes it possible to reduce energy demand, the costs of energy use and greenhouse gas emissions. The energy-efficient modernisation of buildings, the

development of low-carbon construction and measures to reduce energy poverty are of particular importance. These measures are complemented by the development of low-carbon transport, including increasing the role of public transport, cycling and walking, as well as integrating different forms of mobility.

The final area analysed is the transformation and introduction of new functions in post-industrial areas. The decline in mining and industrial activity creates a need to rehabilitate degraded land and establish new foundations for economic development. The regeneration of post-industrial areas can combine the preservation of industrial heritage with the development of new technological, economic, scientific, social and environmental functions.

The analysis conducted aims not only to present examples of good practice applied in different European countries and regions, but also to identify common directions of development and solutions that can be used when planning the energy transition in other regions. This makes it possible to view the transition as a comprehensive process encompassing the simultaneous development of technology, infrastructure, the economy, the environment and social capital, the success of which depends on a coherent and long-term approach to development planning.

CHAPTER II

METHODOLOGY FOR EVALUATING THE CASE STUDIES

Examples of energy transition can be evaluated using various research methods that make it possible to organise empirical material, compare measures undertaken in different regions and identify solutions with the greatest potential for implementation. In the analysis of good practices, it is particularly important to apply an approach that is not limited solely to describing the measures undertaken, but also enables their assessment in terms of effectiveness, efficiency, sustainability, and environmental, social and economic impacts³.

³ F.W. Geels, *Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study*, “Research Policy” 2002, no. 8–9, vol. 31, pp. 1257–1274; A.A.M.H.A. Asbahi et al., *Novel approach of Principal Component Analysis method to assess the national energy performance via Energy Trilemma Index*, “Energy Reports” 2019, vol. 5, pp. 704–713.

In recent years, there has been a rapid increase in the number of studies concerning the evaluation of climate and energy policies and the identification of so-called good practices or best practices. This reflects the fact that countries and regions pursuing the energy transition are at different stages of development and have different natural resources, economic structures and institutional capacities. Solutions that are effective in one region cannot always be directly transferred to another. For this reason, increasing importance is attached to the systematic analysis of examples of energy transition and the identification of factors determining their success or failure. As emphasised by the OECD, the evaluation of public policies should consider not only the extent to which the intended objectives have been achieved, but also their efficiency, sustainability, social impact and the potential to apply the experience gained in other contexts⁴.

There is no single universally accepted definition of good practice in the literature on the subject of energy transition. It is most commonly understood as a solution, measure or project that has been successfully implemented, has produced measurable results and can serve as a source

⁴ J. Markard, R. Raven, B. Truffer, *Sustainability transitions: An emerging field of research and its prospects*, "Research Policy" 2012, no. 6, vol. 41, pp. 955–967; K. Crowley, *Fighting the future: The politics of climate policy failure in Australia (2015–2020)*, "WIREs Climate Change" 2021, no. 5, vol. 12, p. e725.

of inspiration for other regions or countries. Good practice should be characterised by a high degree of effectiveness in achieving the intended objectives, the efficient use of financial resources, positive social and environmental impacts, and the potential for adaptation to different local conditions. In the context of the energy transition, this requires the simultaneous assessment of climate, energy, economic, social and institutional outcomes.

Research on the energy transition is increasingly moving away from assessments based solely on individual quantitative indicators towards multidimensional approaches. This reflects the fact that the transition process encompasses numerous interconnected elements whose significance is difficult to capture using a single measure. For example, the development of renewable energy sources may lead to a significant reduction in greenhouse gas emissions, but at the same time requires the modernisation of electricity networks, the construction of energy storage facilities, increased system flexibility and public acceptance of new investments. Similarly, improvements in energy efficiency provide environmental and economic benefits, but require appropriate financing mechanisms, regulatory changes and the involvement of residents and businesses. For this reason, the evaluation of examples of energy transition should take into account both direct outcomes and their long-term impact on regional development.

A number of methods supporting the evaluation of measures implemented as part of the energy transition have been developed in the literature. Among the most commonly used are Multi-Criteria Decision Analysis (MCDA), benchmarking, indicator-based assessment, SWOT analysis, PESTEL analysis and various Sustainable Energy Transition Assessment Frameworks. In recent years, methods developed for the assessment of the Just Transition have also become increasingly important, particularly those developed by the European Commission, the OECD and the International Labour Organization. The individual approaches differ in terms of the scope of analysis, methods of data aggregation and level of detail; however, their common objective is to provide an assessment of measures implemented in the energy sector that is as objective and comprehensive as possible⁵.

⁵ J.-J. Wang et al., *Review on multi-criteria decision analysis aid in sustainable energy decision-making*, “Renewable and Sustainable Energy Reviews” 2009, no. 9, vol. 13, pp. 2263–2278; B.W. Ang, W.L. Choong, T.S. Ng, *Energy security: Definitions, dimensions and indexes*, “Renewable and Sustainable Energy Reviews” 2015, vol. 42; *Energy Indicators for Sustainable Development: Guidelines and Methodologies*, Vienna 2005.

2.1. Multi-Criteria Decision Analysis

One of the methods most commonly used in energy transition research is Multi-Criteria Decision Analysis (MCDA), also referred to as Multi-Criteria Decision Making (MCDM). Its fundamental assumption is that alternative measures, technologies, scenarios or strategies can be evaluated against multiple criteria simultaneously. This is particularly important in the energy sector, as investment and strategic decisions can rarely be assessed solely on the basis of a single parameter, such as cost. MCDA makes it possible to take into account economic, environmental, social, technological and institutional criteria. Consequently, the method is widely applied to problems in which decisions are strategic in nature and require the consideration of multiple stakeholders⁶.

Various techniques can be applied within MCDA, including the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), ELimination Et Choix Traduisant la REALité (ELECTRE), weighted-sum methods and

⁶ V. Belton, T.J. Stewart, *Multiple Criteria Decision Analysis*, Boston, MA 2002; S.D. Pohekar, M. Ramachandran, *Application of multi-criteria decision making to sustainable energy planning—A review*, “Renewable and Sustainable Energy Reviews” 2004, no. 4, vol. 8, pp. 365–381.

fuzzy-based approaches⁷. The individual methods differ in the way criteria are aggregated and in the procedure used to compare alternatives; however, their common objective is to rank the solutions analysed according to the extent to which they meet the adopted criteria. The choice of a specific technique depends on the aim of the study, data availability and the complexity of the decision-making problem.

For example, AHP is useful when it is necessary to establish a hierarchy of criteria and assign weights to them on the basis of expert judgement. TOPSIS makes it possible to rank alternatives according to their distance from the ideal and anti-ideal solutions, while PROMETHEE and ELECTRE belong to the family of outranking methods and are particularly useful in situations where alternatives are difficult to rank unequivocally.

With regard to examples of energy transition, MCDA can be used to assess whether a particular measure can be regarded as good practice. The assessment criteria

⁷ V. Belton, T.J. Stewart, *Multiple Criteria Decision Analysis*, Boston, MA 2002; A. Mardani et al., *Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014*, “Economic Research-Ekonomska Istraživanja” 2015, no. 1, vol. 28, pp. 516–571; S.K. Sahoo et al., *A Comprehensive Review of Multi-criteria Decision-making (MCDM) Toward Sustainable Renewable Energy Development*, “Spectrum of Operational Research” 2025, no. 1, vol. 2, pp. 309–325.

may include reductions in greenhouse gas emissions, an increased share of renewable energy sources, improvements in energy efficiency, impacts on energy security, the creation of new jobs, impacts on the local community, innovation, the sustainability of outcomes and the potential for applying the solution in other regions⁸.

2.2. Benchmarking

Another useful approach is benchmarking, which involves comparing the results achieved by different projects on the basis of a common set of indicators⁹. Benchmarking makes it possible to determine which areas achieve the best results, what differences exist between them and which factors may explain these differences.

The fundamental principle of benchmarking is the adoption of an appropriate point of reference (benchmark) against which the units analysed are assessed. The benchmark may

⁸ I. Krasniqi, *Evaluating strategic approaches to energy transition: leadership, policy, and innovation in European countries*, “Economics and Environment” 2024, no. 3, vol. 90, p. 929.

⁹ M. Gallo et al., *A Critical Review on Methodologies for the Energy Benchmarking of Wastewater Treatment Plants*, “Sustainability” 2024, no. 5, vol. 16, p. 1922; *Benchmarking Scenario Comparisons: Key Indicators for the Clean Energy Transition*, Abu Dhabi, Brussels 2021.

be an industry leader, the average for a group of regions, a target value resulting from climate policy, or the best result achieved within the group analysed.

Benchmarking may be quantitative or qualitative. In the former case, it is based on statistical data and quantitative indicators, whereas in the latter it is based on the analysis of institutional, organisational and strategic solutions. In energy transition research, the two approaches are often combined.

The purpose of benchmarking is not merely to create a ranking of the units examined, but primarily to identify the factors responsible for achieving the best results and to indicate solutions that may be adapted by other regions.

Closely related to benchmarking is indicator-based assessment¹⁰. It involves developing a set of indicators describing a particular phenomenon, such as sustainable energy transition, regional resilience, energy efficiency, social justice or the development of renewable energy sources. Indicators may be simple, such as CO₂ emissions per capita, the share of renewable energy sources in final energy consumption or energy consumption per unit of

¹⁰ I. Vera, L. Langlois, *Energy indicators for sustainable development*, “Energy” 2007, no. 6, vol. 32, pp. 875–882; I. Gunnarsdottir et al., *Review of indicators for sustainable energy development*, “Renewable and Sustainable Energy Reviews” 2020, vol. 133, p. 110294; P.G. Taylor et al., *Better energy indicators for sustainable development*, “Nature Energy” 2017, no. 8, vol. 2, p. 17117.

GDP, or composite, where several measures are aggregated into a single index.

Unlike methods based on individual measures, indicator-based assessment makes it possible to evaluate multiple dimensions of the transition simultaneously, such as energy security, the development of renewable energy sources, energy efficiency, reductions in greenhouse gas emissions, and economic and social aspects. It is therefore widely used by international organisations, public authorities and the academic community to monitor progress towards the sustainable development of the energy sector.

The literature emphasises that a well-designed system of indicators should be transparent, measurable, comparable, capable of being updated and adapted to the territorial context. There is no single universal set of indicators that would be appropriate for all countries and regions. Indicators should evolve in line with national circumstances, priorities and analytical capacities.

The literature also emphasises the need to maintain a balance between indicators describing environmental, economic and social aspects, so that the resulting picture of the transition is as comprehensive as possible. The transparency of the methodology and the possibility of periodically updating indicators in response to changing economic and technological conditions are also important.

A clear advantage of indicator-based assessment is its objectivity, the possibility of monitoring changes over time and the ease of comparing different regions and countries. Its limitations, however, include the selection of appropriate indicators and their aggregation into composite indices, which may result in the loss of some information. Furthermore, many aspects of the energy transition, such as public acceptance, the quality of governance and institutional innovation, are difficult to describe unambiguously using quantitative indicators.

2.3. SWOT Analysis

Another method that is particularly useful in qualitative analyses is SWOT analysis. It makes it possible to organise information on a given case by identifying its strengths, weaknesses, opportunities and threats. Strengths and weaknesses usually refer to the internal characteristics of a region or project, such as the availability of renewable energy resources, existing infrastructure, industrial potential, institutional capacities or the level of public acceptance. Opportunities and threats, in turn, relate to external factors, such as the availability of European funds, changes in energy prices, climate policy, technological development, regulatory risks or instability in the economic environment.

In the context of the energy transition, SWOT analysis can be applied both to the assessment of entire regional strategies and to individual projects¹¹.

An advantage of SWOT analysis is its transparency and ease of application. It makes it possible to present the key conditions of the transition in a concise manner and is well suited as a tool for organising empirical material. Its limitation, however, is the considerable degree of subjectivity involved and the lack of an inherent mechanism for comparing multiple cases. For this reason, SWOT analysis is often combined in academic research with other methods, such as MCDA or indicator-based assessment. In such an approach, SWOT analysis can be used to identify assessment criteria, while MCDA can be used for their quantitative evaluation and ranking. For example, in regional analyses of the energy transition, SWOT analysis is used to identify renewable energy potential, financial barriers, social risks and opportunities arising from the development of new technologies.

¹¹ M.M. Helms, J. Nixon, *Exploring SWOT analysis – where are we now? A review of academic research from the last decade*, “Journal of Strategy and Management” 2010, no. 3, vol. 3, pp. 215–251; J. Terrados, G. Almonacid, L. Hontoria, *Regional energy planning through SWOT analysis and strategic planning tools*, “Renewable and Sustainable Energy Reviews” 2007, no. 6, vol. 11, pp. 1275–1287; N. Markovska, V. Taseska, J. Pop-Jordanov, *SWOT analyses of the national energy sector for sustainable energy development*, “Energy” 2009, no. 6, vol. 34, pp. 752–756.

An extension of classical SWOT analysis is TOWS analysis, which aims to move from the identification of factors to the formulation of specific strategies for action¹². This method examines the interrelationships between strengths, weaknesses, opportunities and threats. This results in four basic groups of strategies: SO (Strengths–Opportunities), which use strengths to maximise emerging opportunities; WO (Weaknesses–Opportunities), which seek to overcome weaknesses by taking advantage of favourable external conditions; ST (Strengths–Threats), which use existing strengths to mitigate the impact of threats; and WT (Weaknesses–Threats), which aim to minimise both weaknesses and external threats. TOWS analysis therefore serves not only as a diagnostic tool but also supports the development of strategies.

In recent years, hybrid methods combining SWOT analysis with multi-criteria decision-support methods, primarily the Analytic Hierarchy Process (AHP)¹³, have become increasingly popular. This approach, referred to as

¹² H. Weihrich, *The TOWS matrix—A tool for situational analysis*, “Long Range Planning” 1982, no. 2, vol. 15, pp. 54–66.

¹³ E. Yontar, O. Derse, *Evaluation of sustainable energy action plan strategies with a SWOT/TWOS-based AHP/ANP approach: a case study*, “Environment, Development and Sustainability” 2023, no. 6, vol. 25, pp. 5691–5715; G. Di Domenico et al., *Agrivoltaics Systems Potentials in Italy: State of the Art and SWOT-AHP Analysis*, “Sustainability” 2025, no. 3, vol. 17, p. 925.

A'WOT (SWOT-AHP), makes it possible to reduce one of the main limitations of classical SWOT analysis, namely its subjective nature. In the A'WOT method, after strengths, weaknesses, opportunities and threats have been identified, experts conduct pairwise comparisons in accordance with the AHP procedure, making it possible to assign weights to individual factors and determine their significance for the problem under analysis.

As a result, SWOT analysis no longer serves a purely descriptive function, but becomes a tool enabling the quantitative assessment of strategic directions of development. This method is increasingly used in energy transition research, including the assessment of renewable energy development strategies, Sustainable Energy Action Plans (SEAPs), hydrogen technologies and new renewable energy solutions. The results of these studies indicate that combining SWOT with AHP enables investment and strategic measures to be prioritised more effectively than through the use of classical SWOT analysis, particularly in situations requiring the consideration of multiple criteria and the views of different stakeholder groups.

2.4. PESTEL Analysis

SWOT analysis can be complemented by PESTEL analysis, which focuses on the external environment of the process under examination¹⁴. The name of the method derives from six categories of factors: Political, Economic, Social, Technological, Environmental and Legal. The primary aim of the analysis is to identify external factors that may affect the implementation of specific projects and to assess their potential impact on the development of the area under examination. Unlike SWOT analysis, which takes into account both internal and external factors, PESTEL analysis focuses exclusively on the macroeconomic and institutional environment, enabling a better understanding of the conditions influencing the course of transition processes.

PESTEL analysis is particularly useful in assessing the potential for transferring a given example to another region. A solution that functions effectively in one country may be difficult to implement in another because of different legal, economic or social conditions. PESTEL therefore makes it possible to identify which elements of a given example are universal and which are strongly dependent on the local context.

¹⁴ B. Łysa, A. Mularczyk, *PESTEL Analysis of the Photovoltaic Market in Poland—A Systematic Review of Opportunities and Threats, “Resources”* 2024, no. 10, vol. 13, p. 136; M.A. Borojerdi et al., *Developing a PESTLE based model to review the energy transition accelerator parameters in Australia, “Discover Sustainability”* 2026.

2.5. Sustainable Energy Transition Assessment Frameworks

A broader approach is the Sustainable Energy Transition Assessment Framework, i.e., a framework for assessing sustainable energy transition¹⁵. This is not a single, strictly defined method, but rather a family of research approaches that combine technical, economic, environmental and social assessment. Their aim is to capture the multidimensional nature of the energy transition. Such assessment frameworks most commonly consider decarbonisation, energy security, energy accessibility, economic efficiency, social justice, system resilience, innovation and alignment with sustainable development goals. An example of this type of approach is the World Energy Trilemma Framework, which assesses energy systems across three dimensions: energy security, energy equity/accessibility and environmental sustainability¹⁶.

In recent years, energy transition assessment frameworks have continued to evolve. In addition to the three traditional

¹⁵ H. Nguyen, B. Kumar, *Sustainability Assessment Framework for Renewable Energy Enterprises*, “Process Integration and Optimization for Sustainability” 2026; M.L. Giwah et al., *Sustainable Energy Transition Framework for Emerging Economies: Policy Pathways and Implementation Gaps*, “International Journal of Multidisciplinary Evolutionary Research” 2020, no. 1, vol. 1, pp. 1–6.

¹⁶ L. Kaschny, *The EU energy trilemma in transition*, “ERA Forum” 2025, no. 4, vol. 26, pp. 595–609; *World Energy Trilemma Report 2024. Evolving with Resilience and Justice*, London 2024.

pillars, they increasingly incorporate elements such as energy system resilience, social justice (energy justice), resilience to the impacts of climate change, digitalisation of the energy sector and the capacity to adapt under conditions of growing geopolitical uncertainty. Contemporary approaches emphasise that the energy transition should be assessed not only in terms of emissions reductions, but also in terms of the system's capacity to ensure continuity of energy supply, reduce energy poverty and build long-term socio-economic resilience.

An advantage of the Sustainable Energy Transition Assessment Framework is its ability to integrate technical, economic, environmental and social data within a single assessment model. Such frameworks may incorporate both quantitative and qualitative indicators and may be combined with multi-criteria methods, benchmarking or scenario analysis. They can therefore be applied to the assessment of national and regional energy strategies, climate neutrality plans and different energy transition pathways. Their limitation, however, remains the absence of a single universally accepted methodology and the need to adapt the set of indicators to the specific characteristics of the country or region under analysis.

2.6. Just Transition Assessment Framework

A separate but highly important approach is the European Commission's Just Transition framework¹⁷. It was developed within the framework of the European Green Deal and the Just Transition Mechanism. Its fundamental principle is that the transition should be pursued in a manner that minimises the negative social and economic consequences arising from the move away from fossil fuels. The concept assumes that achieving climate neutrality should take place with due regard for the needs of local communities, workers in emissions-intensive sectors and regions that are particularly dependent on the extraction and use of fossil fuels.

In practice, this entails simultaneously supporting the development of new sectors of the economy, job creation, worker retraining, entrepreneurship and improvements in residents' quality of life. Just Transition assessment frameworks have been extensively developed by the European Commission within the European Green Deal, the Just Transition Mechanism and the Just Transition Fund, as

¹⁷ N. Healy, J. Barry, *Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition"*, "Energy Policy" 2017, vol. 108, pp. 451–459; P. Newell, A. Simms, *Towards a fossil fuel non-proliferation treaty*, "Climate Policy" 2020, no. 8, vol. 20, pp. 1043–1054; *The Just Transition Mechanism: Making Sure No One Is Left Behind*, 2020.

well as by the Organisation for Economic Co-operation and Development and the International Labour Organization, which emphasise the need to take social, economic and institutional aspects into account when planning the transition¹⁸.

2.7. Integrated Methodological Approach

The methods discussed above can be applied independently, but their combination offers the greatest research value. Multi-Criteria Decision Analysis provides a structured framework for assessment and enables cases to be compared using a scoring system. Benchmarking makes it possible to compare results with those achieved in other regions. Indicator-based assessment ensures measurability and enables progress to be monitored. SWOT and PESTEL analyses make it possible to capture qualitative conditions, barriers and contextual factors. Sustainable Energy Transition Assessment Frameworks structure the analysis across climate, technical, economic and social dimensions. The European Commission's Just Transition framework,

¹⁸ *Guidelines for a just transition towards environmentally sustainable economies and societies for all*, Geneva 2015; *Job Creation and Local Economic Development 2024: The Geography of Generative AI*, Paris 2024.

in turn, makes it possible to take social, economic and territorial consequences into account. Such an integrated approach enables an assessment of whether a given example of energy transition genuinely constitutes good practice or is merely an interesting local initiative that may be difficult to transfer elsewhere.

It should be emphasised that the aim of this study is not to conduct a detailed assessment of the effectiveness of individual examples of energy transition or to establish a ranking of them. The measures presented are primarily intended to provide an overview and constitute a collection of experiences from different European countries and regions that may serve as a source of inspiration when planning and implementing the energy transition. For this reason, the study focuses on describing the solutions applied, their objectives and the results achieved, while leaving a detailed assessment of their usefulness to the reader.

This approach reflects the fact that the effectiveness of individual measures is strongly dependent on local conditions. A solution that has produced very good results in one region may not be equally effective elsewhere. Its potential for implementation is determined, among other factors, by the availability of local energy resources, the structure of the economy, the level of development of technical infrastructure, spatial conditions, the applicable

legal framework, the social situation, financial capacity and the objectives adopted by regional or national authorities. The time horizon of the planned measures, the level of technological development and the changing economic and geopolitical environment are also important. Consequently, each assessment should be conducted individually, taking into account the specific place, time and initial conditions.

For this reason, this study does not attempt to develop a universal system for assessing good practices, as the development and application of such a system would require the collection of detailed quantitative and qualitative data for each case analysed, as well as the determination of individual priorities and weights for the respective criteria. In practice, this means that the same investment may be assessed differently depending on whether the priority is to maximise reductions in greenhouse gas emissions, improve energy security, create new jobs, develop local industry, reduce energy poverty or increase regional resilience to the impacts of climate change.

In the following sections of the study, the assessment of the examples presented will therefore be limited to identifying the most important conditions and potential barriers to their implementation in Poland. The analysis will focus on identifying factors that may facilitate or hinder the implementation of individual solutions at the national level, without examining them in detail in relation to specific

regions or local conditions. This approach preserves the general applicability of the study while allowing more detailed analyses to be undertaken for specific regions, communities and institutions, and for the implementation of particular objectives, taking into account their specific social, economic, environmental and energy-related conditions.

CHAPTER III

MODERN DISTRICT HEATING SYSTEMS

The district heating sector plays a fundamental role in Poland's energy transition. It accounts for a significant share of the country's final energy consumption and greenhouse gas emissions, while also directly affecting energy security, air quality, economic competitiveness and the costs borne by households and businesses. The scale of the challenges facing the Polish district heating sector is particularly significant. A substantial proportion of the existing infrastructure was constructed several decades ago and requires extensive modernisation or replacement with modern low-carbon solutions¹⁹.

The transformation of the district heating sector requires the simultaneous modernisation of heat generation sources,

¹⁹ *National Energy and Climate Plan to 2030 (Update of the 2019 NECP)*, Warsaw 2025; *District Heating Transformation Strategy to 2040*, Warsaw 2026.

transmission networks, energy storage infrastructure and end-user systems. In Poland, this involves a gradual shift from centralised systems based on the combustion of fossil fuels towards modern, intelligent district heating systems using renewable energy sources, heat pumps, waste heat, geothermal energy, biomass, thermal energy storage and Power-to-Heat technologies. An additional challenge is the considerable diversity of the national district heating sector, ranging from extensive district heating systems operating in the largest urban areas to small local heating plants and individual heating systems, which still rely heavily on fossil fuels.

3.1. Fourth-Generation District Heating in Aarhus

The city of Aarhus in Denmark is regarded as one of the most advanced examples of district heating transformation in Europe²⁰. This success results not only from the application of modern heat generation technologies, but above all from the consistent implementation of an energy planning strategy pursued by the local authorities for several decades. District heating is treated as an integral part of the urban energy system, closely linked to the electricity

²⁰ H.K. Støchkel, *Danish Urban Energy Development Experiences. The Aarhus Case Study*, 2024.

sector, waste management, spatial planning and climate policy. The city aims to achieve climate neutrality by 2030, while the district heating system itself achieved CO₂ neutrality as early as 2017, only seven years after the decision was taken to phase out coal completely.

The system is operated by the municipal company Kredsløb, which is owned by the Municipality of Aarhus. The company is responsible not only for district heating supply, but also for waste management, recycling and the development of the city's district cooling system. District heating is supplied to approximately 95% of buildings within the municipality, serving more than 65,000 customers and approximately 340,000 residents. Annual heat sales exceed 3,100 GWh. The main transmission network is approximately 130 km long and operates at a pressure of around 25 bar and a supply temperature of 110–120°C. Heat is subsequently transported to approximately 50 local distribution networks with a combined length of more than 2,200 km, which operate at considerably lower temperature parameters. Such an extensive system enables the efficient utilisation of multiple distributed heat sources and ensures a high level of supply reliability.

The basis of Aarhus's success has been the move away from a model based on a single dominant fuel and its replacement with a diversified portfolio of technologies. The system currently uses several complementary heat

sources operating in combined heat and power generation. The first of these comprises municipal waste-to-energy facilities, which simultaneously address the problem of waste management and generate electricity and heat. The plant in Lisbjerg plays a particularly important role, processing approximately 225,000 tonnes of waste annually.

The second pillar of the system is a combined heat and power plant fuelled by agricultural biomass, primarily straw, which was commissioned in 2017. The approximately 110 MW unit uses locally sourced straw and wood chips, while the ash produced during combustion is returned to agricultural land as fertiliser, in line with the principles of the circular economy. Biomass is supplied by local farmers under long-term contracts, further strengthening the local economy.

The third element of the system is the Studstrup combined heat and power plant, owned by Ørsted, which used hard coal until 2016 and was subsequently converted to burn wood pellets. As a result, coal was completely eliminated as the system's primary fuel within a few years.

One of the most important directions for further development is currently the utilisation of geothermal energy. In cooperation with Innargi, Kredsløb is implementing the largest geothermal district heating project in the European Union²¹. Ultimately, the system will comprise three geo-

²¹ *Project: Aarhus, Denmark, Innargi.*

thermal plants with a combined capacity of approximately 110 MW, supplying around 20% of the city's heat demand. The project uses geothermal water extracted from a depth of approximately 2–3 km at a temperature of 60–80°C. Once extracted, the thermal energy is transferred to the municipal district heating network through heat exchangers and large-scale heat pumps, while the cooled water is reinjected into the reservoir.

This solution creates a closed-loop system with virtually no impact on water resources and makes it possible to significantly reduce greenhouse gas emissions. According to the operator's estimates, the project will reduce emissions by up to 165,000 tonnes of CO₂ annually and reduce the consumption of biomass imported from outside Denmark. The first installation began supplying heat to the network in 2025, while completion of the entire project is planned by 2030.

Digitalisation of the district heating system is also an important element of the transformation. Kredsløb uses advanced network monitoring systems, Internet of Things (IoT) solutions, cloud-based data processing and machine-learning algorithms to forecast heat demand and optimise the operation of heat sources. This makes it possible to dynamically select the most efficient generation sources according to current electricity prices, weather conditions and consumer demand.

Large-scale thermal energy storage facilities are also being developed, increasing the flexibility of the entire system and enabling better integration of the growing share of energy from renewable sources. In the future, the system will increasingly use large-scale heat pumps and Power-to-Heat technologies, enabling the district heating sector to become an active participant in balancing the national electricity system.

The model adopted in Aarhus may provide a valuable source of inspiration for Poland, particularly for large district heating systems facing the need to move away from fossil fuels. It should be borne in mind, however, that the implementation of similar solutions requires appropriate geological conditions, a stable regulatory framework, substantial investment and a long-term energy policy pursued in close cooperation between local authorities, district heating system operators and central government.

3.2. Hybrid Combined Heat and Power with Hydrogen Storage in Dauerthal

An example of modern district heating is the hybrid combined heat and power plant with hydrogen storage located in Dauerthal near Prenzlau, Brandenburg, Germany²².

²² *The first hybrid electricity-fuel-heat power plant with hydrogen storage in the world*, European Commission, https://ec.europa.eu/regional_

The installation was developed by ENERTRAG in cooperation with Vattenfall, TOTAL Deutschland and DB Energie, with support from the German Federal Government and the State of Brandenburg. The project was the world's first industrial-scale installation integrating wind power, hydrogen production and storage, and its use in cogeneration together with biogas. The main objective of the project was to demonstrate that electricity generated from variable renewable energy sources can be converted into hydrogen, stored and subsequently used to generate electricity and heat or as a transport fuel. The project became one of the first practical examples of the Power-to-Gas (PtG) concept, which is now regarded as one of the most important directions in the development of the hydrogen economy.

The system is based on three Enercon E-82 E2 wind turbines, each with a capacity of 2.3 MW, directly connected to an alkaline electrolyser with a capacity of approximately 600 kW²³. During periods of high electricity generation and low grid demand, surplus electricity is directed to the water electrolysis process, producing green hydrogen at a rate of approximately 120 Nm³/h. The hydrogen produced is stored in tanks at a pressure of approximately 42 bar and

policy/en/projects/germany/the-first-hybrid-electricity-fuel-heat-power-plant-with-hydrogen-storage-in-the-world

²³ D. Stolten, *Hydrogen science and engineering: materials, processes, systems and technology*, Weinheim, Germany 2016.

with a total storage capacity of approximately 1,350 kg, enabling its use independently of the instantaneous level of wind power generation.

This solution addresses one of the main challenges associated with renewable energy, namely the need to curtail wind farm generation during periods of surplus electricity production. Hydrogen storage makes it possible to separate energy generation in time from its subsequent use, thereby increasing the flexibility of the energy system as a whole.

An important element of the project is the integration of hydrogen technology with a local biogas plant producing approximately 350 Nm³ of biogas per hour. Rather than being combusted independently, hydrogen is co-fired with biogas in two cogeneration units, each with an electrical capacity of approximately 366 kW and a thermal capacity of approximately 409 kW. The maximum proportion of hydrogen in the fuel mixture can reach approximately 70%, allowing carbon dioxide emissions to be significantly reduced while maintaining a high degree of combustion stability. The electricity generated is supplied to the national electricity grid, while the waste heat is utilised in Prenzlau's municipal district heating system. This creates a conventional high-efficiency cogeneration system in which the utilisation of the chemical energy contained in both biogas and green hydrogen is maximised.

One of the project's major innovations was the demonstration of the potential for the full integration of three energy sectors: electricity, gas and district heating²⁴. In conventional systems, surplus electricity generated by wind farms often results in the curtailment of their operation or the sale of electricity at very low prices. In Prenzlau, this electricity was used to produce hydrogen, which can be stored for extended periods and used during periods of increased energy demand. As a result, wind power is transformed from a variable source into an element of the energy system capable of providing balancing and ancillary services to the national electricity grid. This model is currently one of the most important solutions being considered in Europe for the integration of large volumes of renewable energy.

Another important element of the project was the use of hydrogen as a fuel for the transport sector. Surplus hydrogen that was not used for electricity or heat generation was transported to hydrogen refuelling stations in Berlin as part of the Clean Energy Partnership (CEP) programme. A single installation could therefore simultaneously perform three functions: stabilising the electricity system, supplying the district heating network and providing fuel for zero-emission transport. This approach is fully consistent with the

²⁴ C. Wulf, J. Linßen, P. Zapp, *Review of Power-to-Gas Projects in Europe*, "Energy Procedia" 2018, vol. 155, pp. 367–378.

increasingly important concept of sector coupling, which involves the close integration of different sectors of the energy economy.

The Prenzlau project also played an important role in the development of Power-to-Gas technology, being one of the first large-scale demonstrators of this solution in Europe. The experience gained during its operation provided a basis for the implementation of subsequent hydrogen projects in Germany and other European countries. ENERTRAG used the knowledge gained in designing new installations involving significantly larger electrolyzers and integration with the national hydrogen transmission infrastructure.

ENERTRAG is currently implementing a project in Prenzlau involving the construction of a 130 MW electrolyser, which will produce approximately 12,500 tonnes of green hydrogen annually and will be connected to the German hydrogen transmission network (H₂ Core)²⁵. This demonstrates the evolution of the technology from a demonstration installation to large-scale industrial projects forming part of the European hydrogen economy.

²⁵ ENERTRAG, *Electrolysis Plant Prenzlau Nord: Using energy where it is generated*, ENERTRAG, <https://enertrag.com/projects-show-cases/featured-projects/hydrogen-projects/prenzlau-north>

3.3. Mine-Water Energy Centre in Bochum

An interesting example of the use of post-mining infrastructure for the purposes of the energy transition is the energy centre project, which has been under development since 2020 on the site of a former hard coal mine in Bochum, North Rhine-Westphalia, Germany²⁶. The project is being developed in the new MARK 51°7 technology and industrial district, established on the site of the former Opel plant, and forms part of the German Wärmenetzsysteme 4.0 (WNS 4.0) programme, which supports the development of low-carbon fourth-generation district heating systems. The aim of the project is to create a modern energy centre using local renewable energy sources and heat stored in mine water to supply district heating and cooling networks.

The system is based on the use of mine water filling the underground workings following the cessation of mining operations. For heating purposes, water at a temperature of approximately 30°C is pumped from a depth of around 810 m. The thermal energy contained in the water is upgraded by means of large-scale heat pumps to a temperature of approximately 48°C and subsequently supplied to the local district heating network. At the same time, mine

²⁶ Construction site opened: Expansion of the heating network in Bochum, Dornier Group, <https://dornier-group.com/en/construction-site-opened-expansion-of-the-heating-network-in-bochum/>

water at a temperature of approximately 18°C, extracted from a shallower level at a depth of around 340 m, is used for cooling. After being further cooled to approximately 10°C, it supplies the district cooling network serving commercial, office and laboratory buildings.

The system has been designed as an integrated energy centre combining heat pumps, district heating and cooling networks, and a high-efficiency cogeneration unit serving as a peak-load and back-up source. According to the project assumptions, energy recovered from mine water is expected to cover approximately 70–75% of the total heating and cooling demand of buildings located within MARK 51°7. The remaining demand will be met by supplementary sources operating only during periods of peak load.

The project represents an example of the efficient use of post-mining infrastructure in accordance with the principles of the circular economy. Rather than simply decommissioning the former mine workings, the natural energy potential stored in mine water has been utilised, thereby reducing fossil fuel consumption and greenhouse gas emissions.

CHAPTER IV

HYDROGEN TECHNOLOGIES AND THE HYDROGEN ECONOMY

The example from Prenzlau presented above clearly illustrates the growing role of hydrogen in modern energy systems. Hydrogen is no longer regarded solely as an alternative fuel, but as a versatile energy carrier that enables the storage of surplus energy from renewable sources, the integration of different sectors of the economy and increased flexibility of electricity and district heating systems. In this way, hydrogen enhances the flexibility of the electricity system and facilitates the integration of variable renewable energy sources.

Furthermore, hydrogen can be used in hard-to-decarbonise sectors, including energy-intensive industry, heavy-duty transport, shipping, aviation and district heating, where the direct electrification of processes is often technically unfeasible or economically unjustified. For this

reason, hydrogen technologies currently occupy an important place in both European and national energy policy.

4.1. Modena Hydrogen Valley

One of the most advanced hydrogen economy development projects in Italy is the Modena Hydrogen Valley, implemented in the Emilia-Romagna region²⁷. The project represents an example of a comprehensive approach to developing a local ecosystem for the production, distribution and use of green hydrogen, integrating public authorities, energy companies, industry, public transport and the research sector. The initiative is aligned with both the objectives of the European Green Deal and the REPowerEU programme, as well as Italy's National Recovery and Resilience Plan (PNRR – Piano Nazionale di Ripresa e Resilienza), one of the priorities of which is the development of Hydrogen Valleys²⁸.

The Modena Hydrogen Valley was officially launched in December 2023 through the signing of an agreement

²⁷ *Modena Hydrogen Valley officially launched in Italy*, Chemical Engineering, <https://www.chemengonline.com/modena-hydrogen-valley-officially-launched-in-italy/>

²⁸ *Piano Nazionale di Ripresa e Resilienza*, Italia Domani, <https://www.italiadomani.gov.it/it/strumenti/documenti/archivio-documenti/piano-nazionale-di-ripresa-e-resilienza.html>

between the City of Modena and the project's principal partners. A broad range of institutions representing different sectors of the economy are involved in the initiative. In addition to the City of Modena, the project participants include the energy companies Hera Group and Snam, the public transport operator SETA, the University of Modena and Reggio Emilia (UNIMORE), the regional Agency for Energy and Sustainable Development (AESS), the Italian research institute ENEA, the Modena Chamber of Commerce, and organisations supporting entrepreneurship and innovation. Such a broad partnership is intended to facilitate the creation of a complete regional hydrogen value chain – from renewable energy generation, through hydrogen production, storage and distribution, to its use in transport and industry.

The central element of the entire initiative is the IdrogeMO project²⁹. It involves the construction of a green hydrogen production facility with an output of approximately 400 tonnes per year, with the possibility of further expansion to approximately 800 tonnes per year during subsequent stages of the investment. The total value of

²⁹ *Modena's Hydrogen Valley takes off: signed the memorandum of understanding centred around the IdrogeMO project of Hera Group and Snam*, Hera Group, <https://eng.gruppohera.it/-/modena-s-hydrogen-valley-takes-off-signed-the-memorandum-of-understanding-centred-around-the-idroge-mo-project-of-hera-group-and-snam>

the project is approximately EUR 20.8 million, of which as much as EUR 19.5 million comes from funding awarded by the Emilia-Romagna region under Italy's National Recovery and Resilience Plan, financed by European Union funds. This high level of financial support demonstrates the importance of the project to the national strategy for the development of the hydrogen economy and the decarbonisation of Italian industry.

Hydrogen production will be based exclusively on renewable energy. Electricity will be supplied by a 6 MW photovoltaic installation, the location of which is one of the most interesting elements of the entire project. The installation will be constructed on a reclaimed municipal waste landfill owned by the City of Modena. Some of the photovoltaic panels will be installed on floating structures on a water reservoir located within the former landfill site. This solution makes it possible to utilise post-industrial land without occupying new agricultural land or areas of high environmental value, while simultaneously supporting the principles of the circular economy.

Electricity from the photovoltaic installation will power a 2.5 MW electrolyser, which will produce renewable hydrogen through water electrolysis. To ensure stable operation of the installation during night-time hours and periods of limited solar irradiation, the project provides for the use of a battery energy storage system operating in conjunction

with the electrolyser. This will make it possible to increase the utilisation of renewable electricity and improve the economic efficiency of the entire system. The electrolysis facility itself will be located on post-industrial land belonging to the Hera Group, which is also consistent with the concept of regenerating degraded sites.

An important element of the project is its organisational model. Hydrogen production and sales will be managed by a specially established special-purpose company. This arrangement enables the investment to be managed efficiently and financial risk to be reduced, while maintaining flexibility for the future expansion of the installation and the acquisition of new hydrogen customers.

The first and most important user of the hydrogen produced will be the public transport sector. The public transport operator has already initiated the purchase of 12 hydrogen-powered buses. It is estimated that the buses will consume approximately 50 tonnes of hydrogen annually, enabling them to travel approximately 660,000 km and reducing CO₂ emissions by approximately 737 tonnes per year compared with diesel-powered buses. In the longer term, hydrogen is also expected to power vehicles operated by TPER, which provides public transport services in the provinces of Bologna, Ferrara and Modena. The project therefore demonstrates a practical application of green hydrogen in the heavy-duty transport

sector, where electrification based exclusively on batteries often faces limitations associated with long operating ranges and the short refuelling times required by public transport operators.

The second strategic area for hydrogen use will be local industry. Emilia-Romagna is one of the most industrialised regions of Italy. The automotive industry is particularly well developed and is often referred to as the Italian Motor Valley, encompassing companies such as Ferrari, Lamborghini, Maserati and Ducati. The region also has a strong ceramics industry, which is among the hard-to-abate sectors. In these industries, hydrogen can replace fossil fuels both as an energy carrier for high-temperature processes and as an industrial feedstock. Local companies expressed interest in using green hydrogen as early as the project preparation stage, increasing the prospects for the rapid commercial utilisation of the infrastructure being developed.

Another distinctive feature of the Modena Hydrogen Valley is the strong involvement of the research sector. The University of Modena and Reggio Emilia is developing the interdisciplinary H2 MO.RE research centre, whose role is to conduct research into hydrogen technologies, support innovation and educate highly qualified specialists. The project also involves the Italian agency ENEA, which is responsible for the development of new energy technologies, as well as regional institutions supporting knowledge

transfer to businesses. Linking scientific research with practical infrastructure investments in this way increases the potential for the commercialisation of new technologies and the development of regional expertise in the hydrogen economy.

The Modena Hydrogen Valley is not an isolated initiative but forms part of a broader strategy for the development of the hydrogen economy in the Emilia-Romagna region. Hera is currently developing the HydrogER project, which aims to create a regional network of Hydrogen Valleys linking Modena and Ravenna and to develop hydrogen transmission infrastructure between the region's principal industrial centres³⁰. In the longer term, planned hydrogen production within this network is expected to reach approximately 9,000 tonnes per year, demonstrating the scale of the region's ambitions to develop a modern low-carbon economy.

4.2. Reference Power Plant Lausitz Project

Another major hydrogen-related initiative is the Reference Power Plant Lausitz (REFLAU). The project integrates renewable energy sources, energy storage and hydrogen

³⁰ *HydrogER, H2Valleys*, <https://h2v.eu/hydrogen-valleys/hydroger>

technologies and is being implemented in the Lusatia region of Germany³¹. The RefLau project was selected in 2019 as one of the winners of the German “Reallabore der Energiewende” (Living Labs of the Energy Transition) programme organised by the Federal Ministry for Economic Affairs and Climate Action (BMWK). The programme supports demonstration facilities that enable innovative energy technologies to be tested under real operating conditions. In February 2023, the project received EUR 28.5 million in funding from the German Climate and Transformation Fund (KTF), enabling the implementation of a full-scale demonstration facility to begin. The project is planned to operate as a research and industrial laboratory until 2027.

The central concept of RefLau is the development of a modern reference power plant whose primary energy source will be electricity generated by wind and photovoltaic installations. Surplus renewable electricity will be directed to an electrolyser, where green hydrogen will be produced through water electrolysis. The hydrogen will subsequently be stored and, during periods of increased energy demand, used to generate electricity using fuel cells. The project therefore demonstrates a complete Power-to-Hydrogen-to-Power (P2H2P) cycle, enabling the seasonal

³¹ Reference Power Plant Lausitz: Real-World Laboratories of the Energy Transition Funding Program, ENERTRAG, ENERTRAG project page

storage of renewable energy and increasing the flexibility of the electricity system as a whole.

The planned first-stage installation includes an electrolyser with a capacity of approximately 12 MW, with the possibility of further expansion to more than 30 MW. Annual green hydrogen production is expected to amount to approximately 1,000 tonnes, while following expansion, production capacity could exceed 2,500 tonnes per year. The hydrogen produced will be supplied to consumers by road transport using high-pressure trailers, through blending into the gas network and, ultimately, via the planned hydrogen pipeline for the Lusatia region. This approach makes it possible to develop a local hydrogen market gradually, even before the completion of the full transmission infrastructure.

One of the most important features of the project is its multi-functionality³². REFLAU is not merely a hydrogen production facility but is intended to function as a complete system power plant. In addition to the electrolyser, the project includes hydrogen storage facilities, large-scale battery energy storage systems, supercapacitors and fuel cells. This will enable the provision of virtually all ancillary services required by electricity system operators,

³² *Reference Power Plant Lusatia*, TU Dresden, https://tu-dresden.de/forschung-transfer/strukturwandel/interaktive-karte/reflau?set_language=en

including frequency regulation, spinning reserve, voltage regulation and grid stabilisation. In practice, this means that the installation is intended to replace functions currently performed by conventional power plants equipped with synchronous generators, while producing no carbon dioxide emissions during normal operation.

An important element of the project is the extensive application of the sector coupling concept, integrating the electricity, heating, industrial and transport sectors. Green hydrogen produced by REFLAU will be used as a fuel in the chemical and metallurgical industries, heavy-duty transport and potentially also for heat generation. At the same time, researchers are investigating opportunities to utilise the remaining energy and material streams generated during the operation of the installation, including waste heat from electrolysis and fuel cells. This approach makes it possible to increase the overall energy efficiency of the system and improve its economic viability.

The project is being implemented by a consortium of companies and research institutions. The investment component is being carried out by ENERTRAG, Energi-equelle GmbH and Zweckverband Industriepark Schwarze Pumpe, which manages the Schwarze Pumpe industrial park. The research partners are Fraunhofer IEG, Brandenburg University of Technology Cottbus-Senftenberg (BTU) and Technische Universität Dresden. The role of

the research institutions is not only to monitor the operation of the installation, but also to develop tools for the optimal management of energy and hydrogen flows and the ancillary services provided by the power plant. Particular emphasis has been placed on developing control algorithms that maximise the utilisation of renewable energy sources while simultaneously ensuring the secure operation of the electricity grid.

Another important aspect of the project is its potential for further scaling. The current demonstration facility is primarily intended to verify the technical and economic aspects of operating a hydrogen-based power plant. Based on the experience gained, significantly larger installations with capacities reaching several hundred megawatts are planned. Even at the planning stage, the possibility of developing subsequent projects with capacities of up to 500 MW using a similar technological architecture was identified. REFLAU is therefore intended to serve as a model for the future transformation of conventional coal-fired power plants, both in Germany and in other European countries undergoing the energy transition.

The project is also of considerable social and economic importance. For many years, the Lusatia region has been undergoing a transformation associated with Germany's move away from lignite-based power generation. The closure of mines and power plants creates a need for new jobs

and new branches of industry. The project is also intended to act as a catalyst for the development of the regional hydrogen economy by establishing a local hydrogen market, supporting the development of new businesses and utilising the skills of workers previously employed in the coal sector. The project demonstrates how existing energy infrastructure in post-mining areas can be used to develop a modern energy system based on renewable energy sources.

4.3. Commercial Hydrogen Installation in Gaj Oławski

An important step in the development of the green hydrogen value chain in Poland was the commissioning, in June 2024, of Poland's first commercial green hydrogen production facility, located in Gaj Oławski near Oława³³. The 5 MW electrolyser is powered by electricity generated by photovoltaic farms and wind power plants owned by the company. As a result, the hydrogen produced meets the criteria for renewable hydrogen (RFNBO – Renewable Fuels of Non-Biological Origin) in accordance with European regulations.

³³ P. Pająk, *Rusza pierwsza w Polsce komercyjna instalacja do produkcji zielonego wodoru*, Gramwzielone.pl, 18.06.2024, <https://www.gramwzielone.pl/woddor/20203817/rusza-pierwsza-w-polsce-komercyjna-instalacja-do-produkcji-zielonego-wodoru>

The hydrogen produced will primarily be used by the Promet-Plast production facility. It will supply a trigeneration system with a capacity of approximately 1 MW, enabling the simultaneous generation of electricity, heat and cooling for use in the company's technological processes. This solution increases the energy efficiency of the facility and reduces fossil fuel consumption.

In addition, hydrogen will be used to supply a hydrogen refuelling station currently under development, equipped with dispensers operating at pressures of 350 and 700 bar, enabling it to serve buses and heavy-duty vehicles as well as passenger cars. The station's target capacity is expected to reach approximately 1.2 tonnes of hydrogen per day.

The project is not limited solely to the company's own requirements. Green hydrogen is also planned to be sold to external customers, primarily in the public transport sector. One of the first partners is the city of Wałbrzych, which is developing a fleet of hydrogen-powered buses and has signed a letter of intent with the investor concerning fuel supplies. This demonstrates that a complete hydrogen economy value chain is gradually emerging in Poland, encompassing hydrogen production, storage, distribution and its use in zero-emission transport.

4.4. Development of the Hydrogen Economy in Konin

One of the most important centres for the development of the hydrogen economy in Poland is Konin and the Eastern Wielkopolska region, which is undergoing an intensive transformation from lignite-based energy towards renewable energy sources and low-carbon technologies³⁴. The development of the hydrogen economy is one of the key elements of the region's Just Transition strategy, which aims to create new jobs and replace activities related to lignite mining and combustion with modern energy technologies.

The first stage of the project involved the construction of a green hydrogen production facility at the Konin Power Plant. Ultimately, the project envisages the development of a facility with a capacity of up to 50 MW, while the first stage comprised a 2.5 MW electrolyser, with the possibility of further expansion based on a modular architecture. The electricity used for the electrolysis process comes from renewable energy sources, including biomass units as well as photovoltaic and wind farms.

³⁴ *Polsat Plus Group and ZE PAK Group begin green hydrogen production in Konin*, Polsat Plus Group, 16.12.2024, <https://grupapolsatplus.pl/en/archive/polsat-plus-group-and-ze-pak-group-begin-green-hydrogen-production-konin>; *Green' hydrogen in ZE PAK*, ZE PAK, <https://zepak.com.pl/en/about-us/press-office/news/12534-green-hydrogen-in-zepak.html>

A major milestone was reached in December 2024 with the commencement of green hydrogen production in Konin. The installation uses a 2.5 MW PEM electrolyser, enabling the production of approximately 1,000 kg of green hydrogen per day.

The project being implemented in Konin is not limited solely to hydrogen production. A complete regional hydrogen economy ecosystem is being developed, encompassing renewable energy sources, hydrogen production, storage, transport and end use. Hydrogen is transported in specialised high-pressure trailers to hydrogen refuelling stations being developed in Poland's largest cities. The network already includes stations in, among others, Warsaw, Gdańsk, Gdynia, Rybnik, and Lublin.

4.5. Hellenic Hydrogen Project

Hellenic Hydrogen is a strategic initiative being developed in the region of Western Macedonia in Greece, with the aim of establishing one of the most important centres for the production and use of green hydrogen in South-Eastern Europe³⁵. The project is being implemented by two of Greece's largest companies in the energy sector.

³⁵ *Hellenic Hydrogen*, Hellenic Hydrogen, <https://www.hellenic-hydrogen.gr/en>

The central element of the initiative is the North-1 project, which involves the construction of a green hydrogen production facility in Amyndeio on the site of former coal-based energy infrastructure. The facility will use electricity generated from renewable energy sources to power electrolyzers with an initial capacity of 50 MW, with the possibility of expansion to as much as 200 MW. In the first stage, approximately 12,600 tonnes of green hydrogen are expected to be produced annually, while ultimately the project is intended to become one of the largest hydrogen production centres in South-Eastern Europe. A particular advantage of the location is the possibility of using the existing electricity and gas infrastructure, as well as the skilled workforce previously employed in the lignite sector.

The Hellenic Hydrogen project is not limited solely to hydrogen production, but envisages the creation of a complete regional hydrogen ecosystem (Hydrogen Valley). It encompasses the entire value chain – from hydrogen production using renewable energy, through its storage, transport and distribution, to its use in the energy sector, heavy-duty transport, district heating and industry.

CHAPTER V

INTEGRATION OF RENEWABLE ENERGY AND ENERGY STORAGE

The dynamic development of renewable energy sources means that the integration of renewable energy installations with energy storage systems is becoming increasingly important. Due to the variable nature of electricity generation from wind farms and photovoltaic installations, energy storage systems make it possible to balance short-term fluctuations in generation, thereby increasing the stability and security of the electricity system. They enable surplus energy to be stored during periods of high generation and used during periods of increased demand or limited availability of renewable energy sources.

The integration of energy storage systems with renewable energy sources also enables the provision of ancillary services, such as frequency regulation, voltage stabilisation and the reduction of grid congestion, which is becoming

increasingly important as the share of non-dispatchable energy sources grows. For this reason, energy storage systems are now regarded as one of the key components of modern electricity systems supporting the energy transition and the achievement of climate neutrality.

5.1. Hybrid Wind Power Plant with Battery Energy Storage

One of the pioneering European projects integrating renewable energy sources with energy storage was a hybrid energy storage installation commissioned in 2017 at a wind farm in Barásoain, in the Navarra region of northern Spain³⁶. The project was demonstrative in nature and represented one of the first deployments in Europe of a battery energy storage system operating directly with an individual wind turbine. The main objective of the project was to increase the operational flexibility of wind power plants, improve the quality of electricity supplied to the grid and test the potential for energy storage systems operating with renewable energy sources to provide ancillary services.

The installation was developed alongside a wind turbine with a rated capacity of 3 MW and comprises two independent lithium-ion battery energy storage systems housed

³⁶ Barásoain Experimental Wind Farm, ACCIONA, <https://www.accionacom/projects/wind-power-area-experimental-barasoain/>

in separate containers. Each storage system was designed to perform different operational functions. The first battery has a storage capacity of 0.39 MWh and a power rating of 1 MW, enabling it to discharge electricity to the grid very rapidly and maintain full power for approximately 20 minutes. It is used primarily for rapid power regulation, compensation for short-term fluctuations in wind power generation and the provision of frequency regulation services to the electricity system.

The second energy storage system has a power rating of 0.7 MW and a storage capacity of 0.7 MWh. Unlike the first battery, it was designed for longer charging and discharging cycles, enabling electricity to be supplied to the grid more evenly. The combined operation of the two storage systems makes it possible both to respond to short-term fluctuations in electricity generation and to mitigate larger changes in power output resulting from variations in wind speed. This solution significantly improves the operational stability of the installation and increases the predictability of electricity generation.

The Barásain project was also of considerable research significance. The installation was equipped with an advanced monitoring and control system, enabling battery operation to be analysed under real operating conditions. The experience gained was used to develop new algorithms for managing energy flows and to assess the economic

viability of energy storage systems operating in conjunction with wind farms. The project results confirmed that the use of energy storage systems can increase the value of electricity generated from renewable sources by improving the quality of supply and enabling the provision of additional ancillary services.

5.2. Battery Energy Storage System in Offaly

Among the most advanced energy storage projects in Europe is Shannonbridge B, developed by Hanwha Energy in cooperation with Lumcloon Energy in County Offaly, central Ireland³⁷. The project was commissioned in 2024 and represents Hanwha Energy's third investment in energy storage in Ireland. The company had previously commissioned two energy storage facilities with capacities of 60 MWh (2019) and 120 MWh (2021). The development of successive installations forms part of Ireland's strategy to rapidly increase the share of renewable energy sources,

³⁷ *Hanwha Energy Promotes Third Energy Storage System (ESS) Project in Ireland*, Hanwha, 11.10.2022, <https://www.hanwha.com/newsroom/news/press-releases/hanwha-energy-promotes-third-energy-storage-system-ess-project-in-ireland.do>; C. Murray, *Construction starts on 170MWh hybrid energy storage project in Ireland*, Energy-Storage.news, <https://www.energy-storage.news/construction-starts-on-170mwh-hybrid-energy-storage-project-in-ireland/>

particularly wind power, which accounts for more than one-third of the country's electricity generation.

The principal component of the project is a battery energy storage system (BESS) with a capacity of approximately 160 MWh, located adjacent to the 220 kV Shannonbridge substation. The installation has been integrated with a synchronous condenser, creating Ireland's first hybrid system combining large-scale battery energy storage with equipment providing grid stabilisation services. This solution enables not only energy storage but also improvements in the operating parameters and stability of the national electricity system.

The battery energy storage system stores surplus electricity generated by wind farms and supplies it to the grid during periods of increased demand or reduced renewable energy generation. Owing to its very short response time, the installation provides frequency regulation services, power reserves and mitigation of rapid fluctuations in power supplied to the grid. The synchronous condenser, in turn, provides reactive power, supports voltage stability and supplies system inertia, which is becoming increasingly important as conventional synchronous power plants are decommissioned and the share of inverter-based renewable energy sources increases.

The project is located in the Midlands, a region that for many years was associated with peat extraction and

electricity generation in conventional power plants. The development of a modern energy storage facility close to the former Shannonbridge power station provides an example of how existing energy infrastructure can be repurposed as part of the Just Transition of regions moving away from fossil fuels. At the same time, the investment increases the capacity of the electricity system to accommodate new wind farms without requiring extensive and costly expansion of the transmission network.

5.3. Indeland Solar Park

A particularly interesting example of the integration of renewable energy sources with energy storage is the Indeland Solarpark, developed on the site of the Inden lignite open-cast mine in North Rhine-Westphalia, Germany³⁸. The power plant was commissioned in December 2022 and represents RWE's first hybrid installation in Europe combining a large-scale photovoltaic farm with a battery energy storage system.

³⁸ *Hybrid photovoltaic and storage system in Inden, North Rhine-Westphalia: "RWE indeland Solar Farm", RWE, RWE project page; Solar power from Inden Mine: RWE commissions photovoltaic plant with battery storage, RWE, 20.12.2022, RWE press release*

The project was developed on an area of approximately 15 hectares located on the western edge of the active Inden open-cast mine. Following the planned closure of the mine in 2029, this area will form part of the shoreline of the future Indesee lake. The investment represents an example of the use of post-mining land for the development of modern energy infrastructure and forms part of the transformation of regions moving away from lignite mining.

The principal component of the installation is a 14.4 MWp photovoltaic farm comprising approximately 26,500 bifacial photovoltaic modules. The panels are capable of utilising solar radiation reaching both the front and rear surfaces of the modules. Light reflected from the relatively bright ground surface increases electricity generation compared with conventional monofacial modules, thereby improving the efficiency of the installation without increasing the land area required. Annual electricity generation is estimated at approximately 14 GWh, corresponding to the electricity demand of several thousand households.

An integral part of the project is a battery energy storage system (BESS) with a capacity of 9.6 MWh. The system has been designed for an approximately two-hour charge and discharge cycle, enabling it to store surplus electricity generated by the photovoltaic farm during periods of high solar irradiation and supply it to the grid during periods of increased demand. The energy storage system acts

as a buffer between electricity generation and the grid, reducing short-term power fluctuations and increasing the utilisation of electricity generated from renewable energy sources.

The Indeland Solarpark is also an important element of the energy transition in North Rhine-Westphalia. For many years, the Inden open-cast mine formed part of one of Europe's largest lignite-mining regions. The construction of a modern photovoltaic power plant combined with battery energy storage demonstrates how post-mining areas can be successfully repurposed for the development of zero-emission energy infrastructure. The use of existing electricity infrastructure can reduce the cost of connecting new renewable energy installations to the grid and accelerate the redevelopment of former mining areas following the cessation of mining activities.

CHAPTER VI

BIOMASS, BIOGAS AND BIOMETHANE

Biomass, biomethane and biogas are renewable energy sources whose important advantage is their ability to provide stable energy production independently of prevailing weather conditions. Unlike wind and solar energy, they can be relatively easily stored and transported, allowing them to function as dispatchable energy carriers. Their development will play an important role in stabilising the electricity system by complementing weather-dependent renewable energy sources.

Biomass and biogas are also important for the decarbonisation of district heating systems and for replacing fossil fuels in individual heating systems, particularly where the deployment of other low-carbon technologies is difficult. For this reason, they are regarded as important components of the energy transition and the achievement of climate neutrality.

6.1. AGROinLOG Project

The AGROinLOG project (*Promoting the Bioeconomy by Developing Integrated Biomass Logistic Centres*) represents one of the most interesting European examples of the practical implementation of bioeconomy and circular economy principles in rural areas³⁹. The project was implemented between 2016 and 2020 under the Horizon 2020 programme, and its main objective was to develop and demonstrate a new model for organising biomass supply chains through the establishment of Integrated Biomass Logistic Centres (IBLCs). The project was carried out in three demonstration regions located in Spain, Greece and Sweden, representing different climatic conditions, agricultural structures and patterns of biomass utilisation. This made it possible to assess the feasibility of implementing

³⁹ *Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe (AGROinLOG)*, CORDIS – European Commission, <https://cordis.europa.eu/project/id/727961>; *AGROinLOG: Integrated Biomass Logistic Centres*, AGROinLOG, <http://agroinlog-h2020.eu/en/home/>; J. Casimir, J. Lund, *A roadmap to develop Integrated Biomass Logistic Centres in Skåne Sweden – Case study grain milling industry*, RISE Research Institutes of Sweden, Uppsala 2020; *Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe*, Zaragoza Logistics Center, <https://www.zlc.edu.es/research/projects/demonstration-of-innovative-integrated-biomass-logistics-centres-for-the-agro-industry-sector-in-europe>

the proposed solutions in different parts of Europe and to evaluate their transferability.

The fundamental problem addressed by the project was the low efficiency of agricultural biomass utilisation. In many European regions, significant quantities of straw, crop residues, orchard residues and by-products from the agri-food industry remain unused or are managed inefficiently. At the same time, the fragmented structure of agricultural holdings means that individual producers often lack the technical and economic capacity to organise the collection, storage and transport of biomass. Consequently, potentially valuable raw materials do not reach industrial or energy users, while their utilisation is constrained by high logistics costs.

The response to this problem was the concept of Integrated Biomass Logistic Centres, designed to function as regional hubs coordinating the entire biomass supply chain. Such centres are responsible for coordinating the collection of feedstock from multiple agricultural producers, its initial processing, storage, drying, size reduction and subsequent distribution to end users. The centralisation of logistics processes can significantly reduce transport costs and improve the quality of the biomass supplied. At the same time, the centres enable the integration of numerous small agricultural holdings that would not individually

be capable of supplying sufficient quantities of feedstock to large energy installations or industrial plants.

An important premise of the project was to consider biomass not only as an energy fuel but also as a feedstock for the developing bioeconomy. Within AGROinLOG, opportunities were analysed for processing biomass into higher-value-added products, such as biofuels, biomethane, biochemicals, organic fertilisers and biocomponents used by the chemical industry. This approach is consistent with the principles of the circular economy, according to which waste and by-products should be reused as valuable resources, thereby reducing the consumption of natural resources and the amount of waste sent to landfill.

The project included three demonstration installations located in different parts of Europe. In Spain, activities focused on the utilisation of cereal straw and residues from maize cultivation. Biomass was used both for energy purposes and for the production of pellets and biofuels. In Greece, the principal biomass sources included residues from cotton and maize cultivation as well as by-products from the agri-food industry. Particular attention was devoted to their potential use in local energy installations and biogas plants. Sweden, in turn, focused on integrating agricultural and forestry residues with the country's well-developed bioenergy sector, where biomass has long constituted one of the principal energy sources.

One of the project's most important findings was that the principal constraint on the development of bioenergy is often not the availability of biomass itself, but rather the inadequate organisation of its supply chain. The analyses carried out within the project demonstrated that appropriate coordination of collection, storage and transport can significantly reduce logistics costs and improve the competitiveness of biomass relative to fossil fuels. At the same time, the integration of numerous agricultural producers makes it possible to achieve economies of scale, thereby improving the economic viability of the entire undertaking. The project also developed business models and digital tools to support biomass supply planning and the assessment of feedstock potential in individual regions.

The AGROinLOG project also demonstrated significant social benefits associated with the development of regional biomass logistics centres. The establishment of such facilities supports the creation of new jobs in logistics, transport, storage and biomass processing. In addition, farmers can obtain new sources of income from the sale of by-products that had previously often remained unused. The development of local value chains can also contribute to strengthening regional energy security and reducing dependence on imported fossil fuels.

The AGROinLOG project confirmed that the successful development of the bioeconomy requires not only advanced

biomass-processing technologies but, above all, a properly organised logistics system covering the entire supply chain – from feedstock producer to end user. The integration of agricultural producers, logistics companies, processing facilities and energy consumers can significantly increase the economic efficiency of biomass utilisation and establish a sustainable foundation for the development of the regional bioeconomy.

6.2. BioYorkshire Programme

One of the most comprehensive European initiatives aimed at developing a regional bioeconomy is the BioYorkshire programme, implemented across York and North Yorkshire in northern England⁴⁰. The programme was launched in 2021 and is planned to run until 2031. BioYorkshire represents an example of a long-term public-private partnership aimed at establishing one of the United Kingdom's leading bioeconomy clusters. The initiative is closely linked to the regional economic development strategy and the climate policy of York and North Yorkshire, which aims to achieve net-zero emissions by 2034 (originally targeted for 2030), while simultaneously strengthening the

⁴⁰ BioYorkshire: *Driving prosperity and innovation through the bioeconomy*, BioYorkshire, <https://www.bioyorkshire.co.uk>

competitiveness of a knowledge- and innovation-based economy.

BioYorkshire was initiated by the University of York in collaboration with Fera Science Ltd., the local authorities of York and North Yorkshire, biotechnology companies, agricultural organisations and numerous industrial partners. The project has received financial support through the York and North Yorkshire Devolution Deal, UK government funding and private investment. The total value of planned investment exceeds GBP 200 million, making BioYorkshire one of the largest bioeconomy development programmes currently being implemented in the United Kingdom⁴¹.

The fundamental concept underlying the programme is to harness the potential of agriculture, science and advanced biological technologies to create a regional economy based on renewable biological resources. North Yorkshire has a well-developed agricultural sector, extensive agricultural land and a large number of businesses involved in food production. At the same time, the region is home to renowned research institutions conducting research in molecular biology, biotechnology, plant protection, environmental engineering and food technology. BioYorkshire aims

⁴¹ *Biomass Strategy 2023*, Department for Energy Security and Net Zero, London 2023, <https://www.gov.uk/government/publications/biomass-strategy>

to bring together the capabilities of these sectors to create a comprehensive innovation ecosystem encompassing scientific research, technology development, the implementation of new solutions and their commercialisation.

A distinctive feature of the programme is its application of the “end-to-end bioeconomy” concept, involving the transformation of the entire value chain – from biomass production, through logistics, processing and technology development, to the manufacture of final products and their introduction to the market. Unlike many earlier projects focused primarily on bioenergy production, BioYorkshire encompasses all stages of the bioeconomy, integrating biomass producers, the agri-food sector, biotechnology companies, the chemical industry and research institutions. This approach makes it possible to increase the added value of the products generated and to develop regional supply chains based on local resources.

One of the programme’s principal areas of activity is the development of advanced technologies for processing agricultural biomass and biological waste. Particular attention is given to the use of agricultural by-products, food-processing residues and organic waste for the production of biofuels, biogas, biomethane, biochemicals, biomaterials and bioplastics. The application of advanced biotechnology makes it possible to convert biomass into high-value-added products capable of replacing fossil-based

raw materials currently used in the chemical, pharmaceutical and materials industries. Biomass therefore becomes not only an energy source but also an important feedstock for the development of modern low-carbon industries.

Another important component of the programme concerns the development of precision agriculture and sustainable food production. BioYorkshire envisages the application of advanced digital technologies, artificial intelligence, data analytics and molecular biology to increase agricultural productivity while reducing environmental pressures. Technologies are being developed to monitor soil quality, manage nutrients, reduce the use of plant protection products and increase crop resilience to climate change. These activities are intended to improve agricultural productivity while increasing the availability of biomass for industrial applications.

The development of research infrastructure represents a particularly important area of the programme. BioYorkshire includes the establishment of advanced laboratories, demonstration facilities and innovation centres enabling new technologies to be tested under conditions approaching those of industrial-scale operation. The University of York plays a key role, developing interdisciplinary research in industrial biotechnology, synthetic biology, fermentation technologies and solutions supporting the circular economy. In parallel, Fera Science conducts research into

food security, plant protection and the use of biological approaches to improve agricultural productivity.

The programme also sets ambitious economic objectives. According to its assumptions, by 2031 BioYorkshire is expected to contribute to the creation of approximately 29,000 new jobs, attract additional private investment and increase the value of the regional economy by several billion pounds. Particular emphasis is placed on supporting start-ups and spin-off companies commercialising research conducted at universities and research institutions. Under the programme's assumptions, the development of the bio-economy sector is intended to become one of the principal drivers of economic growth across the region.

BioYorkshire represents one of the most comprehensive approaches to regional bioeconomy development in Europe. The initiative demonstrates that an effective economic transition requires the simultaneous development of scientific research, modern agriculture and innovative industry, supported by close cooperation between the public and private sectors.

6.3. Madsen Bioenergi Biogas and Biomethane Plant

One interesting example of the use of biogas in agriculture is the Madsen Bioenergi biomethane plant, commissioned

in 2014 in Skive, Denmark⁴². The facility was developed by the three Madsen brothers, who operate a family farm covering approximately 350 hectares and specialising in pig farming and the cultivation of maize, grass and cereals.

The biogas plant uses anaerobic digestion technology based on continuously stirred tank reactors (CSTRs) and processes approximately 146,000 tonnes of biomass annually, equivalent to around 400 tonnes per day. The principal feedstocks are pig slurry (51%) and cattle slurry (32%), supplied by farms located within a radius of approximately 10 km, thereby reducing transport costs and emissions associated with feedstock logistics.

The facility was designed to achieve a high level of energy efficiency. The digesters are heated using heat pumps, a straw-fired boiler and waste heat recovered from the biogas upgrading process. A biological air treatment system has also been installed to reduce odour emissions.

The biogas produced is upgraded to biomethane quality and subsequently injected into the national gas grid, where it can be used for heat and electricity generation or as a transport fuel.

⁴² *Case study 2 – Boe Madsen / Madsen Bioenergi*, World Biogas Association, 19.05.2020, <https://www.worldbiogasassociation.org/7-case-study-2-boe-madsen-madsen-bioenergi>

CHAPTER VII

SMART AND MODERNISED ELECTRICITY GRIDS

The development of renewable energy sources, energy storage systems, electromobility and distributed energy generation means that electricity grids are becoming one of the key elements of the energy transition. The growing share of non-dispatchable energy sources, such as wind farms and photovoltaic installations, presents system operators with new challenges related to maintaining system stability and ensuring security of electricity supply. Two-way electricity flows resulting from the rapid development of prosumers and local energy communities are also becoming increasingly important. These challenges are being addressed through the development of smart grids, which use advanced monitoring, automation, communication and digital management systems. Modern electricity grids enable the efficient integration of renewable energy

sources, energy storage systems and consumers actively participating in the energy market, and therefore constitute one of the fundamental prerequisites for achieving climate neutrality and developing a secure and flexible electricity system.

7.1. WindNODE Project

The WindNODE (Wind Energy Northeast Germany) project was one of the most important European demonstration initiatives focusing on the energy transition and the digitalisation of electricity systems. It was implemented between 2017 and 2021 in north-eastern Germany, covering six federal states: Berlin, Brandenburg, Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt and Thuringia⁴³. The region is one of the most advanced areas for renewable energy development in Europe. The large number of wind farms located in northern Germany, combined with the rapidly expanding photovoltaic sector, means that electricity generation exceeds local demand during certain periods.

⁴³ M. Graebig, *WindNODE – showcasing smart energy systems from northeastern Germany Status quo and prospects for German-Japanese cooperation*, Tokyo and Osaka 2019; I Uhlig, *WindNODE as a blueprint for a transition towards 100% renewables*, 2022; *WindNODE ABW Documentation*, WindNODE, <https://windnode-abw.readthedocs.io/en/latest/>

This creates a need to transmit electricity to other parts of the country and presents electricity system operators with new challenges related to maintaining grid stability.

WindNODE sought to address these challenges by developing and testing advanced solutions based on digitalisation, smart grids and active management of energy system flexibility. The project was implemented under the SINTEG programme (*Schaufenster Intelligente Energie – Digitale Agenda für die Energiewende*), funded by the German Federal Ministry for Economic Affairs and Energy (BMWi, now BMWK). The SINTEG programme comprised five regional demonstration projects aimed at developing practical solutions enabling electricity systems to operate with a very high share of renewable energy sources.

WindNODE was the largest of these initiatives in terms of both the number of partners and the scope of activities undertaken. More than 70 partners participated in the project, representing transmission and distribution system operators, energy companies, technology manufacturers, universities, research institutes, public authorities and industrial consumers. Approximately 50 pilot projects were implemented, covering virtually all components of a modern energy system.

The primary objective of WindNODE was to develop a model for a smart electricity system capable of integrating very large quantities of renewable electricity without

compromising grid security. The project developed solutions enabling active demand-side management (DSM). Cooperation between smart meters, building management systems, heat pumps, electric vehicle charging stations and industrial processes was tested in conjunction with electricity system operators. Appropriate algorithms made it possible to automatically increase electricity consumption during periods of high renewable generation and reduce it when generation was limited. This helped alleviate grid congestion and reduce the need to curtail electricity generation from wind farms.

One of the most important elements of WindNODE was the digitalisation of the electricity system. The project developed data exchange platforms enabling communication between electricity producers, grid operators, end users and energy service aggregators. Smart metering technologies, the Internet of Things (IoT), Big Data analytics and cloud computing were applied. This enabled the electricity system to be monitored in real time and allowed automated decisions to be made regarding the control of energy-consuming equipment. The project demonstrated that digitalisation is becoming one of the key components of the energy transition, enabling considerably more efficient use of existing electricity infrastructure.

Energy storage and Power-to-X technologies also played a significant role in the project, particularly the production

of green hydrogen using surplus electricity. In the regions covered by the project, the integration of electrolyzers with wind farms was tested, together with potential applications of hydrogen in industry and transport. The interaction between energy storage systems and renewable energy sources and their impact on electricity grid stability were also investigated. The project results confirmed that energy storage and hydrogen production technologies can significantly reduce renewable energy curtailment during periods of high generation and limited transmission grid capacity.

Another important component of WindNODE was the establishment of so-called real-world laboratories (*Reallabore*). Unlike conventional research projects, new solutions were tested not under laboratory conditions but in operational electricity grids, industrial facilities, residential buildings and businesses. This made it possible to assess not only the technical performance of the proposed technologies, but also their economic viability, social acceptance and potential for large-scale deployment. This approach subsequently became a model for further German demonstration projects related to the energy transition.

The significance of the project was also closely linked to its geographical location. Brandenburg and Saxony encompass a substantial part of Lusatia (*Lausitz*), a region that has been associated with lignite mining and electricity generation for many decades. Solutions developed within

WindNODE contributed to the foundations for subsequent investments in post-mining areas, including the development of the hydrogen economy, large-scale energy storage and smart energy management systems. Examples include the Reference Power Plant Lausitz (RefLau), green hydrogen production projects developed by ENERTRAG and subsequent investments in energy storage. In this way, WindNODE played an important role not only in the development of energy technologies but also in the Just Transition of mining regions.

Following the completion of the project, a series of recommendations were developed concerning the regulatory and organisational changes required for the further development of smart energy systems. These included the need to strengthen demand-side flexibility, develop local energy markets, integrate energy storage into the electricity system and expand the use of digital technologies. The importance of open data exchange platforms facilitating cooperation between different energy market participants was also emphasised.

WindNODE is regarded as one of the most comprehensive European demonstration projects addressing the digitalisation of the energy transition.

7.2. Smart Rural Grid (SRG) Project

The Smart Rural Grid (SRG) project represents one of the first European examples of the comprehensive modernisation of a rural electricity distribution network using smart grid technologies⁴⁴. The project was implemented between 2014 and 2017 in the municipality of Vallfogona del Ripollès in Catalonia, in cooperation with the distribution system operator Estabanell Energia (EyPESA) and research and industrial partners from several European countries. Co-funded under the Horizon 2020 programme, the project aimed to develop solutions for modernising relatively weak electricity networks in rural areas, where the growing number of distributed energy resources was beginning to create challenges related to the quality and reliability of electricity supply.

The distribution network covered by the project supplies electricity to approximately 56,000 customers through a medium-voltage network extending over approximately 1,500 km. Around half of the infrastructure is located in sparsely populated rural areas. Before the project began, the network had a conventional radial (tree-like) structure

⁴⁴ F. Girbau-Llistuella et al., *Smart Grid Architecture for Rural Distribution Networks: Application to a Spanish Pilot Network*, „Energies” 2018, no. 4, vol. 11, p. 844; R.G. Fernández, S.M. Farrero, L. Candido, *Smart Rural Grid*, Ljubljana 2017.

characterised by long branches and a limited number of interconnections between individual lines. This configuration made it more difficult to connect new renewable energy installations, increased the risk of supply interruptions and limited the possibilities for automatic power supply switching in the event of faults.

The fundamental objective of the project was to transform the conventional distribution network into a smart electricity grid capable of actively managing electricity flows. To achieve this, the network topology was modified by establishing additional interconnections between its branches, thereby increasing the possibilities for network reconfiguration during disturbances and improving security and reliability of supply. At the same time, local energy storage systems were installed at selected locations. These systems were integrated with renewable energy sources and used to alleviate short-term network congestion and stabilise voltage levels.

One of the project's most innovative elements was the development and implementation of a device known as the Intelligent Distribution Power Router (IDPR). This power-electronics-based control system enables intelligent management of electricity flows between different sections of the distribution network, energy storage systems and distributed generation sources. The IDPR makes it possible to dynamically control the direction of electricity flows,

alleviate network congestion and increase the capacity to integrate additional renewable energy sources without requiring costly expansion of the electricity infrastructure. The solution represented one of the project's most important technological achievements and has subsequently been discussed in numerous scientific publications.

The modernisation also covered the network's information and communication infrastructure. The project implemented a hybrid communication system combining Power Line Communication (PLC) with wireless WiMAX technology, enabling two-way data exchange between devices installed across the network and the operator's control centre. A decentralised supervisory system operating in conjunction with the conventional Supervisory Control and Data Acquisition (SCADA) system was also developed. This enabled real-time monitoring of network operating parameters and automated decision-making concerning network reconfiguration and the operation of energy storage systems.

CHAPTER VIII

ENERGY EFFICIENCY AND LOW-CARBON DEVELOPMENT

8.1. Energy Poverty Mitigation in Western Macedonia

For many decades, Western Macedonia was the centre of Greece's lignite mining and lignite-fired power generation industry. Following the decision to phase out this fuel, the region was included in the Just Transition process, one of the most important components of which is the *Socioeconomic Transition of Western Macedonia* project⁴⁵. The initiative was launched in 2023 with a planned implementation period of 36 months. It is the first project

⁴⁵ *Socioeconomic Transition of Western Macedonia*, European Investment Bank, 2022, EIB project page; *The transition towards a greener future of Western Macedonia is the first project supported by the European Union's Public Sector Loan Facility*, European Climate, Infrastructure and Environment Executive Agency, 7.11.2023, European Commission/CINEA page; D. Ziouzos et al.,

financed under the Public Sector Loan Facility (PSLF), which constitutes the third pillar of the European Union's Just Transition Mechanism.

The total value of the programme amounts to approximately EUR 80.7 million, of which EUR 58 million is provided in the form of a European Investment Bank loan, while EUR 14.5 million constitutes a non-repayable European Commission grant. The programme comprises 15 investment projects implemented across six municipalities in the region: Argos Orestiko, Kozani, Kastoria, Florina, Eordaia and Grevena. In terms of the investment structure, energy efficiency measures predominate, with 8 of the 15 projects concerning the energy renovation of public buildings. The remaining investments include the development of road infrastructure and the modernisation of healthcare facilities, cultural facilities and tourism infrastructure. The programme is multisectoral in nature and is directly linked to the implementation of the Territorial Just Transition Plan for Western Macedonia.

The largest share of the planned works concerns improvements in the energy efficiency of public infrastructure. Schools, administrative buildings, sports facilities and healthcare facilities are being modernised. The measures include thermal insulation of building envelopes,

replacement of windows and doors, modernisation of heating and cooling systems, installation of Building Energy Management Systems (BEMS), replacement of conventional lighting with LED technology and installation of renewable energy systems. Depending on the type of facility, final energy consumption is expected to be reduced by between 60% and as much as 97%, resulting in a significant reduction in the operating costs of local authorities and lower overall energy demand across the region.

The programme is expected to reduce greenhouse gas emissions by approximately 8,650 tonnes of CO₂ per year, primarily as a result of lower energy consumption in public buildings. In addition to its environmental benefits, the project is expected to create approximately 200 new jobs, particularly in the construction sector, energy services and companies involved in infrastructure modernisation. The upgrading of public facilities is also intended to increase the region's attractiveness to investors and improve the quality of public services.

An important feature of the programme is its departure from the conventional approach to energy poverty based primarily on subsidising household energy bills. In Western Macedonia, the adopted model focuses instead on achieving a lasting reduction in energy demand through improvements in the energy efficiency of infrastructure, while simultaneously stimulating the region's economic

development. The modernisation of public buildings reduces energy expenditure by local authorities, while infrastructure investment and the creation of new jobs are intended to increase residents' incomes and improve the region's socio-economic situation following the phase-out of lignite mining.

8.2. Low-Carbon Building Development

The buildings sector accounts for a significant share of final energy consumption and greenhouse gas emissions. Improving the energy efficiency of new buildings and renovating the existing building stock therefore constitute important elements of the energy transition. The development of low-carbon buildings involves both reducing energy demand through improvements in the thermal performance of building envelopes and implementing highly efficient heating, cooling and ventilation systems, waste heat recovery and local renewable energy generation. Increasingly, a whole-life-cycle approach is being adopted, taking into account the energy consumption and emissions associated with the production of construction materials, the construction process, building operation and eventual demolition. Examples of projects implementing these principles include One Angel Square in Manchester,

Powerhouse Kjørbo and Powerhouse Brattørkaia, as well as the refurbishment of the Skattedirektoratet complex in Norway⁴⁶.

One Angel Square is an office building in Manchester whose construction began in 2010 and was completed in 2013⁴⁷. The building, with a floor area of approximately 30,000 m², was designed as the headquarters of the Co-operative Group and achieved a BREEAM Outstanding rating. At the time of completion, it achieved a score of 95.16%, one of the highest ratings awarded to a large office building. The building was designed to combine reduced energy demand with the use of natural ventilation and daylight, as well as highly efficient on-site energy generation. A distinctive feature of the building is its triangular atrium and double-skin façade. These solutions facilitate the use of daylight and natural ventilation while reducing energy demand for lighting, heating and cooling. The building

⁴⁶ *One Angel Square*, OnGreening, <https://ongreening.com/en/Projects/one-angel-square-1181>; *Powerhouse Kjørbo: Making old buildings energy-positive*, Snøhetta, <https://www.snohetta.com/projects/powerhouse-kjorbo>; *Powerhouse Brattørkaia: The world's northernmost energy-positive building*, Snøhetta, <https://www.snohetta.com/projects/powerhouse-brattorkaia>; J. Kwiatkowski, *Definicje standardów i przykłady termomodernizacji budynków do standardu nZEB na świecie*, 2017; J. Sowa, *Modernizacja budynków użyteczności publicznej do standardu niemal zeroenergetycznego – przykłady obiektów norweskich*, 2017.

⁴⁷ *One Angel Square*, OnGreening, <https://ongreening.com/en/Projects/one-angel-square-1181>

has an air permeability of approximately $3.37 \text{ m}^3/(\text{h}\cdot\text{m}^2)$. Its U-values are approximately $0.20 \text{ W}/(\text{m}^2\text{K})$ for the walls, $0.25 \text{ W}/(\text{m}^2\text{K})$ for the floor and $0.16 \text{ W}/(\text{m}^2\text{K})$ for the terrace roof. The building also incorporates a rainwater harvesting system and solutions designed to reduce mains water consumption.

An important component of One Angel Square's energy system was the on-site generation of electricity and heat. Biofuel-powered combined heat and power (CHP) units were installed, with the electricity generated being used to meet the building's needs and the recovered heat supplying its heating systems. The heat could also be used in absorption chillers, thereby creating a trigeneration system. This combination of reduced energy demand, high-efficiency cogeneration and passive design solutions made it possible to significantly reduce primary energy consumption and CO_2 emissions compared with typical office buildings constructed during the same period. One Angel Square demonstrates that achieving a high environmental standard in large office buildings requires the integration of architectural, structural and energy solutions from the design stage onwards.

A different approach was adopted in the case of Powerhouse Kjørbo in Sandvika, Norway⁴⁸. The project involved

⁴⁸ *Powerhouse Kjørbo. Making old buildings energy-positive*, Snøhetta, <https://www.snohetta.com/projects/powerhouse-kjorbo>;

the refurbishment of two office buildings dating from the 1980s, with a combined floor area of approximately 5,180 m². The works began in 2012 and were completed in 2014. The objective was to transform the existing buildings into energy-positive buildings that, over their lifetime, would generate more renewable energy than the energy used for the production of construction materials, the construction process, operation and eventual demolition.

The principal measure was to reduce energy demand. The U-value of the external walls was reduced from approximately 0.30 to 0.13 W/(m²K), that of the roof from 0.22 to 0.08 W/(m²K), and that of the windows from 2.5 to approximately 0.8 W/(m²K). Particular attention was paid to reducing thermal bridging and improving the airtightness of the buildings. A ventilation system with approximately 85% heat recovery efficiency was installed, together with energy-efficient lighting and control systems that adjust building services according to actual occupancy and use.

Electricity is generated by a photovoltaic installation with a capacity of approximately 312 kWp and an area of around 1,550 m², installed on the roofs of the buildings and the garage. Annual electricity generation amounts to approximately 210 MWh. The heating system uses heat

pumps connected to ten vertical boreholes approximately 200 m deep. The ground heat exchangers provide a stable energy source for space heating and domestic hot water production. As a result of the comprehensive refurbishment, energy demand was reduced by more than 80%. Powerhouse Kjørbo is a particularly important example because it demonstrates that very high energy performance standards can be achieved not only in new buildings but also through the deep renovation of the existing building stock.

The energy-positive building concept was further developed in the Powerhouse Brattørkaia project in Trondheim⁴⁹. The building was completed in 2019 and designed to achieve a positive energy balance over its entire life cycle. This means that renewable energy generation is intended to compensate for the energy consumed in the production of construction materials, construction, operation and eventual demolition of the building. The building has approximately 18,000 m² of floor space and is one of the largest developments constructed according to the Powerhouse standard.

The geometry of the building and the appropriate orientation of surfaces used for solar energy generation are

⁴⁹ Powerhouse Brattørkaia: *The World's Northernmost Energy-Positive Building*, Snøhetta, <https://www.snohetta.com/projects/powerhouse-brattorkaia>

of particular importance. The sloping roof and parts of the façade are covered by a photovoltaic installation with an area of approximately 3,000 m². The system generates approximately 500 MWh of electricity annually, with surplus electricity available for supply to neighbouring buildings and transport infrastructure. Energy demand has been reduced through high levels of thermal insulation, efficient use of daylight, heat recovery from ventilation, energy-efficient lighting and intelligent control of technical building systems.

The heating and cooling system uses seawater and a heat pump with a capacity of approximately 140 kW. The use of this local energy source reduces electricity consumption required to maintain thermal comfort. The thermal storage properties of concrete are also utilised to stabilise the building's internal temperature and reduce peak heating and cooling demand. Powerhouse Brattørkaia achieved a BREEAM-NOR Outstanding rating and illustrates the development of buildings that are not merely energy consumers but can also function as local energy producers interacting with the electricity grid.

The fourth example concerns the refurbishment of the Skattedirektoratet office complex in Oslo, which houses the Norwegian Tax Administration⁵⁰. The complex, consisting

⁵⁰ J. Kwiatkowski, *Definicje standardów i przykłady termomodernizacji budynków do standardu nZEB na świecie*, 2017.

of five office buildings constructed in the early 1980s, underwent comprehensive refurbishment between 2010 and 2013. The project represents an example of the deep energy renovation of a large administrative complex combined with a reconfiguration of its spatial layout.

As part of the project, the form of the complex was modified, creating approximately 4,000 m² of additional usable floor area while simultaneously reducing the external envelope area by approximately 5,900 m². Improving the compactness of the buildings helped reduce heat losses. Thermal insulation with a thickness of up to 350 mm was installed, together with high-performance building envelope components. Wall U-values were reduced to below 0.16 W/(m²K), roof U-values to approximately 0.12 W/(m²K), and window U-values to approximately 0.72 W/(m²K). At the same time, daylight utilisation was optimised and energy-efficient LED lighting was installed.

An interesting solution was the utilisation of waste heat generated by the server room. Through a heat recovery system, this energy covers approximately 70% of the buildings' heating demand. The remaining heat demand is supplied by the municipal district heating network. Before refurbishment, energy consumption amounted to approximately 165 kWh/(m²·year), whereas following completion of the works it was reduced to approximately

68.7 kWh/(m²·year), enabling the building to achieve energy performance class A.

The examples presented illustrate different approaches to the development of low-carbon buildings. One Angel Square combines passive design solutions with on-site energy generation through cogeneration and trigeneration. Powerhouse Kjørbo demonstrates the possibility of transforming existing buildings into energy-positive buildings through deep energy renovation, heat pumps and photovoltaic systems. Powerhouse Brattørkaia further develops the concept of a building that generates an energy surplus over its entire life cycle, while the refurbishment of the Skattedirektoratet complex demonstrates the importance of waste heat recovery, improved building compactness and reduced heat losses through the building envelope. A common feature of all these projects is a comprehensive approach to reducing energy consumption, combining improvements in building performance with efficient technical systems, the utilisation of local energy resources and advanced energy management.

8.3. Low-Carbon Transport Development

Reducing emissions from transport requires not only replacing internal combustion engine vehicles with electric

vehicles, but also reducing demand for individual car transport and increasing the share of public transport, cycling and walking. Mobility management, the integration of different modes of transport, the digitalisation of mobility services and the reorganisation of urban space also play an important role. Different approaches to these challenges are illustrated by measures promoting cycling in Dortmund, the WienMobil mobility platform and the Superblocks programme in Barcelona⁵¹.

Since the beginning of the second decade of the 21st century, Dortmund has been implementing measures aimed at increasing the share of cycling in the urban modal split⁵². The city's cycling policy includes the expansion and improvement of the continuity of the cycle route network, the development of bicycle parking facilities and cycle stations, public bicycle-sharing systems and infrastructure for electric bicycles. An important direction is the

⁵¹ Radverkehrsstrategie. *Teilkonzept Radverkehr und Verkehrssicherheit. Masterplan Mobilität Dortmund 2030*, Stadt Dortmund, Dortmund 2022; *City of the Future*, WienTourismus, <https://www.wien.info/en/livable-vienna/smart-city-vienna>; *WienMobil – the App for All Routes in Vienna*, WienTourismus, WienMobil source; R. Postaria, *Superblock (Superilla) Barcelona—A City Redefined*, Cities Forum, 31.05.2021, Cities Forum article.

⁵² Radverkehrsstrategie. *Teilkonzept Radverkehr und Verkehrssicherheit. Masterplan Mobilität Dortmund 2030*, Stadt Dortmund, Dortmund 2022; *Radverkehr*, Stadt Dortmund, <https://www.dortmund.de/themen/mobilitaet-und-verkehr/radverkehr/>

development of high-speed cycle routes, including regional connections such as the RS1, which are intended to facilitate everyday commuting over longer distances between cities in the Ruhr region. Infrastructure for cargo bikes is also being developed, providing an alternative to cars for transporting people and small loads.

Infrastructure measures are complemented by mobility management instruments. The city cooperates with businesses, schools, cycling organisations and public institutions in developing employee mobility plans and providing bicycle parking and related facilities. Initiatives such as *Bike to Work* and *STADTRADELN* record kilometres travelled by bicycle and the resulting reductions in CO₂ emissions achieved by replacing car journeys with cycling. Dortmund therefore combines infrastructure, organisational and information-based measures to increase the share of cycling in the urban modal split.

A different approach has been adopted in Vienna, where the WienMobil system integrates various mobility services within a single digital platform⁵³. Managed by Wiener Linien, the system enables users to plan journeys combining public transport, walking, bicycle-sharing, car-sharing

⁵³ *City of the Future*, Vienna Tourist Board, <https://www.wien.info/en/livable-vienna/smart-city-vienna>; *WienMobil – the App for All Routes in Vienna*, Vienna Tourist Board, <https://www.wien.info/en/travel-info/transport/wienmobil-365934>

and other mobility services. The application uses timetable and real-time departure data, enables users to search for multimodal connections and allows them to purchase public transport tickets.

The digital platform is complemented by the physical infrastructure of WienMobil Stations. These are mobility hubs located near public transport stops and in residential areas, integrating bicycle-sharing, bicycle parking, car-sharing and, depending on the location, electric vehicle charging facilities. The network comprises approximately 240 stations across all 23 districts of Vienna and around 3,000 shared bicycles. The system is intended to reduce first- and last-mile barriers and improve access to public transport without requiring the use of a private car. WienMobil represents an example of the implementation of the Mobility as a Service (MaaS) concept, in which data, journey planning, service provision and transport infrastructure are integrated within a single system.

A considerably more extensive intervention in the urban transport system has been implemented in Barcelona⁵⁴. The Superblocks programme, developed in its current form since 2016 on the basis of earlier urban planning

⁵⁴ R. Postaria, *Superblock (Superilla) Barcelona—A City Redefined*, Cities Forum, 31.05.2021, Cities Forum website; N. Mueller et al., *Changing the urban design of cities for health: The superblock model*, “Environment International” 2020, vol. 134, art. 105132.

initiatives, involves changing the hierarchy of streets and restricting through traffic within groups of several urban blocks. A typical Superblock generally consists of nine conventional city blocks. Through traffic is directed along the perimeter streets, while the internal street network is primarily intended for local traffic, pedestrians and cyclists.

Within Superblocks, measures include lower speed limits, changes in traffic direction designed to prevent through traffic, the removal of some parking spaces and the redesign of intersections and streets. The reclaimed space is allocated to pavements, cycle lanes, green areas, public squares and recreational spaces. As part of the broader *Superilla Barcelona* programme, so-called green streets and green squares are also being developed. The programme's targets included the creation of 21 green streets and 21 new squares in the Eixample district, with implementation taking place in stages.

Modelling of the potential implementation of 503 Superblocks across Barcelona indicated that the scheme could reduce the number of car journeys by approximately 230,000 per week, equivalent to around 19–21%, decrease NO₂ concentrations by approximately 24% and reduce traffic noise. It was also estimated that the model could increase green space by approximately 5.8 m² per inhabitant and mitigate the urban heat island effect. It should be emphasised, however, that these figures relate to a scenario involving

the full city-wide implementation of the model rather than to effects already achieved across all existing Superblocks.

The examples presented represent three different groups of instruments for the decarbonisation of urban transport. Dortmund is developing cycling infrastructure and mobility management measures to change the modal split. Vienna uses digital technologies and mobility hubs to integrate public transport with shared mobility services. Barcelona employs urban planning and traffic management measures to reduce car use and increase the amount of space available to pedestrians and cyclists. A common feature of these approaches is the reduction of the energy intensity of the transport system by decreasing the number of car journeys and increasing the use of more energy-efficient modes of transport.

CHAPTER IX

REGENERATION AND REPURPOSING OF POST-INDUSTRIAL AREAS

The energy and economic transition is leading to the gradual reduction or cessation of activities at many industrial plants, mines and power stations, leaving extensive areas that require remediation and redevelopment. The revitalisation of post-industrial areas makes it possible to reuse existing infrastructure and assign new economic, technological, scientific, social and environmental functions to degraded sites. Of particular importance is the integration of land remediation, infrastructure modernisation and the preservation of industrial heritage with the creation of new jobs and the development of innovative sectors of the economy. Properly planned transformation of post-industrial areas can mitigate the negative effects of the restructuring of traditional industries and support the long-term development of regions undergoing decarbonisation.

9.1. Green Regeneration of Essen

Essen is an example of the long-term transformation of an industrial city and region in which environmental measures have been combined with infrastructure redevelopment, the development of new economic functions and the establishment of organisational structures enabling projects to be implemented over several decades⁵⁵. The last hard coal mine in Essen was closed in 1986, while the transformation process continued through successive municipal and regional programmes. Cooperation between the city and other local authorities in the Ruhr region, the state of North Rhine-Westphalia, municipal companies, civil society organisations and residents was particularly important. Over the following decades, more than 500 projects were implemented in areas including the restoration of water-courses, the development of green spaces, mobility, energy efficiency and improvements in the quality of urban space. The scale and comprehensive nature of these measures contributed to Essen being awarded the title of European Green Capital in 2017⁵⁶.

⁵⁵ *European Future Formats. Results, Modes of Effect and Shared Features of European Future Formats – Based on the Ruhr Metropolis Example, Essen 2017.*

⁵⁶ *Essen – European Green Capital 2017*, European Commission, https://environment.ec.europa.eu/topics/urban-environment/european-green-capital-award/winning-cities/essen-2017_en

An important area of the transformation was the restructuring of the water management system. Historically, the River Emscher and its tributaries served as an open wastewater drainage system for this heavily industrialised area. The transformation involved the construction of underground sewer infrastructure, the restoration of rivers and streams, and the recovery of the natural water retention functions of riverside areas. More than 20 watercourses in Essen were restored. At the same time, a decentralised stormwater management system was developed, incorporating green roofs, infiltration areas, retention basins and areas capable of temporarily storing water. A target was adopted to disconnect stormwater from the combined sewer system across at least 15% of the area served by this system. These measures reduce pressure on the sewer system during heavy rainfall, increase water infiltration into the ground and improve the city's resilience to the impacts of climate change.

A second area of activity was the development of green infrastructure. More than half of Essen's area now consists of green spaces, forests, agricultural land and other undeveloped areas. The city has developed a network of interconnected parks, recreational areas, ecological corridors, and walking and cycling routes. Of particular importance was the conversion of former industrial and mining sites into areas with new environmental, economic

and social functions. One example is the former Zollverein coal mine complex, which, following the end of industrial operations, was transformed into a centre for culture, education and tourism. According to data presented as part of the European Green Capital programme, 95% of Essen's residents had access to green space within 300 metres of their homes.

The transformation also encompassed the transport system. Essen developed its public transport infrastructure, cycle route network and pedestrian connections between residential areas, service centres and green spaces. At the time the city held the European Green Capital title, it had approximately 376 km of cycle routes. The long-term objective of its transport policy was to achieve, by 2035, an equal modal split between public transport, private cars, cycling and walking, with each accounting for 25% of journeys. The city also aimed to reduce the share of car journeys by 29% by 2035.

An important element of Essen's transformation model was the combination of infrastructure investment with economic, educational and organisational measures. Industrial restructuring was accompanied by investment in education, vocational training and the development of new sectors of the economy. The city adopted a target of creating 20,000 jobs in sectors related to environmental protection and the green economy by 2025. The European Green Capital

programme also included more than 400 projects and events divided into five thematic areas covering mobility, water, green spaces, resource management and quality of life. Educational initiatives addressed waste reduction, recycling, local food, responsible consumption and fair trade.

Essen's experience demonstrates that the transformation of a former mining region requires permanent organisational structures and cooperation among numerous stakeholders rather than the implementation of a single investment programme. Of particular importance was the continuity of measures undertaken by public authorities in cooperation with businesses, scientific institutions, civil society organisations and residents. The model adopted in Essen demonstrates that organisational support for transformation can play an integrating role, bringing together infrastructure, environmental, social and economic projects and ensuring their continuation over a period of several decades.

9.2. Lavrion Technological and Cultural Park

The Lavrion Technological Cultural Park (LTCP) is an example of the reuse of a post-industrial site for the development of scientific, technological, educational and cultural

activities⁵⁷. The complex is located in Lavrion in the Attica region, approximately 50 km from Athens, on the former premises of the *Compagnie Française des Mines du Laurium*. The industrial facility was involved in the extraction and processing of lead, silver and other metal ores. Industrial operations ceased in the late 1980s, leaving behind an extensive complex of historic industrial buildings and land requiring remediation. In 1992, the site was transferred to the National Technical University of Athens (NTUA), and in 1995 its transformation into a technological and cultural park began. The main works associated with the first stage of revitalisation and the establishment of the park were carried out between 1994 and 1997.

The park covers approximately 245,000 m² and comprises several dozen industrial buildings constructed mainly between 1875 and 1940. The first stage of the project involved the renovation of 17 of the 42 existing buildings and the construction of two new facilities. The works were carried out while preserving the historic character of the industrial complex and included the adaptation of buildings for laboratories, technology companies, educational

⁵⁷ *Lavrion Technological and Cultural Park*, National Technical University of Athens, LTCP official website; M.Á. Maté-González et al., *Integrating Advanced Technologies for Environmental Valuation in Legacy Mining Sites: The Role of Digital Twins at Lavrion Technological and Cultural Park*, “Sensors” 2025, vol. 25, no. 19, art. 5941.

activities and events. At the same time, remediation of the heavily contaminated site was required. A pilot remediation programme covered approximately 10,000 m² of land where the soil had been contaminated with heavy metals as a result of decades of ore extraction and processing.

The primary function of LTCP is to support technology transfer and cooperation between research institutions and businesses. The park is managed by the National Technical University of Athens and provides companies with access to technical infrastructure, laboratory and office space, as well as the university's research facilities. The site accommodates NTUA laboratories, technology companies, start-ups and entities engaged in educational and research and development activities. Areas of activity supported by the park include information and communication technologies, electronics, telecommunications, automation, robotics, environmental technologies and renewable energy. The park facilitates the implementation of research projects, the development of prototypes and technology demonstrators, and the establishment of new companies using the results of scientific research.

An important element of the park's activities is its research infrastructure related to energy and environmental technologies. Projects concerning renewable energy sources, energy efficiency, energy storage and smart energy systems are carried out at LTCP. One example is

the development of an energy microgrid incorporating photovoltaic installations, wind turbines, energy storage systems and control systems. The park's infrastructure enables research to be conducted under real operating conditions and allows different technologies to be tested as part of an integrated local energy system.

Another important area of LTCP's activities is education and knowledge dissemination. Training courses, workshops, lectures, conferences and activities for university and school students are organised at the park. Its infrastructure is used for international research projects, doctoral and diploma projects, and experiments conducted by research teams from the National Technical University of Athens. The preserved industrial equipment, technological installations and buildings also constitute tangible heritage documenting the history of mining and the metallurgical industry in the region.

The park also performs a cultural function. Its historic industrial halls and open spaces are used for exhibitions, concerts, theatrical performances, conferences and other events. The distinctive industrial architecture of the complex has also made it a location for film and television productions. Combining technological, scientific, educational and cultural functions has made it possible to preserve Lavrion's industrial heritage while giving the former industrial complex new economic functions.

The experience of the Lavrion Technological Cultural Park demonstrates the importance of scientific institutions in the transformation of post-industrial sites. In this case, the National Technical University of Athens acts as the owner and manager of the infrastructure, coordinator of research activities and an institution supporting the development of technology companies. The model adopted in Lavrion combines the remediation of degraded land, adaptive reuse of existing industrial infrastructure, technology transfer, entrepreneurship development, and educational and cultural activities.

CONCLUSIONS

The analysis of energy transition examples implemented in different European countries and regions indicates that there is considerable potential for adapting international solutions to Polish conditions. However, such adaptation requires consideration of the specific characteristics of the national energy system, economic structure, resource availability, and institutional and social conditions. The projects analysed represent different areas of the transition, including district heating, hydrogen technologies, energy storage, biomass and biomethane, smart electricity grids, energy efficiency, sustainable transport, and the revitalisation of post-industrial areas. Their comparison makes it possible to identify solutions with implementation potential in Poland, as well as barriers that may limit their direct transfer.

In the area of modern district heating, the fourth-generation district heating system in Aarhus demonstrates the importance of gradually reducing network operating temperatures, integrating different heat sources, and using energy storage. Solutions of this type are particularly relevant to Poland, which has extensive district heating infrastructure. Adapting the experience of Aarhus would, however, require comprehensive modernisation of heat sources, networks and buildings, as the efficient operation of low-temperature systems depends on reducing heat demand among end users and appropriately adapting internal building installations.

The experience of the hybrid combined heat and power plant with hydrogen storage in Dauerthal illustrates the potential for integrating wind power, electrolysis, hydrogen storage and energy production. The project demonstrates that hydrogen installations can be used to utilise part of the energy generated from renewable sources and to integrate the electricity, gas and heating sectors. In Poland, solutions of this type could be developed primarily in regions with a high concentration of renewable energy sources and in proximity to hydrogen consumers. The main barriers remain the cost of electrolyzers, the efficiency of the entire energy conversion chain and the need to ensure stable demand for the hydrogen produced.

The energy centre in Bochum provides an example of using infrastructure remaining from mining activities for the production of heating and cooling. The use of mine water as a low-temperature heat source for heat pumps may be particularly relevant to Polish mining regions. In Silesia and other areas with closed or closing mines, infrastructure exists that could potentially be used to develop local energy systems. Adapting this solution would require a detailed assessment of mine water parameters, demand for heating and cooling, and the possibilities for integrating such installations with existing district heating systems. The hydrogen projects analysed demonstrate a variety of models for developing a hydrogen economy.

Modena Hydrogen Valley confirms the importance of creating regional ecosystems encompassing the production, distribution and use of renewable hydrogen. From the Polish perspective, it is particularly important to link hydrogen production with specific consumers and to develop regional hydrogen valleys in areas characterised by concentrations of industry, heavy transport and renewable energy sources. This model could be applied, among others, in industrial and port regions.

The Reference Power Plant Lausitz (REFLAU) demonstrates the potential for using hydrogen as an element in the transformation of regions historically associated with coal-based energy production. The project is relevant to Poland

because of the similarity of the challenges faced by mining and energy regions. The development of demonstration and research installations on the sites of existing power plants could enable the continued use of grid infrastructure, technical facilities and workforce expertise. Under Polish conditions, similar projects could be developed in regions undergoing the gradual reduction of coal mining and use.

Hydrogen technologies are also being implemented in Poland and are progressing from research and demonstration projects towards commercial applications. The development of domestic installations should be used to build technological expertise, develop supply chains and gain operational experience. At the same time, it is important that future projects are linked to local renewable energy production and consumers capable of providing stable demand for hydrogen.

Hellenic Hydrogen in Western Macedonia confirms the importance of cooperation between large energy companies in developing hydrogen production on an industrial scale. An important lesson for Poland is the need to involve companies with adequate capital resources, technical expertise and potential hydrogen consumers. Hydrogen projects require substantial investment; therefore, their development should be based on partnerships involving energy producers, industry, infrastructure operators and public authorities.

In the area of renewable energy and energy storage integration, the hybrid installation in Barásoain demonstrates the potential of battery storage to improve the controllability of electricity generation from wind farms. The use of storage systems with different power and capacity characteristics enables them to perform different system functions. In Poland, solutions of this type could be applied to existing and new wind and photovoltaic farms, particularly in areas affected by grid constraints.

The energy storage system in Offaly illustrates the growing importance of large-scale energy storage facilities operating in conjunction with equipment that stabilises the parameters of the electricity system. As the share of conventional synchronous generating units decreases, similar solutions will become increasingly important in Poland. Energy storage systems can not only shift electricity supply over time but also provide ancillary services, support frequency regulation and improve grid stability.

Indeland Solarpark confirms the benefits of developing hybrid installations combining photovoltaic farms with energy storage systems. Particularly noteworthy is the use of land associated with mining activities for the development of new energy infrastructure. In Poland, this approach could be applied to post-mining and post-industrial sites where electricity infrastructure and substantial areas of land suitable for redevelopment are available.

The AGROinLOG project represents a comprehensive approach to improving the efficiency of biomass utilisation through the establishment of integrated biomass logistics centres. In Poland, given the fragmentation of agricultural holdings and the geographical dispersion of biomass resources, the development of similar structures could improve the organisation of feedstock collection, transport, storage and processing. Logistics centres could also support the development of local biomass markets and reduce feedstock supply costs.

BioYorkshire presents a more holistic approach to the development of a regional bioeconomy, involving cooperation between businesses, agriculture, research institutions and public administration. Adapting this model in Poland could support the development of regional economic specialisations related to biofuels, biochemicals, biomaterials and the use of biomass for energy purposes. Of particular importance is linking research activities with the creation of new businesses and jobs and with the commercialisation of technologies.

The Madsen Bioenergi biomethane plant demonstrates the potential for developing biomethane production based on local agricultural waste and by-products. Given Poland's considerable agricultural potential, similar installations could contribute to increasing domestic production of renewable gases, reducing methane emissions and creating

additional sources of income for farms. Their development, however, depends on stable regulations concerning grid connection, support schemes and digestate management.

The WindNODE project confirms the importance of digitalisation, flexibility management and cooperation among a large number of stakeholders in the integration of renewable energy sources. For Poland, it is particularly important to develop mechanisms enabling the utilisation of flexibility provided by consumers, energy storage systems and distributed generation. Regional-scale demonstration projects could be used to test new market mechanisms and technologies before their implementation at national level.

Smart Rural Grid highlights the need to modernise electricity grids in rural areas. Infrastructure automation, network reconfiguration, the development of communication systems and the integration of energy storage can increase the capacity of distribution networks to accommodate distributed renewable energy sources. This is particularly important in Poland given the rapid development of photovoltaic installations and the constraints affecting distribution infrastructure in many rural areas.

The programme implemented in Western Macedonia demonstrates that measures related to the energy transition should be combined with the modernisation of public infrastructure, improvements in energy efficiency and job creation. A similar approach could be applied in Poland in

regions undergoing industrial transformation and in areas affected by high levels of energy poverty. Investment programmes should combine technical measures with social and economic instruments.

The examples of One Angel Square, Powerhouse Kjørbo, Powerhouse Brattørkaia and Skattedirektoratet illustrate the considerable potential for reducing energy consumption in both new and existing buildings. One Angel Square demonstrates the importance of integrating architectural solutions with cogeneration, energy recovery and building management systems. Powerhouse Kjørbo confirms the potential of deep renovation of existing buildings to achieve substantial reductions in energy demand. Powerhouse Brattørkaia demonstrates the feasibility of designing buildings with a positive energy balance over their entire life cycle. The modernisation of the Skattedirektoratet complex, in turn, demonstrates the importance of a comprehensive approach involving changes to building form, improved thermal insulation, heat recovery and the use of energy-efficient technical systems.

Adapting these experiences to Polish conditions requires greater emphasis on the deep energy renovation of buildings. Support programmes should place greater emphasis on comprehensive projects combining improvements in building envelope performance, modernisation of heating and ventilation systems, the use of renewable energy

sources and energy management. Major barriers include high investment costs, insufficient technical expertise and the fragmentation of the investment preparation and implementation process.

In the transport sector, the comprehensive measures implemented in Dortmund demonstrate that the development of cycling mobility requires both infrastructure and long-term educational and organisational measures aimed at changing residents' travel behaviour. In Poland, these experiences could be applied particularly in cities where cycling infrastructure needs to be developed as a coherent transport system rather than as a collection of individual sections of cycle routes.

The experience of the Superblocks project in Barcelona confirms the considerable importance of changes in the organisation of urban space for reducing car use, improving air quality and increasing the availability of public space. Adapting this model in Poland should not involve directly replicating Barcelona's spatial layout, but rather applying its fundamental principles: restricting through traffic in residential areas, traffic calming, developing green spaces and increasing the share of walking, cycling and public transport.

The green transformation of Essen is an example of the long-term restructuring of a city and region previously strongly associated with industry and mining. Particularly

important is the broad scope of measures encompassing land revitalisation, water management, the development of green infrastructure, transport, and the creation of new economic functions and jobs. Essen's experience could be applied in Polish mining regions, particularly in Silesia, Eastern Wielkopolska and areas associated with lignite mining. The key lesson is the need to pursue transformation from a long-term perspective and to integrate energy-related changes with spatial, economic, environmental and social policies.

The Lavrion Technological and Cultural Park presents a model for adapting post-industrial infrastructure to new technological, scientific, educational and cultural functions. Particularly important in this case is cooperation between universities, businesses and public administration, as well as the use of existing buildings and infrastructure as a basis for developing new activities. In Poland, similar solutions could be implemented at closed or closing mines, power plants and industrial facilities, particularly in regions with strong academic and research centres.

Based on the analysis, one of the principal directions of green transition policy in Poland should be to strengthen regional and local planning. National climate and energy objectives should be translated into regional transition scenarios that take into account the structure of the energy system, resource availability, the condition of infrastructure

and the characteristics of the regional economy. The projects analysed demonstrate that successful initiatives are strongly embedded in local conditions and respond to the specific needs of individual regions.

A second direction should be the development of demonstration projects and real-world laboratories enabling new technologies, business models and regulatory solutions to be tested. The experience of WindNODE, Smart Rural Grid, REFLAU and energy storage projects indicates that demonstrating solutions under real operating conditions can reduce technological and regulatory risks before large-scale deployment. Pilot projects should, however, be accompanied by systems for monitoring results and transferring knowledge so that the experience gained can be utilised by other regions.

A third direction is the establishment of permanent organisational structures responsible for preparing and coordinating transition projects. The experience of regional projects demonstrates the importance of cooperation between public administration, businesses, infrastructure operators, research institutions and local communities. In Poland, this role could be performed by regional energy agencies, energy clusters and cooperatives, competence centres and partnerships focused on specific technologies or areas of the transition.

In conclusion, the projects analysed demonstrate considerable potential for adapting international experience to Polish conditions, although their applicability varies. Solutions related to district heating modernisation, the utilisation of mine water, the integration of renewable energy sources with energy storage, grid digitalisation, the development of biogas and biomethane, deep energy renovation of buildings, and the revitalisation of post-industrial areas have relatively high implementation potential. Hydrogen technologies require a more selective approach, geographical concentration and a close link between production and specific consumers.

The most important conclusion arising from the analysis is the need to move away from a sectoral and project-based approach to the transition towards integrated energy system and regional development planning. The adaptation of international experience should be preceded by technical, economic, environmental, social and institutional assessment, followed by adjustment of the proposed solution to the specific characteristics of the region concerned. Green transition policy in Poland should create stable conditions for long-term investment, support the development of infrastructure and expertise, and strengthen the capacity of regions to independently plan and implement transition processes.

The experience of all the initiatives analysed confirms that the success of the energy transition depends not only on the availability of technologies and financial resources. Equally important are the quality of planning, the capacity to integrate different sectors, regulatory stability, access to data, institutional capabilities, and cooperation between public administration, business, science and society. Under Polish conditions, the use of international experience should therefore lead to the development of Poland's own regionally differentiated transition models, reflecting local circumstances while simultaneously contributing to national energy, climate and economic objectives.

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