What's next after coal?

RES potential in Poland

Instrat Policy Paper 06/2021

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Spis treści

Abbreviations and definitions

ARE	Agencja Rynku Energii
CCGT	Combined Cycle Gas Turbine
CHP	Combined heat-and-power plant
E	Electricity
PSPP	Pumped storage power plant
GHG	Greenhouse gases
IND	Industrial generating units
CDGU	Centrally dispatched generating units (PL: JWCD)
EC	European Commission
NECP	National Energy and Climate Plan for the years 2021-2030 (PL: KPEiK)
NPS	National Power System (PL: KSE)
LDP	Local Development Plan (PL: MPZP)
EIA	Environmental Impact Assessment (PL: OOŚ)
RES	Renewable energy sources
PEP2040	Polish Energy Policy until 2040
PGE	Polska Grupa Energetyczna
PNPP	Polish Nuclear Power Program (PL: PPEJ)
TNDP	Transmission Network Development Plan for the years 2021-2030
PSE	Polskie Sieci Elektroenergetyczne
PV	Photovoltaics
RED	Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, Renewable Energy Directive
SRMC	Short-Run Marginal Cost
EU	European Union

Summary and key recommendations

1. Despite restrictive spatial development, technical, economic and social conditions, Poland will be able to achieve the installed capacity level of 44 GW for onshore wind farms, 31 GW for offshore wind farms and 79 GW for rooftop and ground-mounted photovoltaic systems.

2. The RES potential in Poland is sufficient to reach the EU climatic goals by 2030, to almost fully decarbonize the power mix by 2040, and to gradually phase out coal combustion from the power sector in 2030s.

3. Current and historical trends indicate that the goal of 71% RES share in overall electricity generation may be reached by 2030, whereas the 32% PEP2040 value seems completely unrealistic and should be increased as part of the “Fit for 55” package implementation.

4. The PEP2040 scenario will lead to a rapid rise of energy production costs, by 61% between 2021 and 2030. The application of the RES development scenario proposed by Instrat may reduce the cost of energy generation by 31–50% in relation to PEP2040 in 2030, ultimately reducing the import by half of the 2020 value.

5. PEP2040 also assumes blocking of electricity imports, which on the EU energy market is not possible. Permitting energy import in PEP2040 would cause almost four-fold increase in its volume, from 13 TWh in 2020 to 48 TWh in 2030. In the PEP2040 scenario with energy imports allowed, by 2030 the share of coal in electricity generation would drop to 22% and the RES share would increase to 44%, which only confirms the ungrounded nature of the declared 32% RES share.

6. The Instrat scenario assumes a deep reduction of CO_2 emissions in the power sector thanks to RES development, in line with the EU’s GHG-55% targets. The scenario foresees a reduction of 65% compared to 2015 levels as well as more than double reduction of emissions by 2030 compared to values from the PEP2040 document, which is incompatible with the climate targets.

7. The proposed power structure allows safe balancing during yearly peak load, even under complete loss of wind and solar production or unavailability of cross-border power connections. Balancing based solely on national sources is possible in the PEP2040 scenario but only if the nuclear power plant is timely completed. In case of any delays in the PNPP, the Poland’s dependency on energy imports would deepen.

In the context of the ongoing negotiations of the "Fit for 55" package, the values presented in PEP2040 need to be urgently updated. The 70% RES share is achievable and the 32% PEP2040 value is completely unrealistic and it would require artificial blocking of energy imports, which is against EU laws. Further negation of the RES role in the power sector would result in a huge increase of energy generation costs that would seriously undermine the competitiveness of Polish economy.

To avoid this, it will be necessary to:

- *resume onshore wind farms development as soon as possible and permit the existing wind turbines upgrades,*
- *ensure timely construction of offshore wind farms,*
- *postpone the changes to the prosumer power sector settlement system, spreading them over time and ensuring that they do not interfere with the development of photovoltaic sector, which is indispensable for successful energy transition,*
- *create incentives for energy storage facilities development, also within the scope of RES auctions,*
- *adopt the "Polish Hydrogen Strategy" and establish ambitious targets for construction of electrolysers on the 10 GW level by 2040,*
- *plan construction of large-scale pumped storage power plants in brown coal mine excavations,*
- *adopt a responsible development program for biogas plants and biomethane plants,*
- *provide adequate financial support for network operators to rapidly increase the available connection capacity,*
- *phase out coal in combined heat and power plants and in industrial facilities by converting them to gas/hydrogen units,*
- *adapt the planned gas-fired power units (including in combined heat and power plants) to the green hydrogen combustion option,*
- *stabilize the energy law, ensuring a friendly regulatory environment for investors,*
- *declare shutdown dates of individual coal-fired power units, the date of complete departure from coal fuel, the climatic neutrality date, ambitious targets for the RES share in the overall energy consumption mix for 2030, so as to enable sourcing*

of funds for the energy transition, including, for example, the required network infrastructure upgrade and a fair transition process for coal-rich regions,

- *update the PEP2040 document to reflect current economic situation, the RES potential and market trends, while proposing a scenario consistent with the EU climate targets and taking into account the impact of high energy generation costs on energy imports.*

1. Introduction

This publication is the second one in the series of three studies showing that Poland can actively participate in decarbonization efforts of the European Union (EU) without jeopardizing national energy security, taking into account the current social and technological environment. Most importantly, participation in the energy transition will bring a number of benefits to the Polish economy and citizens. It will reduce the cost of energy generation, increasing the competitiveness of Polish companies and lowering electricity prices, limit energy imports, increase energy security, and finally open Poland to international investments and the related growth of green jobs.

In the first publication of the series, titled: *Achieving the goal. Coal phase-out in the Polish power sector* (Czyżak, Wrona, 2021), we proposed a phase-out scenario for coal-fired power plants and combined heat and power plants in Poland, and we evaluated options of their substitution with renewable energy sources (RES). We anticipate that by 2030, the RES share in the power mix may exceed 70%, and we think that the 32% value declared in the Polish Energy Policy until 2040 (PEP2040) is significantly understated, considering current market trends and economic conditions.

The Polish government's activities in the power sector, which are inconsistent with the EU policy, result from multiple factors, such as for example downplaying the potential of mature RES technologies. On the other hand, the estimates of the potential proposed by the European Commission (EC) and used in a number of studies, fail to consider certain key technical or social constraints. The disparity between the two approaches results in a low quality of government strategies and legislation work, destabilizes the investment environment and slows down RES development in Poland.

This publication complements the Achieving the goal report, by presenting a comprehensive diagnosis of the Polish RES potential. According to our knowledge, the calculations presented here are the most complex among the publicly available studies of Polish wind and solar potential. Our data may be used in energy modeling or to update assumptions of the PEP2040 document.

We supplement the analysis of the RES capacity potentials with a description of the legislative framework determining the RES role in the energy market, and with development forecasts of various technologies until 2040. Finally, using the PyPSA-PL energy model, we assess the impact of RES development on the National Power System (NPS), including the structure of energy generation, imports, average generation costs and CO_2 emissions of the power sector.

The results show that the RES implementation on a scale adequate to the EU climate targets would require decisive actions, but not a technological revolution or a development pace far beyond the levels already attainable in Poland. To protect the Polish energy market against catastrophic price and import increases, it will be necessary to abolish legislative barriers and acknowledge the RES role in the energy mix. It is crucial to adapt the Polish energy transition plans to the updated and now binding EU 55% GHG reduction target by 2030 compared to 1990 values. Achieving this target will require a quick deployment of RES technologies, up to twice the pace indicated in PEP2040. This is however perfectly achievable and brings additional benefits to the economy.

2. The impact of the regulatory environment on RES development in Poland

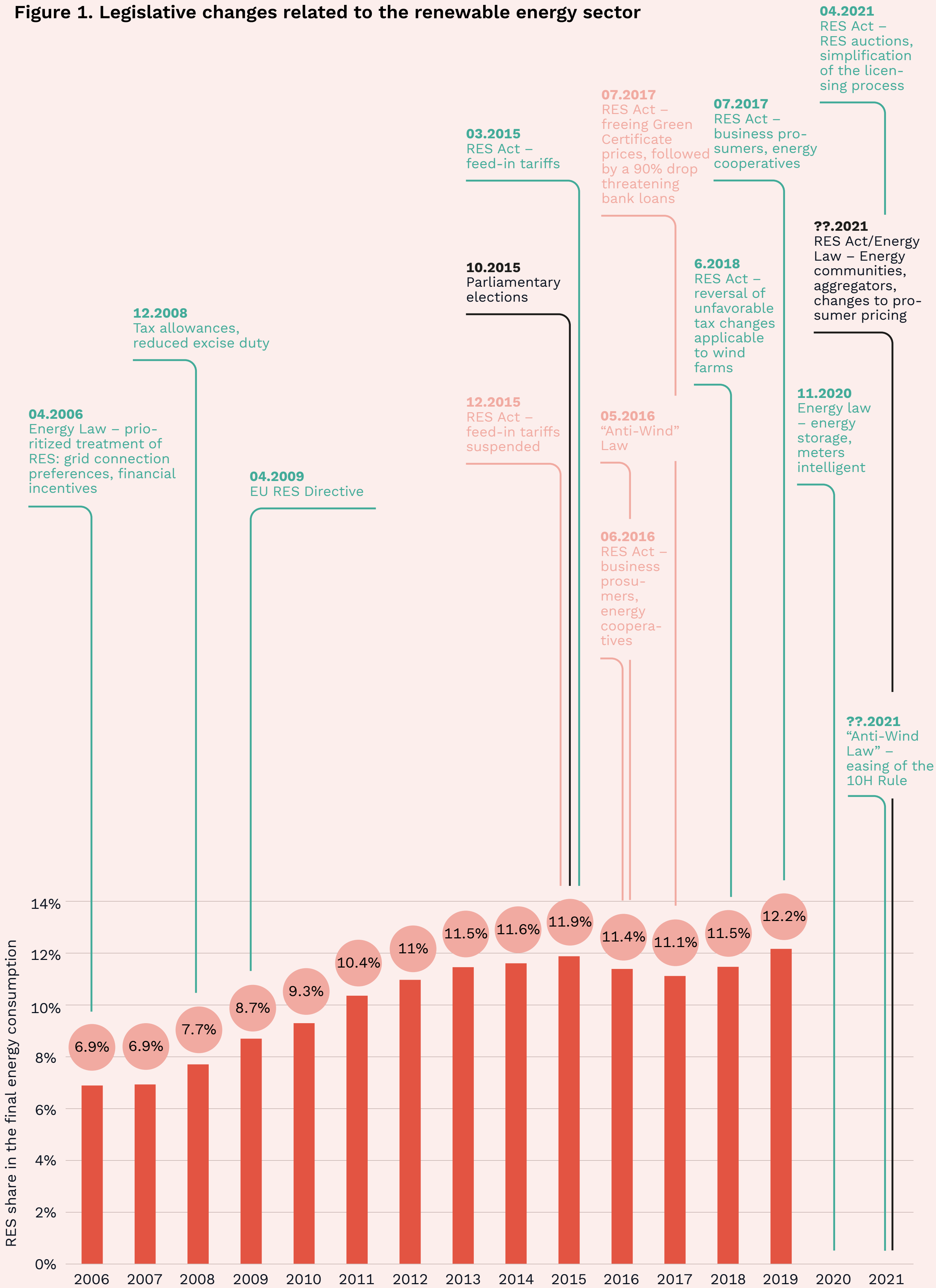
The target of reducing greenhouse gases (GHG) by 55% in 2030, compared to 1990, proposed by the European Commission in autumn 2020 was approved in April 2021 by the Member States of the European Union and the European Parliament, becoming legally binding also for Poland. This means that the Polish Energy Policy until 2040[1], adopted in February 2021, must be updated – at the moment, it envisages a reduction in greenhouse gas emissions only by approx. 30% – almost two times less than the expected EU average. The European Commission also estimates that the reduction of CO_2 emissions in the power sector alone should amount to approx. 70% in 2015-2030 (European Commission, 2020), in PEP2040 it is only 25%. Achieving the required level of emission reduction in the electricity sector requires a rapid pace of development of renewable energy sources. The share of renewable energy in electricity production in 2030 is expected to amount to 68% in the EU (European Commission, 2020), while in PEP2040 it is only 32%. As shown in this publication, it is possible to achieve the share of RES in Polish electricity generation at a level of over 70%, leading to a reduction of emissions in the sector by 65%, i.e. only slightly below the value required for the entire EU.

Utilizing the potential of renewable energy sources and their development in line with the EU climate goals requires the removal of legislative barriers, which are one of the key factors determining the pace of RES implementation in Poland. Frequent changes of legal acts governing the RES sector make long-term planning difficult. Some of these changes may even block the whole sector altogether. Stable laws and the implementation of the European RES Directive[2] (“RED”) between 2006 and 2015 contributed to a systematic growth of the RES share in the final energy consumption (Fig. 1), which was one of the three RED targets for 2020. Poland declared to reach a 15% RES share by 2020 and between 2006 and 2015 it did grow from 6.9% to 11.9%. Unfortunately, a number of unfavorable regulatory shifts implemented following the autumn of 2015, halted the RES development and even reduced the RES share in the overall energy consumption. Only in 2019, the RES share recovered to 2015 levels. The chances for reaching 15% by 2020 were extremely low, even considering the reduced energy demand due to the COVID-19 pandemic.

1 Announcement of the Ministry of Climate and Environment from 2 march 2021 about the introduction of the Polish Energy Policy until 2040 [PL: Obwieszczenie Ministra Klimatu i Środowiska z dnia 2 marca 2021 r. w sprawie polityki energetycznej państwa do 2040 r.]

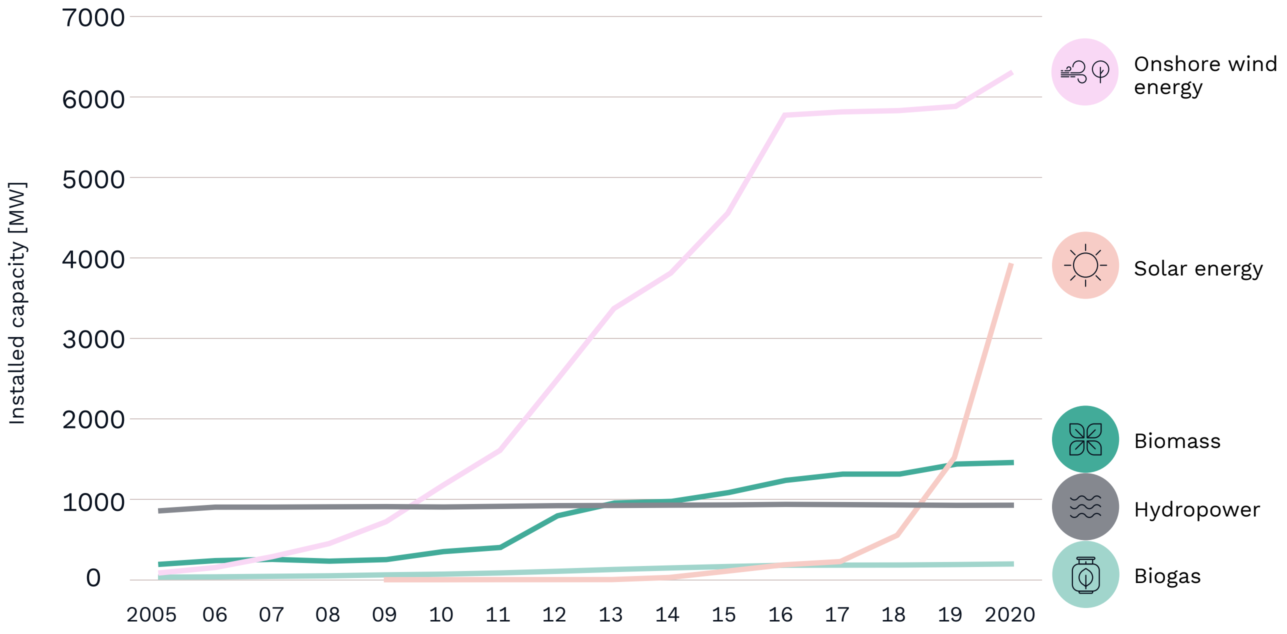
2 The Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, 2009/28/EC, dated 23.04.2009

Figure 1. Legislative changes related to the renewable energy sector



Source: Instrat's internal analysis

Figure 2. RES installed capacity between 2005 and 2020



Source: Internal analysis based on the Energy Regulatory Office (ERO) and ARE data

Another worthy factor is the instability of the law. Since 2015, the RES Act was amended on multiple occasions, and a number of changes were also introduced to the Energy Law Act (Fig. 1). As the duration of an average RES investment is between 20 and 30 years, such large regulatory instability poses a huge risk for investors.

The volatility of the law and its unfavorable modifications stopped the installed capacity growth in onshore wind power sector, which was very prominent between 2005 and 2016 (Fig. 2). At the same time, other RES technologies were also blocked, through the amendments to the Act on Renewable Energy Sources of 2015[3] and 2016,[4] which initially postponed the introduction of the guaranteed feed-in tariffs for RES prosumers and then rolled them back altogether. In 2016, the so-called "Anti-Wind Law" was also adopted[5]. It introduced unrealistic spatial development requirements for wind systems, which put many projects to a halt.

3 Act of December 29, 2015 amending the Act on Renewable Energy Sources and the Energy Law Act, Journal of Laws of 2015, item 2365

4 Act of June 22, 2016 amending the Act on Renewable Energy Sources and certain other acts, Journal of Laws of 2016, item 925

5 Act of May 20, 2016 on investment in wind turbines, Journal of Laws of 2016, item 961

Some positive changes were initiated in 2018. Under the amendment to the RES Act of 2019,[6] companies were allowed to apply for a prosumer status, energy cooperatives were introduced and new RES auctions were announced. The introduction of the "My electricity" program, which guaranteed direct funding of o household photovoltaic micro-systems, also played a role. Thanks to the program, the installed capacity in the photovoltaic sector grew from below 1 GW in 2018 to 4.5 GW currently (energy.instrat.pl, 2021). After long delays, in January 2021, the "Offshore Act"[7] was passed, enabling the development of wind power in the Baltic Sea, where the installed capacity is expected to reach 5.9 GW by 2030 and 9.6 GW in 2040. In April 2021, another amendment to the RES Act (MKiŚ, 2021) was adopted, which extended the maximum deadlines for RES generating entities to apply for public funding, thus effectively extending until June 30, 2047 the maximum term for obtaining the support for the systems under the so-called FIT and FIP systems. The RES auction system system was also extended until 2027.[8] It also introduced provisions reducing licensing obligations in the case of small RES systems for enterprises carrying on economic activities, which further motivated entrepreneurs to invest in renewable technologies.

Unfortunately, the legislative solutions from the 2015–2017 period delayed RES development by several years, which will be difficult to make up. This means that the 2020 climate targets have not been achieved, and it also threatens the 2030 targets. To achieve them, a significant acceleration of the RES development, in line with the Instrat's scenario presented in the report, would be required.

In this chapter we look at regulations and support mechanisms currently in place, which are the most important from the RES development perspective.

2.1. The 10H Rule

Between 2005 and 2016 the onshore wind sector witnessed a dynamic growth of its installed capacity. However, this growth slowed down after 2016. (Fig. 2.) due to introduction of the so-called 10H rule in the so-called "Anti-Wind Energy Law"[9]. The 10H rule prevented new wind turbines from being erected within the radius of 10 times their height from residential buildings, certain forms of nature protection and forest complexes. The 10H rule also prevented upgrades of existing wind turbines that failed to meet

6 Act of July 19, 2019 amending the Act on Renewable Energy Sources and certain other acts, Journal of Laws of 2019, item 1524

7 Act of December 17, 2020 on promoting electricity generation in offshore wind farms (Journal of Laws of February 3, 2021, item 234)

8 However, these changes are subject to the European Commission's approval for public aid.

9 Act of May 20, 2016 on investment in wind turbines, Journal of Laws of 2016, item 961

the distance requirement. This stopped many projects and caused gross losses of almost PLN 3 billion to 70% of wind farms operating in Poland in 2016 (WysokieNapięcie, 2017).

In the effect of the 10H rule, Polish regulations on wind turbines location distances are currently one of the most stringent in Europe. The only other Member State with such restrictive approach is Germany, where a similar rule is in force, yet only in the Bavaria region. In the majority of EU countries, the distance regulations are only recommendations. The most frequent limit is 500 meters from residential development (applicable in France, Greece, Spain, Ireland and in Italy). Belgium and Denmark use the 4 times the wind turbine height limit. Another frequent practice is to perform acoustic forecasts and to base decisions concerning the possibility of the project implementation on their results (this approach is used in UK and in the Nordic countries).

The new draft amendment to the Act on investments in wind turbines being currently discussed, to[10] some extent resembles the approach assumed by other EU countries. Although it assumes that the 10H rule would be preserved, also permits reduction of minimal distances in the Local Development Plans (LDP) to values specified in the Environmental Impact Assessment (EIA), with the minimum distance of 500 m.Communes without Local Development Plans would have to adopt them in the process of intense public consultations. A new solution is to include so-called nearby communes in this decision-making process. This means communes located wholly or partially within the area resulting from the 10H rule. Therefore, the Local Development Plans will have to be consulted also outside the commune contemplating a wind farm project, but potentially in neighboring communes as well. Moreover, if the range of the project impact established in the Environmental Impact Assessment includes nearby communes, these communes would also have to draft their local development plans. Finally, the amendment postulates for establishing of a system for certification and verification of wind farms servicing companies.

The minimum distance of the wind turbine from forms of nature protection will be abolished. The decisions in this respect are to be made solely on the basis of environmental impact assessments and resolved in Local Development Plans and in the procedures for issuing environmental decisions for the respective project by the Regional Director for Environmental Protection (RDOŚ). As we pointed out in our publication of May 2021, the fact that there is no minimum requirement regarding the distance from certain forms of nature protection is raising some ecological concerns while having limited impact on the wind turbines potential (Czyżak, Sikorski, Wrona, 2021).Therefore it is recommended to leave the minimum 500 m distance limit, as for residential buildings.

10 Draft Act amending the Act on investments in wind turbines and certain other acts, of April 27, 2021, UD207

The proposed amendment to the 10H rule is unquestionably a step in a good direction and a chance for unlocking wind power investments necessary for decarbonization of the Polish power sector, for ensuring energy security and for achieving the 2030 climate targets. However, the increased administrative burden raises concerns that the pace of projects development may be too slow for achieving a CO_2 emission reduction consistent with the EU's GHG-55% target (Czyżak, Sikorski, Wrona, 2021). It is therefore recommended to simplify procedures and to speed up investment processes, naturally, while respecting the rights of local communities. The amendments proposed by Instrat to the draft regulation include, among others:

- **Elimination of the requirement for nearby communes to draft their local development plans;**
- **Reduction of the number of public consultations from 4 to 1 or 2;**
- **Speed up of responses, announcements, presentations, etc. in the commune in question and in communes nearby;**
- **Proposal of a simplified environmental decision procedure.**

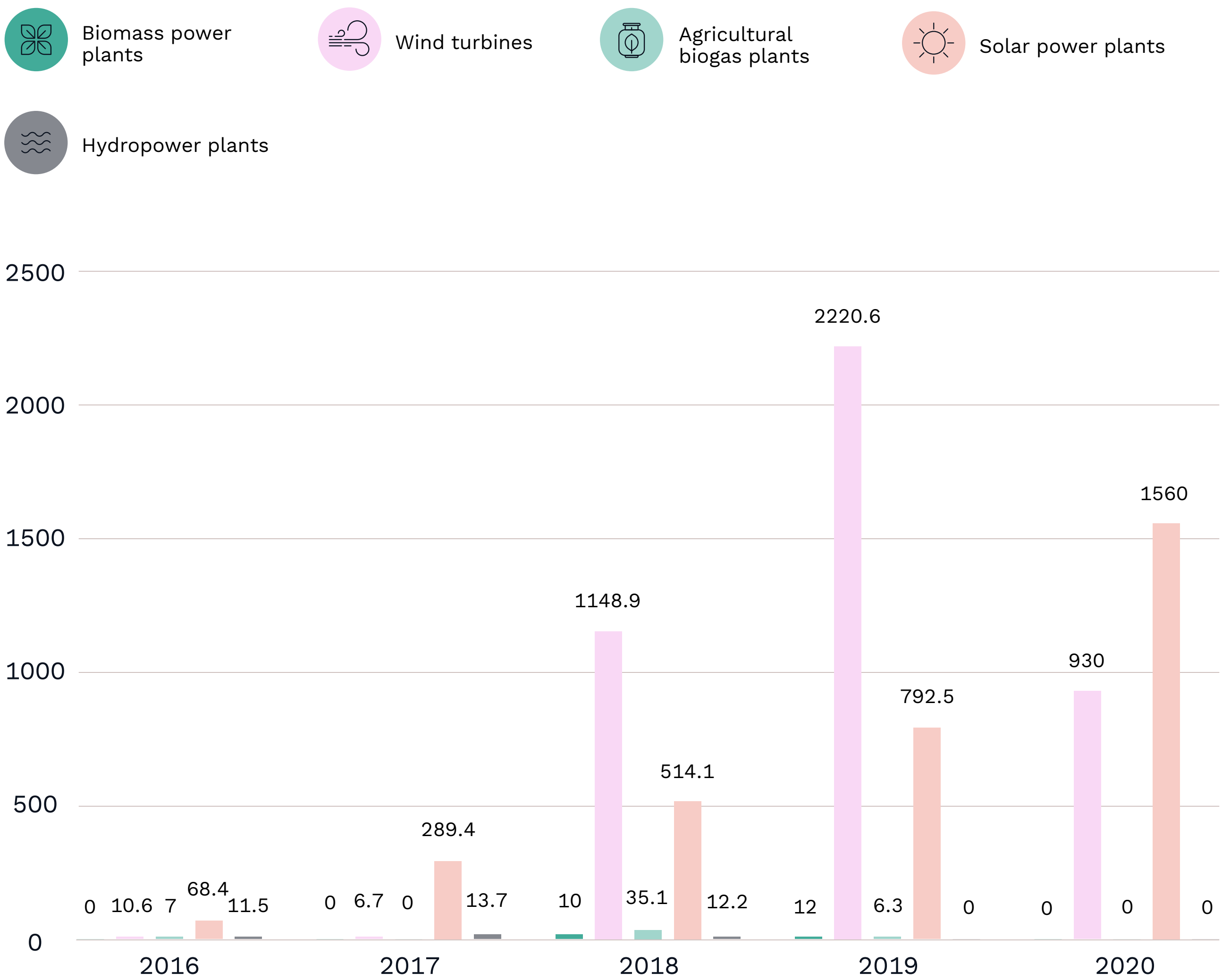
2.2. RES auctions

The auction system is the primary supporting tool for large RES systems in Poland. The first RES auctions took place in December 2016, replacing the green certificate mechanism that was used by then.[11,12] The largest beneficiaries of the auction system were the onshore wind and solar energy generating entities. These were the technologies which reported dynamic growth in the contracted capacity (Fig. 3). In result of the 2016 auction, 97.5 MW of capacity was added. In 2018 the total grew to over 1.7 GW, mainly due to increased output from onshore wind farms, plus further 3 GW in 2019. In 2020, the contracted capacity dropped, but it is still expected that auctions will lead to creation of PV systems yielding more than 1.56 GW and new wind farms producing 0.93 GW (with approx. 4 MW of power in other RES technologies) (ERO, 2020). In 2020, for the first time ever, the number of bids from PV systems in the large systems segment leveled with bids from wind farms and the PV contracted capacity exceeded that from the wind generation.

11 Act of February 20, 2015 on renewable energy sources

12 Back in 2016 and 2017 the winners of the action were determined solely on the lowest offered price basis. However, the 2018 amendment introduced additional competitiveness requirement, under which the winning bidders would be selected not only on the lowest price basis, but also with the consideration of the requirement that winning bids jointly should not exceed 100% of the power required in the auction notice nor 80% of the overall electricity of all bids submitted.

Figure 3. Total installed capacity of systems of generating entities producing energy from RES and winning auctions between 2016 and 2020



Source: Internal analysis based on the ERO data

Due to 10H rule, new wind farm projects were unable to participate in 2016 and 2017 auctions. Since 2018, projects that received building permits prior to introduction of the "Anti-Wind Law" were admitted to take part in the auction. However, the pool of these projects is being exhausted and it is now expected that the contracted capacity of wind power projects in 2021 auctions will be diminished. It will be substituted by increasingly more price-competitive large PV farms. In 2020, in the basket with large RES systems (over 1 MW), the price ranged between PLN 249.90/MWh and minimum PLN 190/MWh. This is more than in 2019, when sold energy prices ranged between maximum PLN 233.29/MWh and minimum PLN 162.83/MWh. This in fact results from the reduced supply of more cost-effective wind projects. The situation is the opposite in small farms (below 1 MW) auctions, in case of which in 2020 prices dropped compared to 2019 levels (Hanas, 2020). Only PV energy generating entities took part in these auctions (ERO, 2020). 2021 auctions will be settled by the end of June at the latest.

It is worth to note the special situation of offshore wind farms. The first pool of projects (5.9 GW capacity) received public support under the “Offshore Act” for the period of 25 years. Further projects will be qualified for public support through competitive auction process. The first auction for offshore wind farms was scheduled for 2025 and the next one for 2027. The auction mechanism will be similar to that used in onshore solar and wind power sector. Due to the scale of the investments and related capital expenditures, it was assumed that the support period will be longer than for the other technologies, that is 25 years (ERO, 2021).

2.3. Prosumer power sector

Since the wind projects were blocked, it is the prosumer power sector, i.e. PV micro-systems (up to 50 kW) in single-family houses and in businesses (from 2018 onwards), used for electricity generation for own consumption, that has been the driving factor of RES development in Poland. PV micro-systems constitute approx. 77% of approx. 4.5 GW of the installed capacity in the solar power sector (IEO, 2021; energy.instrat.pl, 2021).

The development of PV micro-systems was strongly influenced by the “My electricity” program, which provided direct funding for households solar systems. So far (May 2021) more than 200 thousand households have benefited from the co-financing (National Fund for Environmental Protection and Water Management, 2021) and 1.15 GW of such systems have beeninstalled.

Currently prosumers are using the so-called discount system, with the National Power System used as a means of energy storage, sending the surplus energy generated (at 20% discount) e.g. on sunny days to the NPS and drawing the energy from it for example at night. The discount system allows prosumers to avoid distribution fees and to reduce energy costs when local production is low – e.g. in the winter season and at night. As on the date of this report writing, authorities are still consulting the draft amendment to the Energy Law[13], which will replace the discount system with another settlement mechanism less beneficial for prosumers. According to this draft, prosumers would be selling the surplus energy generated during the day at prices set by the Polish Power Exchange and during energy shortage periods they would be buying the energy – usually at significantly higher prices (WysokieNapięcie.pl, 2021a).

13 Draft Act amending the Energy Law and the Act on Renewable Energy Sources of April 30, 2021, UC74

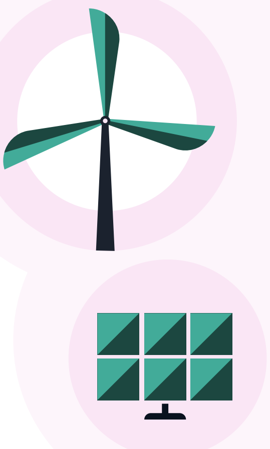
The proposed amendment abruptly reduces the profitability of PV micro--systems, forcing prosumers to incur additional costs related to local energy storage purchases[14]. Thus it is anticipated that the development of PV micro-systems will slow down, threatening the 2030 climate targets. In particular, the reduction of the PV systems development combined with the delayed roll-out of wind farm projects may freeze the RES installed capacity at the current, insufficient level, preventing the replacement of phased-out coal-fired power units (for more information see the *Achieving the goal* report):

It is worth noting that the proposed amendment raises a number of questions, also within the government itself. Therefore, it is not certain whether the changes will be ultimately implemented in their present form. However, legal volatility and increasing pressure from Distribution Network Operators and trading companies means that barriers for PV micro-systems development may increase in future.

14 These latter will receive additional support under the third installment of the "My electricity" program, which may slightly reduce the negative impact of the amendment.

3. Achievable installed capacity of individual RES types

The regulatory environment determines primarily the pace of the RES development. This chapter focuses on the maximum achievable RES installed capacity, disregarding somehow the issue of how fast these targets will be achieved. Although the preparation of energy transition scenarios for the power sector requires a prior thorough assessment of the renewable energy sources potential, the calculations of this potential tend to vary widely. Many studies use the estimates of the European Commission, produced under the ENSPRESO project (Ruiz Castello, 2019). However, these figures are not representative for the Polish technical, economic, social or legal environment. Therefore, we have developed our internal analysis of the Polish RES potential, based on the methodology used in current scientific literature and applying it for the first time to the specific challenges present in Poland. The description of the analytical process is included in subchapters dedicated to respective technologies.



The GLAES (Geospatial Land Availability for Energy Systems) software (Ryberg, Robinius & Stolten, 2017), implemented in the Python programming language and developed at the Institute for Energy and Climate Research (IEK-3) of the German Research Center Jülich was used to calculate the renewable energy potential in Poland, and in particular to assess the areas where it is possible to build wind or solar farms. GLAES is based on user-defined area exclusion criteria, including spatial factors (e.g. distance from forests, rivers and lakes, roads), social (distance from residential buildings), economic (windiness, insolation, distance from the connection point to the grid). Each pixel of the map of a given area (here: Poland) is verified in terms of selected criteria and considered available or unavailable for RES investments. The process of applying exclusions is described in the following sections. The final result of the program is a concrete proposal for the siting of new power plants, taking into account the selected criteria. According to the authors' knowledge, the presented study is the first such detailed analysis of the distribution of RES in Poland. The results take into account Polish legal and social conditions, the shape of the Polish transmission network and many other factors overlooked by pan-European research. This means that the presented values should be considered not only achievable, but even conservative – the development of technology and falling investment costs may open up additional areas for RES localization.

The results of the calculations are shown in Tab. 1. The detail level of the performed analyses lets us believe that the values presented are achievable in Polish conditions, and that the only barriers to their implementation are the political and legal constraints, which also determine the availability of funding (including the required upgrade of distribution and transmission networks).

Table 1. Potential installed capacity of respective technologies [GW]

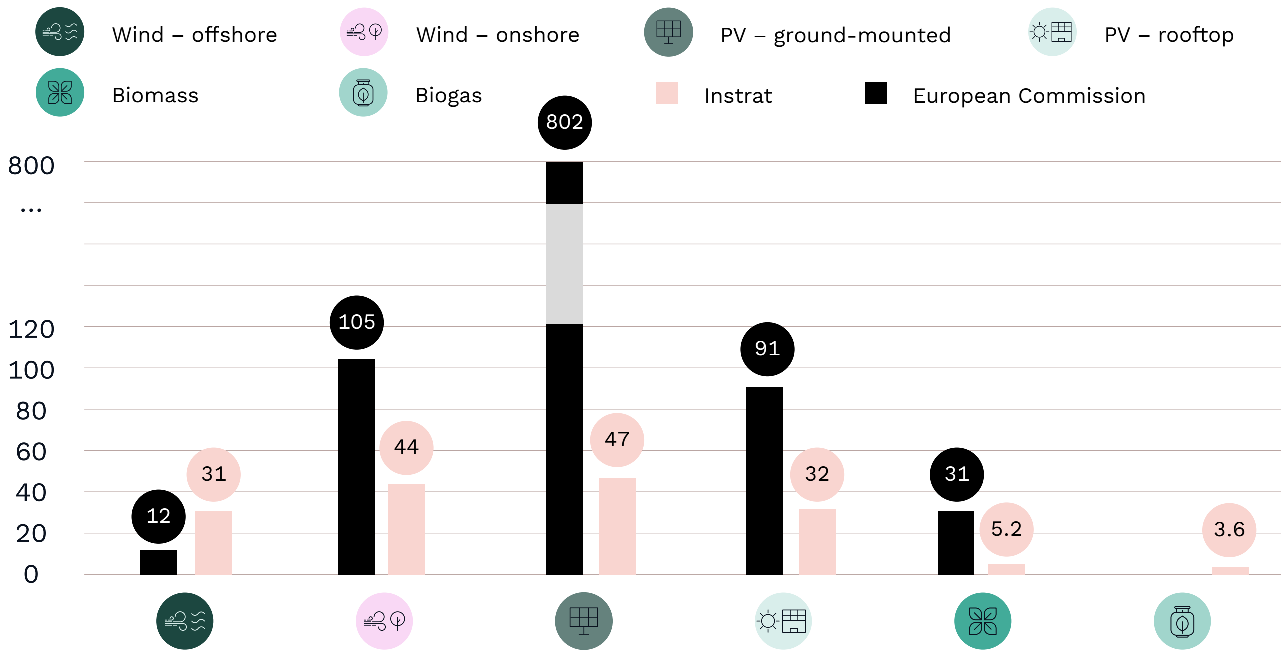
Technology	European Commission	Instrat
Wind – offshore	12	31
Wind – onshore	105	44
PV – ground-mounted	802	47
PV – rooftop	91	32
Biomass	31	5,2
Biogas	N/A	3,6

Source: Instrat's internal analysis based on own calculations and (Ruiz Castello, 2019); for wind and biomass the reference scenario, for PV the 170 MW/km2 scenario with 3% land availability

For almost all technologies, the results obtained by Instrat are significantly lower than the European Commission estimates (Tab. 1 and Fig. 4). Only offshore wind turbines with very low EC-estimated potential, i.e. amounting to just 12 GW compared to Instrat's 31 GW are the exception here. Considering all technical, environmental, social and economic factors, we estimate the total potential for onshore wind turbines at approx. 44 GW (including the upgrade of the existing turbines). The EC assessment is 2.5 times higher, which should be deemed unlikely, especially in terms of social acceptance. In large solar farms there is an even wider gap between the forecasts. According to our assessment, the potential installed capacity may reach 47 GW, whereas the EC estimates it at over 800 GW. The potential of the rooftop PV systems (on residential and non-residential buildings) is 32 GW according to Instrat's forecast, which is almost 3 times less than the EC's forecast. In the case of bioenergy, the potential should not be understood as Instrat's recommendation concerning its implementation. However, in our opinion, the technical potential is 5.2 GW and 3.6 GW for biomass and biogas respectively. In the ENSPRESO project, only the biomass potential was estimated, amounting to approx. 31 GW – that is 6 times more than in the Instrat figures.

The potential presented by Instrat was calculated while taking into account not only technical, but social and economic factors as well. Despite the fact that strict criteria were assumed, the achievable RES installed capacity is sufficient to meet the transformation scenario proposed in this report, and thus to achieve decarbonization rate compliant with the EU greenhouse gas emission reduction targets for 2030 and to ensure departure from coal in the power sector in the 2030s. Moreover, the available potential will allow for almost complete power mix decarbonization by 2040.

Figure 4. Comparison of the RES potential in Poland according to Instrat and European Commission estimates [in GW]



Source: Instrat's internal analysis based on own calculations and (Ruiz Castello, 2019); for wind and biomass the reference scenario, for PV the 170 MW/km2 scenario with 3% land availability

Geothermal energy was excluded from the analysis and water energy constraints were also noted. In Polish conditions, geothermal energy applications focus almost exclusively on heat generation, with limited electricity generation options due to low temperatures of geothermal sources (or their large depths) and thus due to its limited profitability. On the other hand, hydropower (with the exception of pumped storage power plants) faces a number of ecological controversies and low production capabilities due to low river gradients and the increasing drought problems. Therefore, its installed capacity growth is not to be expected.

The following chapter focuses on the potential of the installed capacity while omitting the discussion of its development pace, which is described in Chapter 4.

3.1. Onshore wind energy

Between 2005 and 2016 the onshore wind power sector recorded a dynamic installed capacity growth – up to 6 GW of the installed capacity in 2016. However, the introduction of the so-called 10H rule stopped investment projects underway and rendered new wind power plants construction impossible, consequently threatening Poland's accomplishment of the EU's targets of 15% RES share in the final energy consumption mix in 2020 and the climate targets for 2030.

In response to huge social support for wind power in Poland (MKiŚ, 2021b) and the need to transform the Polish power system, a liberalization of the 10H rule is planned (BIP, 2021). At the time of writing of this report, the draft amendment to the 10H rule was in the public consultation stage, but its final form is still likely to change. Therefore, four scenarios discussing different possible forms of this amendment were developed for purposes of the wind power generation potential analysis in Poland:

- **The 10H rule**
  the act in its current form requires the distance to buildings and certain forms of nature protection to be a minimum of 1500 m for some older wind turbines, such as Vestas V90 and approx. 2000 m for new Vestas V150 wind turbines;

- **Environment protection**
  abolishment of the 10H rule limit for residential buildings and forms of nature protection, subject to the provisions of the Local Development Plan (LDP) and environmental decision (EIA), while maintaining a minimum threshold of 500 m from buildings and forms of nature protection

- **Liberalization**
  abolishment of the 10H rule for residential buildings and forms of nature protection subject to the LDP and EIA, while maintaining the minimum distance of 500 m from residential buildings. For forests and forms of nature protection, the minimum distance of 300 m is assumed, as implied by technical conditions, rather than by legislative ones.

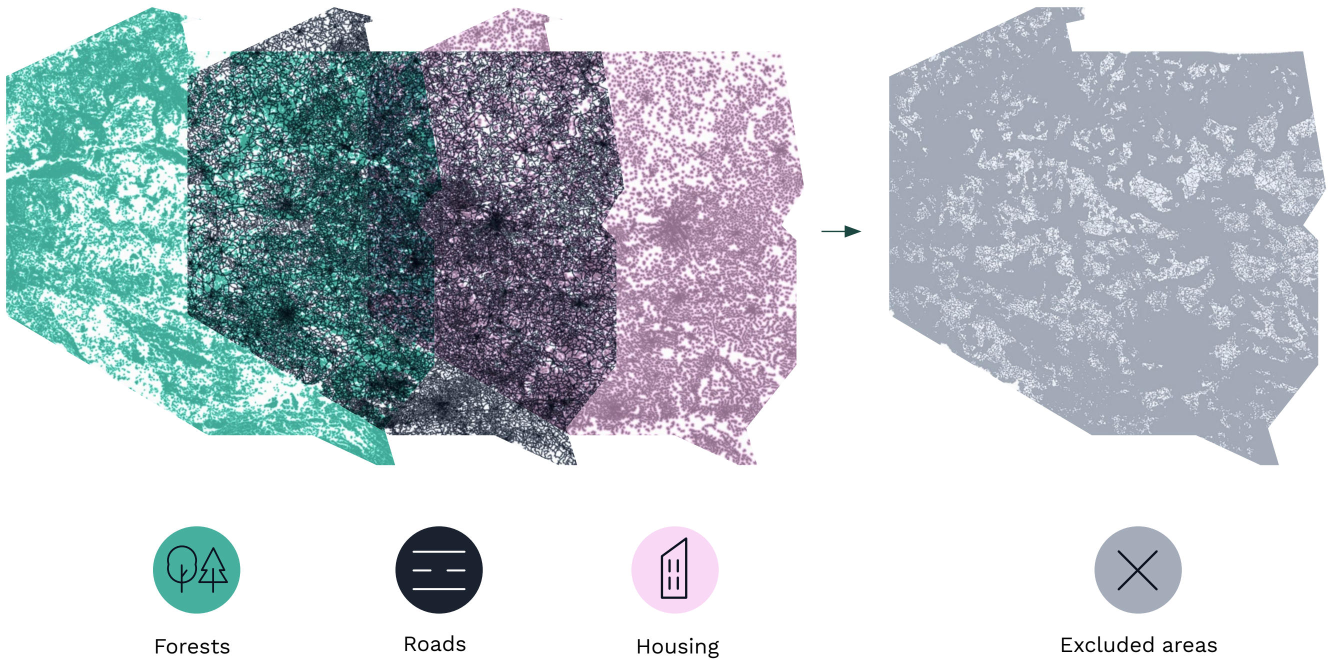
- **Maximum potential**
  abolishment of the 10H rule limit for residential buildings and forms of nature protection subject to the LDP and EIA, while maintaining the 500 m minimum distance from residential buildings only. Complete abolishment of the minimum distance requirement for forests and forms of nature protection – this should be considered as technically unfeasible, yet this scenario illustrates the maximum development potential.

As mentioned, the wind energy potential calculations were performed using the GLAES software (Ryberg, Robinius & Stolten, 2017). The process of applying consecutive exclusions on the territory of Poland is shown in Fig. 5. For each point on the map of Poland, criteria from Tab. 2 are validated one by one, thus eliminating individual areas from the list of potential wind farm locations.

Exclusions (Tab. 2) were matched to the examined scenarios, taking into account the potential legislation forms and basing on the scientific literature (Ryberg, 2017). The information needed for criteria evaluation were obtained from a number of spatial data sources:

- CLC (Copernicus Land Monitoring Service, 2012)
- EuroStat (GISCO, 2013)
- OSM (OpenStreetMap, 2012)
- EuroDEM (EEA, 2013)
- HydroLakes, WWF (GISCO, 2014)
- WDPA (UNEP-WCMC, 2016)
- GWA (DTU, 2021).

Figure 5. Illustration of the wind farm land evaluation process



Source: Instrat's internal analysis

Apart from the exclusions resulting from Tab. 2., also economic factors were taken into account when planning the new wind farm locations. The areas appropriate for investment projects must not only be outside exclusion zones, but also financially attractive – that is, they must ensure adequate energy production, dependent on wind conditions, and not require excessive expenditures on power grid connection.

The analysis also took into account the locations of the existing wind turbines (as of the end of 2020) assuming that new turbines could be built within the distance of min. 1500 m from the existing ones. Modern Vestas V150 turbines with the power output of 4.2 MW, adapted to moderate Polish wind conditions, were used in the model.

To determine the threshold of profitable wind conditions, the average wind speed all existing wind farms in Poland was examined. The average amounted to 7.47 m/s and this value was assumed in the model. It was also assumed that the new wind farms will be constructed within the maximum distance of 10 km from 110 kV lines, so as to keep connection costs at a level that does not threaten the profitability of the project[15]. The 1500 m distance between individual turbines was assumed (which is 10 times the diameter of Vestas V150 turbine). This is a conservative assumption and in real-life implementations, the distance may be significantly lower[16].

As the 10H rule loosening decisions are to be made by local authorities, the assessment of the socio-economic potential also included the results of wind energy social acceptance surveys conducted out by the Ministry of Climate and Environment (MKiŚ, 2021b). In these surveys, 75% of the respondents who live near existing wind turbines were supportive for continued investments in the wind energy sector. Therefore, it was assumed that the same percentage of communes would opt for the 10H rule loosening down to the assumed minimum distance from residential buildings of 500 m and therefore ultimately the potential value was rescaled accordingly.

15 For existing wind farms, the average distance from the 110 kV line is 2.5 km. In 98% of cases this distance does not exceed 10 km. However, due to the growth of the wind power industry, it should be assumed that the average distance will increase, and the 10 km is the value used in scientific literature (Ryberg, 2017).

16 For example, for the “Lotnisko” farm in Kopaniewo, the distance is approximately 5 times the turbine diameter

Table 2. Wind farm location criteria

Criterion	10H	Environmental protection	Liberalization	Maximum potential
Distance from buildings and structures	>2000 m	>500 m	>500 m	>500 m
Distance from forms of nature protection (national parks and landscape parks, reserves, Natura 2000 sites)	>2000 m	>500 m	>300 m	>0 m
Distance from forests not subject to protection	>300 m	>300 m	>300 m	>0 m
Distance from rivers and lakes			>300 m	
Distance from transport infrastructure (roads, railways)			>300 m	
Distance from high voltage lines			>250 m	
Distance from existing wind farms			>1500 m	
Distance from industrial facilities			>300 m	
Distance from airports			>5100 m	
Elevation			<1750 m a.s.l.	
Ground slope			<8.5 degrees	

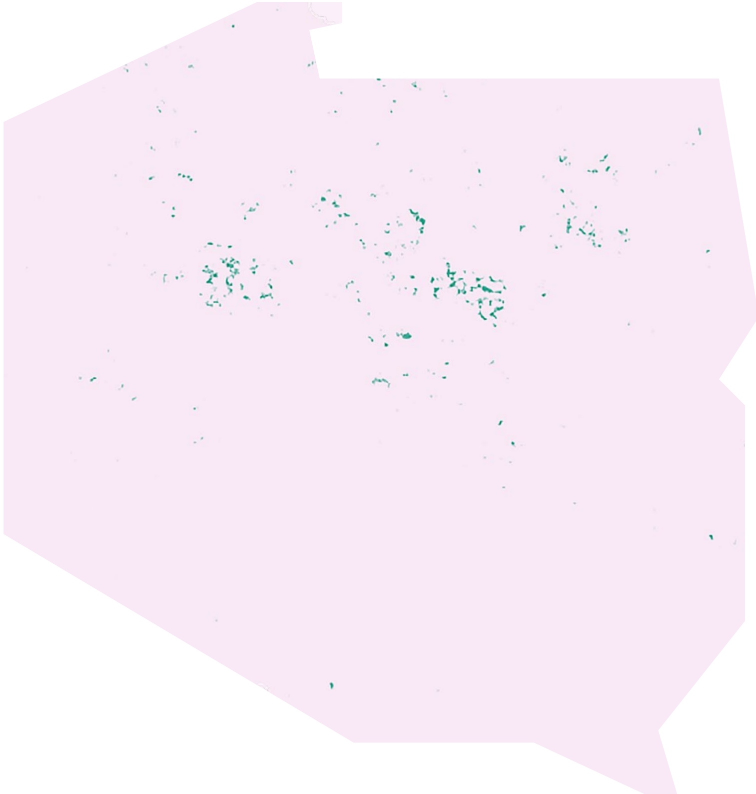
Source: Internal analysis based on our own calculations and (Ryberg, 2020; Ryberg, 2017)

Considering the criteria under the 10H rule, only 0.28% of the land in Poland is available for wind turbines (Fig. 6). Liberalization of the 10H rule, as suggested in the Environment protection scenario, would allow for the land availability to be increased to 7.08% – that is 25 times more. Importantly, many attractive areas in the northern part of the country would be unlocked, in particular in Pomorskie and Zachodniopomorskie voivodeships.

Figure 6. Availability of wind farm locations before and after the 10H rule liberalization

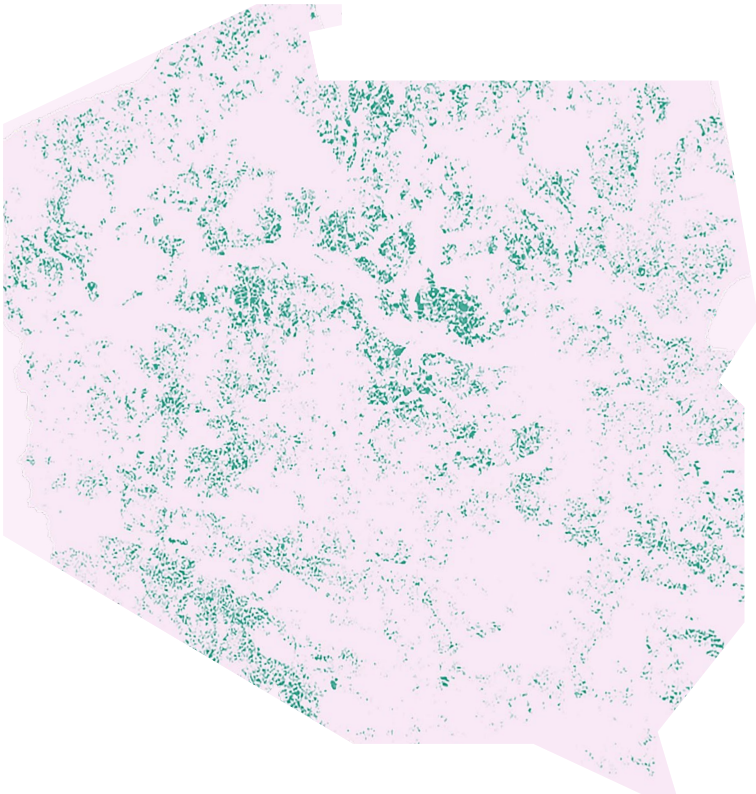
10H

Excluded: 99.72%
Available: 0.28%



Environment protection

Excluded: 92.92%
Available: 7.08%



Source: Instrat's internal analysis

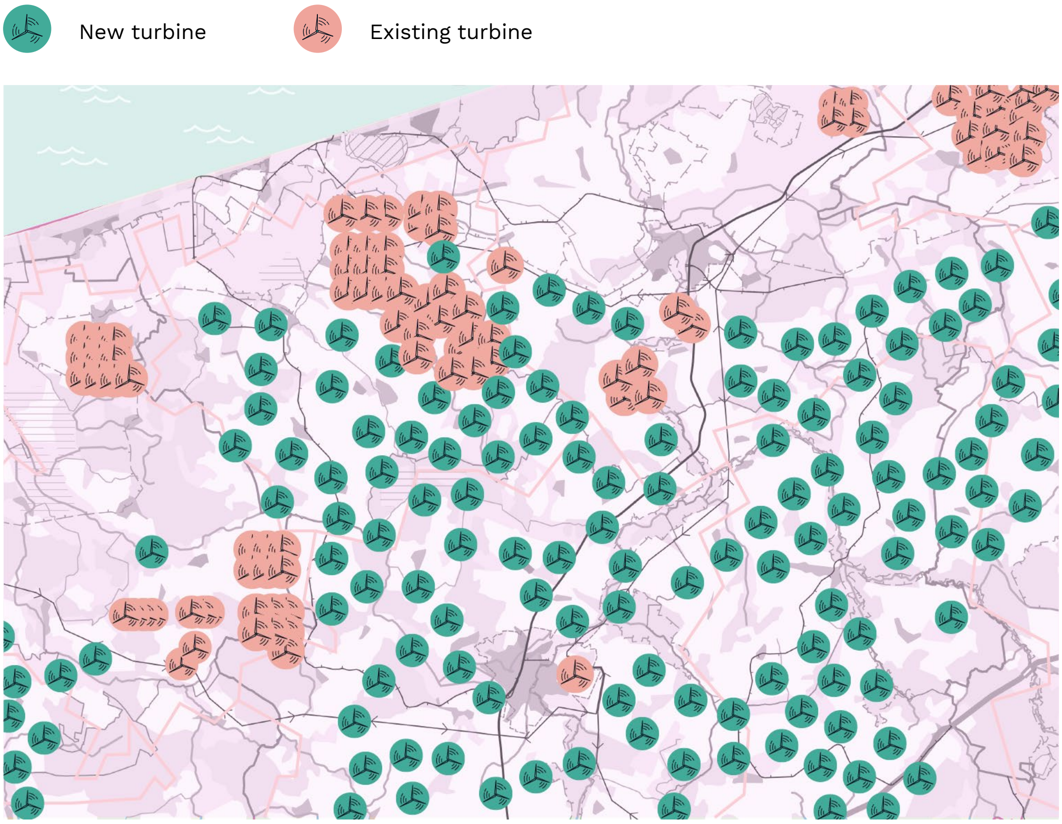
Considering the criteria under the 10H rule, only 0.28% of the land in Poland is available for wind turbines (Fig. 6). Liberalization of the 10H rule, as suggested in the *Environment protection* scenario, would allow for the land availability to be increased to 7.08% – that is 25 times more. Importantly, many attractive areas in the northern part of the country would be unlocked, in particular in Pomorskie and Zachodniopomorskie voivodeships.

In case of the *Liberalization* scenario, a reduction of the minimum distance from forms of nature protection to values resulting from technical considerations (300 m), leads to similar results.The land availability increased by only 0.33% compared to the Environment protection scenario (Tab. 3). Finally, the *Maximum potential* scenario increased the availability to 11.41%, but as mentioned in its description, the scenario should be considered unrealistic – for turbines with diameters of over 100 m, the minimum distance from forests would have be 200–300 m.

In the next step, economic conditions were imposed on the result of the land availability assessment, that is wind conditions and distances from transformer stations. These criteria allowed to determine locations in which wind turbines could achieve the level of profitability expected by investors. Adding these aspects into the equation lowered the land availability to only 365 km^2 for the 10H scenario. In the *Nature protection* and *Liberalization* scenarios, the area increased to approx. 5 thousand km^2.

In the last stage of the analysis, GLAES recommended wind turbine arrangement in economically viable and socially acceptable areas, while maintaining the assumed distances between turbines. Fig. 7 shows an example of such arrangement for a part of the Zachodniopomorskie voivodeship. New turbines are to be located outside developed areas, forests, lakes and rivers, infrastructural facilities, etc., in accordance with the presented exclusion criteria. Fig. 7 shows that the proposed arrangement of new turbines is significantly sparser than in the existing wind farms. This is caused by higher towers, larger rotor diameters and by the assumed distance between turbines of 10 times the rotor diameter. The distance may be reduced in order to group turbines together, e.g. closer to a shared transformer station, which means that the presented estimates should be considered as conservative.

Figure 7. Example of the wind turbine placement



Source: Instrat's internal analysis

The number of wind turbines translates into the total installed capacity. The model assumes Vestas V150 turbines with 4.2 MW rated power. In the 10H scenario, the availability of land is limiting the potential capacity of new turbines to 2.3 GW. Combined with the existing units (6447 MW as on January 2021), the capacity of onshore wind farms would amount to 8.7 GW – which is significantly below the values needed to achieve EU's 2030 climate targets. In the Environment protection scenario, the potential of new wind turbines is increased to 30.7 GW, whereas in the *Liberalization* scenario it reached 32 GW.

The last column of Tab. 3 shows the total achievable wind power in Poland, taking into account upgrades of the existing turbines, the potential of which was estimated at additional 6–7 GW following the liberalization of the 10H rule.[17] This means that ultimately wind turbine capacity in Poland could reach over 44 GW. At the same time, this is over two times less than the figures provided in the European Commission's forecasts, which should be considered unrealistic from the social, technical and economic perspectives.

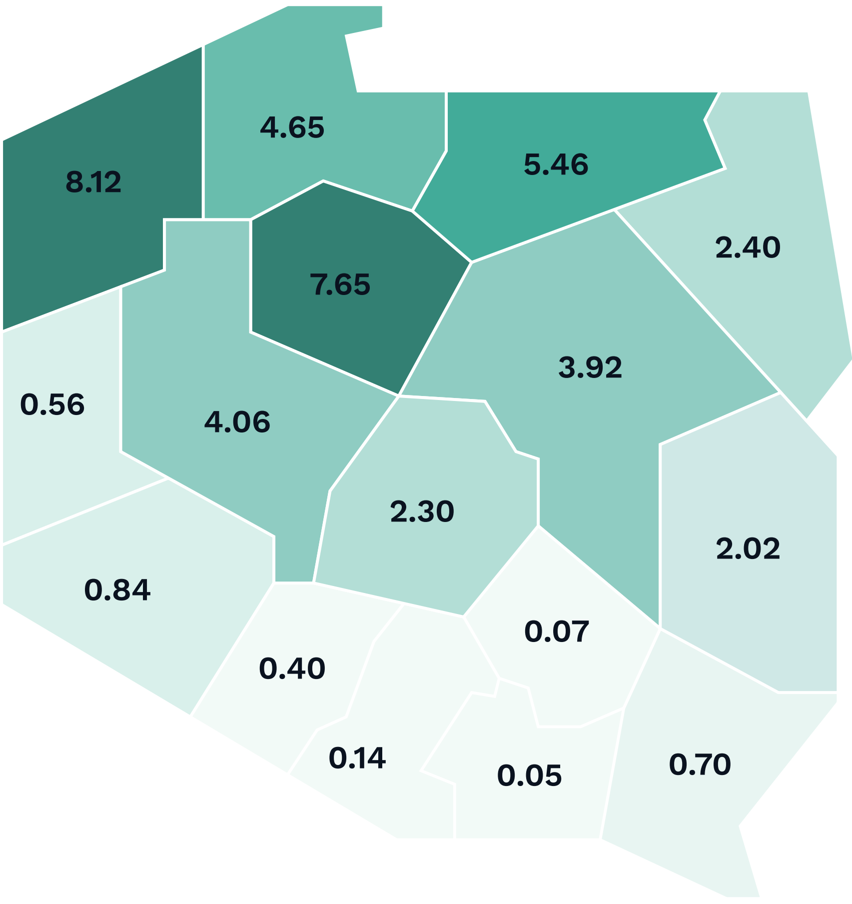
17 The issue of existing turbine upgrades is described in more detail in Chapter 4.

Table 3. Results of simulation of onshore wind turbine arrangement for various legislative solutions

Scenario	Excluded areas (%)	Investment areas (km^2)	Socio--economic potential (#)	Socio--economic potential (GW)	Installed capacity new + upgrades (GW)
10H	99.7%	375	543	2.3	8.7
Environment protection	92.9%	4831	7298	30.7	44.2
Liberalization	92.6%	5042	7619	32.0	45.5
Maximum potential	88.6%	6871	9683	40.7	54.2

Source: Instrat's internal analysis; capacity of the existing wind turbines: ARE data, for energy.instrat.pl

Figure 8. Installed capacity of wind farms by voivodeship



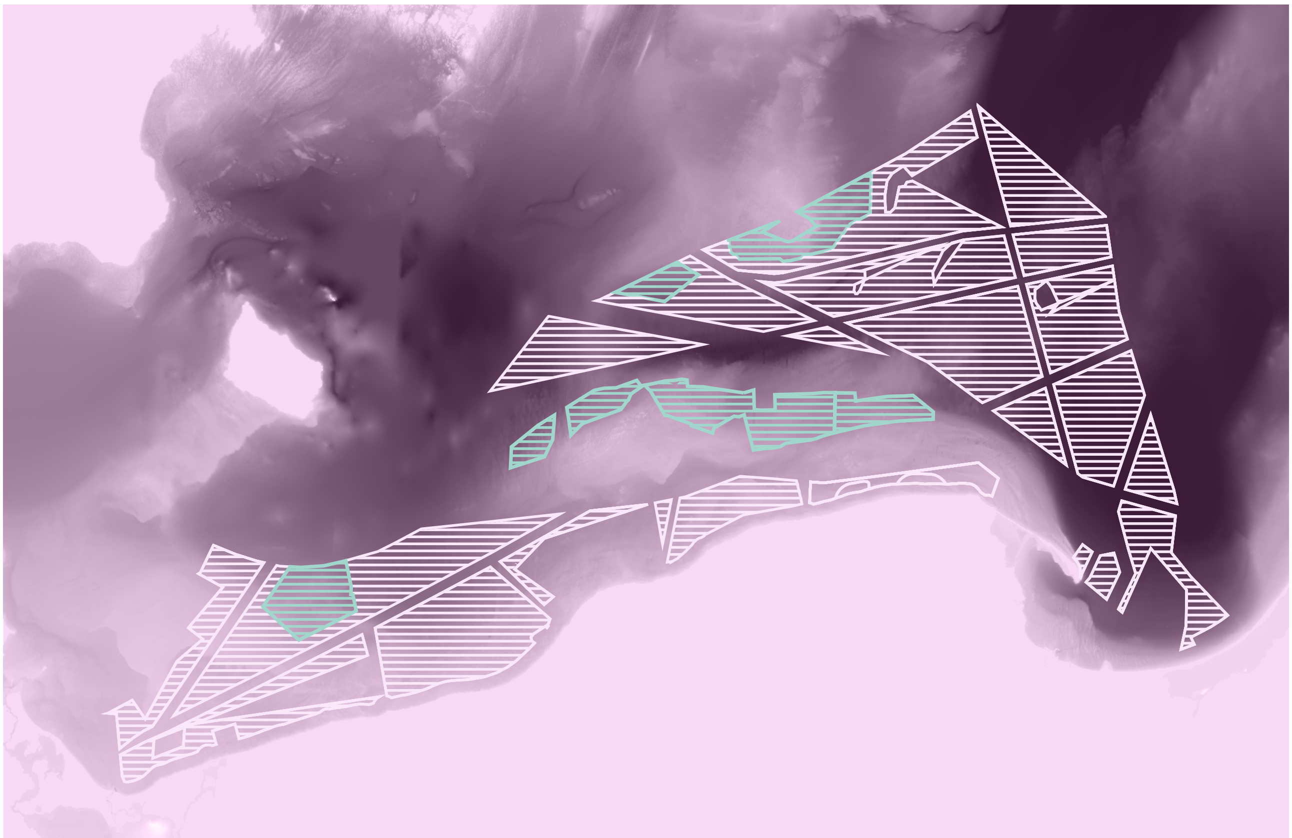
Source: Instrat's internal analysis

The onshore wind turbine potential concentrates in the northern part of Poland, namely in Zachodniopomorskie, Kujawsko-Pomorskie, Pomorskie and Warmińsko-Mazurskie voivodeships (Fig. 8)[18]. In the southern part of the country the potential is close to zero, also in voivodeships with very high power consumption, such as Silesian, Małopolskie or Dolnośląskie voivodeships. This poses challenges to local system balancing and to long-distance energy transmissions.

3.2. Offshore wind farms

Offshore wind farms are among governmental energy policy priorities. PEP2040 foresees the commissioning of 5.9 GW in offshore wind farms by 2030 and 9.6 GW by 2040. However, the offshore energy development potential is even higher. In this analysis, we calculated the maximum in vestment potential for offshore systems taking into consideration technical conditions.

Figure 9. Map of sea basins against the seabed depth map



Source: Internal analysis based on (EMODnet, 2021) data and on the Internal Marine Waters, Territorial Sea and Exclusive Economic Zone Spatial Development Plan.

18 The figure shows the total potential of new turbines and the potential resulting from existing wind turbine upgrades.

As the basis for our calculations in GLAES, we used the area of Polish territorial sea and the exclusive economic zone, amounting to approx. 28.5 thousand km^2. Since the main technical factor determining the location options for offshore wind turbines is the seabed depth (Fig. 9)[19], the calculations excluded waters more than 50 meters deep. This narrowed down the space available for offshore wind energy development to approx. 14 thousand km^2. Then, using data from the SIPAM resources (SIPAM, 2021), Natura 2000 sites were excluded from further calculations. This reduced the available investment area to approx. 8.2 thousand km^2.

Legal constraints are another factor determining the investment feasibility. According to the Internal Marine Waters, Territorial Sea and Exclusive Economic Zone Spatial Development Plan[20], the construction of offshore wind turbines will be possible only in those water regions, whose primary function is renewable energy production (i.e. ones marked "E") and on those assigned as the future development reserve (marked "P" and "PW"). As of today, there are 7 areas in the E class and 24 areas in "P" and "PW" classes (Fig. 9). The Offshore Act specifies precise coordinates of maritime areas intended for E-class water region wind projects. The E-class water regions themselves occupy approx. 2.3 thousand km^2 and are divided into 21 smaller areas[21]. Preparatory works are under way on seven of these areas with the total reported capacity of approx. 8.4 GW (Energy.instrat.pl, 2021). However, assuming a similar average density of the installed capacity as in projects being currently planned under the Offshore Act, that is 8 MW km^2, it can be assumed that another 9.5 GW of capacity can be installed in other E-class areas. In total, this would translate to a potential of 17.5 GW in areas already designated and subject to the Offshore Act.

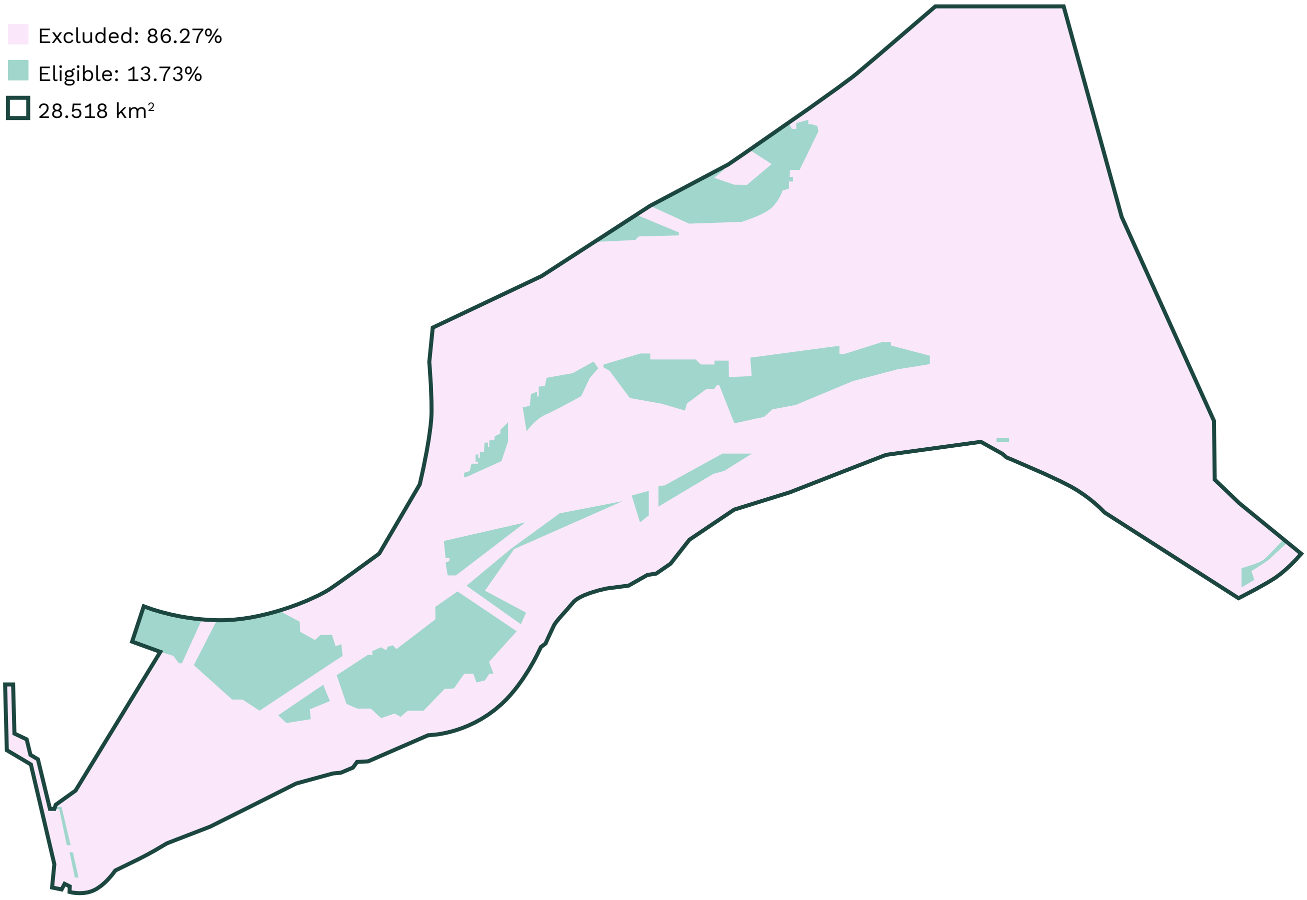
The planned expansion of investments with "P" and "PW"-class water regions will contribute to continued growth of offshore wind farms capacity. The surface area of all water regions compatible with the required conditions (including "P" and "PW"-class water regions) is approx. 3.9 thousand km^2 (Fig. 10). With the average 8 MW/km^2 capacity density, this gives the potential of 31.2 GW. This figure is approximately two and half times higher than the value estimated by the EC (Tab. 1), but quite close to estimates of the Polish Wind Energy Association – 28 GW (PWEA, 2020). It should be noted that in reserve areas, structures permanently connected with the seabed cannot be erected and that this may significantly affect the economic profitability of wind projects in these locations.

19 The bathymetric map from the EMODnet# project was also used in this study.

20 Ordinance of the Council of Ministers of April 14, 2021 on the adoption of the internal marine water, territorial sea and the exclusive economic zone spatial development plan at a scale of 1:200,000 (Journal of Laws of 2021, item 935)

21 Act on promoting electricity generation in offshore wind farms (Journal of Laws of 2021, item 234)

Figure 10. Map of areas available for offshore wind energy projects



Source: Instrat's internal analysis

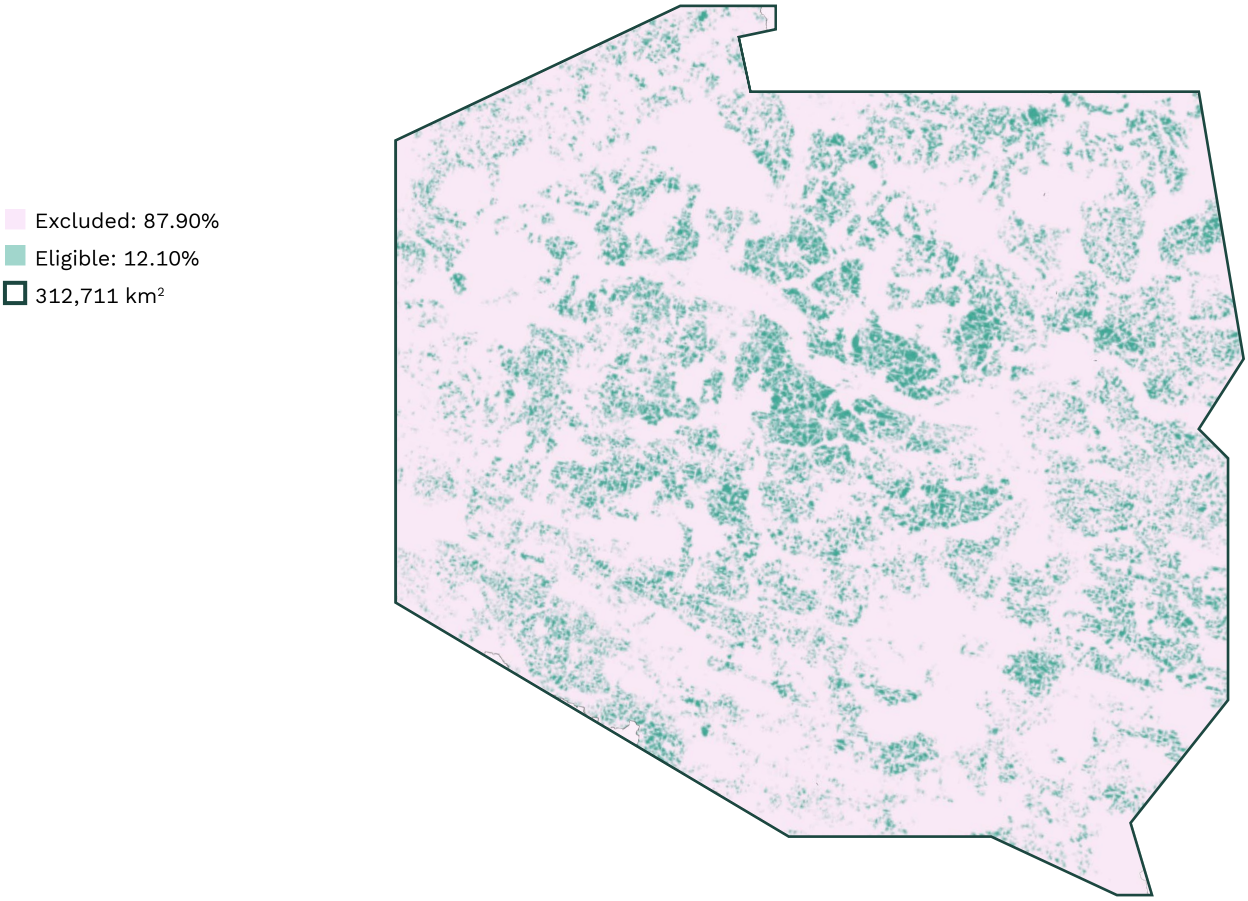
3.3. Large solar power plants

Currently, prosumer PV micro-systems are predominant in Poland. This is also due to the introduction of the "My electricity" program. However, the share of large power plants in the overall solar capacity is expected to grow in future. Until now the potential of ground-mounted PV systems in Poland has not yet been fully estimated and the commonly used forecasts of the European Commission (of over 800 GW) are largely unrealistic. Investors have already been reporting that finding land suitable for large solar power plants is not a trivial task.

As in the case of the assessment of wind energy potential, the estimates of the solar power plants potential were made using GLAES software. In the first phase, the size of the areas meeting the basic location criteria (e.g. distance from forests, rivers and lakes, roads) and social criteria (distance from residential buildings) was determined. This yielded the base area (Fig. 11), which was then subjected to more refined analyses.

The baseline exclusions were sourced from the current scientific literature (Tab. 4) and should be treated as conservative minima. In reality, PV farms can be constructed closer to, e.g. buildings, forests, etc., but this could lead to technical difficulties and cause public resistance.

Figure 11. PV farms location availability after basic exclusions



Source: Instrat's internal analysis

When planning ground-mounted solar power plants, there are additional factors which have to be taken into account to determine the legal and economic feasibility of projects. These are:

- **Arable land class determining the possibility of its use for non-agricultural purposes,**
- **Provisions of the Local Development Plan (if existing),**
- **Presence of forms of environmental protection on the land,**
- **Shading,**
- **Plot area and shape,**
- **Distance from the connection points (in case of small farms it may be up to several hundred meters from the medium voltage line, and up to several kilometers to a high voltage line in case of large farms),**
- **No risk of flooding, no wetlands,**
- **Legal status of the real property.**

The model uses selected factors from the above list to determine the potential of solar farms in Poland.

There are 8 soil classes distinguished in Poland (I, II, IIIa, IIIb, IVa, IVb, V, VI)[22]. According to the provisions of the law currently in force, the use of category I-IIIb soils for non-agricultural and non-forestry purposes (which includes solar panels) requires the consent of the Minister competent for rural development. This obligation does not apply to category IV-VI soils, where for farmland conversion only a relevant entry in the Local Development Plan or a decision on land development conditions is required[23].

22 Ordinance of the Council of Ministers of September 12, 2012 on soil classification (Journal of Laws of 2012, item 1246)

23 Act of February 3, 1995 on the protection of agricultural and forest lands. (Journal of Laws of 1995 No. 16, item 78)

Table 4. Basic selection criteria for ground-mounted PV system locations

Criterion	Distance
Distance from buildings and structures	>500m
Distance from forms of nature protection (national parks and landscape parks, reserves, Natura 2000 sites)	>300m
Distance from forests not subject to protection	>300m
Distance from rivers and lakes	>300m
Distance from transport infrastructure (roads, railways)	>300m
Distance from high voltage lines	>250m
Distance from industrial facilities	>300m
Distance from airports	>5100m
Elevation	<1750 m a.s.l.
Ground slope	<20 degrees
Slope in the northern direction	<5 degrees

Source: Internal analysis based on own calculations and (Ryberg, 2020; Ryberg, 2017)

Based on the map of soil agricultural suitability complexes containing 17 subtypes of soils (IUNG, 2021) (Fig. 12), a map of soil valuation classes was prepared, which was used as the basis in the exclusion process (Tab. 5). The applied criteria reduced the space available for projects 2.5 times to 4.55%. (approx. 14.2 thousand km^2). It is worth noting that the majority of the qualifying land in Poland does not have any established Local Development Plans, but if there is such a plan for the given real property, the plan must provide for solar power plants construction.

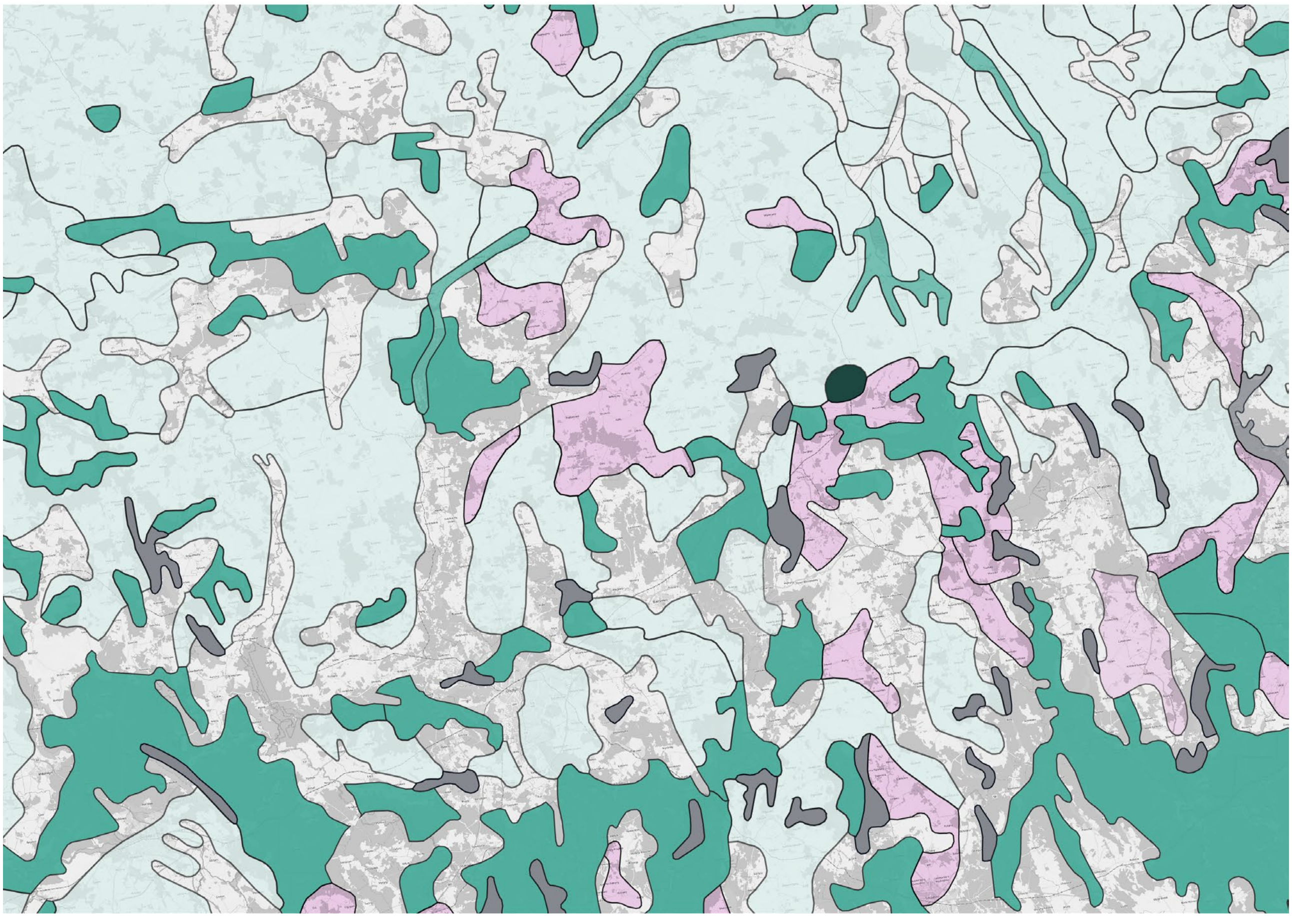
Table 5. Agricultural suitability complexes and soil valuation classes

Symbol	Name of the complex	Soil valuation class
3	defective-wheat	IIIb, IVa, IVb
5	good-rye	IVa, IVb
6	weak-rye	IVb, V
7	very weak-rye	VI
9	weak cereal-fodder	IVb, V
11	mountain-cereal	IVa, IVb
12	mountain oats-potatoes	
13	mountain oats-fodder	
14	arable land intended for grassland	
3z	grassland weak and very weak	V, VI

Source: Internal analysis based on the Ordinance of the Council of Ministers of September 12, 2012 on soil classification (Journal of Laws of 2012, item 1246) and (Fajer, 2014)

Figure 12. Soil and agricultural map for the example area

Wheat, very good complex
Rye, very good complex
Forests
Water
Strong cereal-fodder complex



Source: Internal analysis based on the IUNG Puławy data

Solar farm cannot be built on protected areas – such as the Natura 2000 sites. However, this criterion has already been addressed in the basic exclusion factors listed in Tab. 4. Basic exclusions also addressed the problem of shading – as significant buffer distances from typical shading elements (buildings, power lines or forests) were assumed. In the next step of the analysis, the risk of flooding was taken into account – on the basis of data from the Water & Wetness 2018 (Copernicus Land Monitoring Service, 2018) study, water regions (permanent and floodplains) as well as wetlands (permanent and temporary) were excluded (Fig. 13).

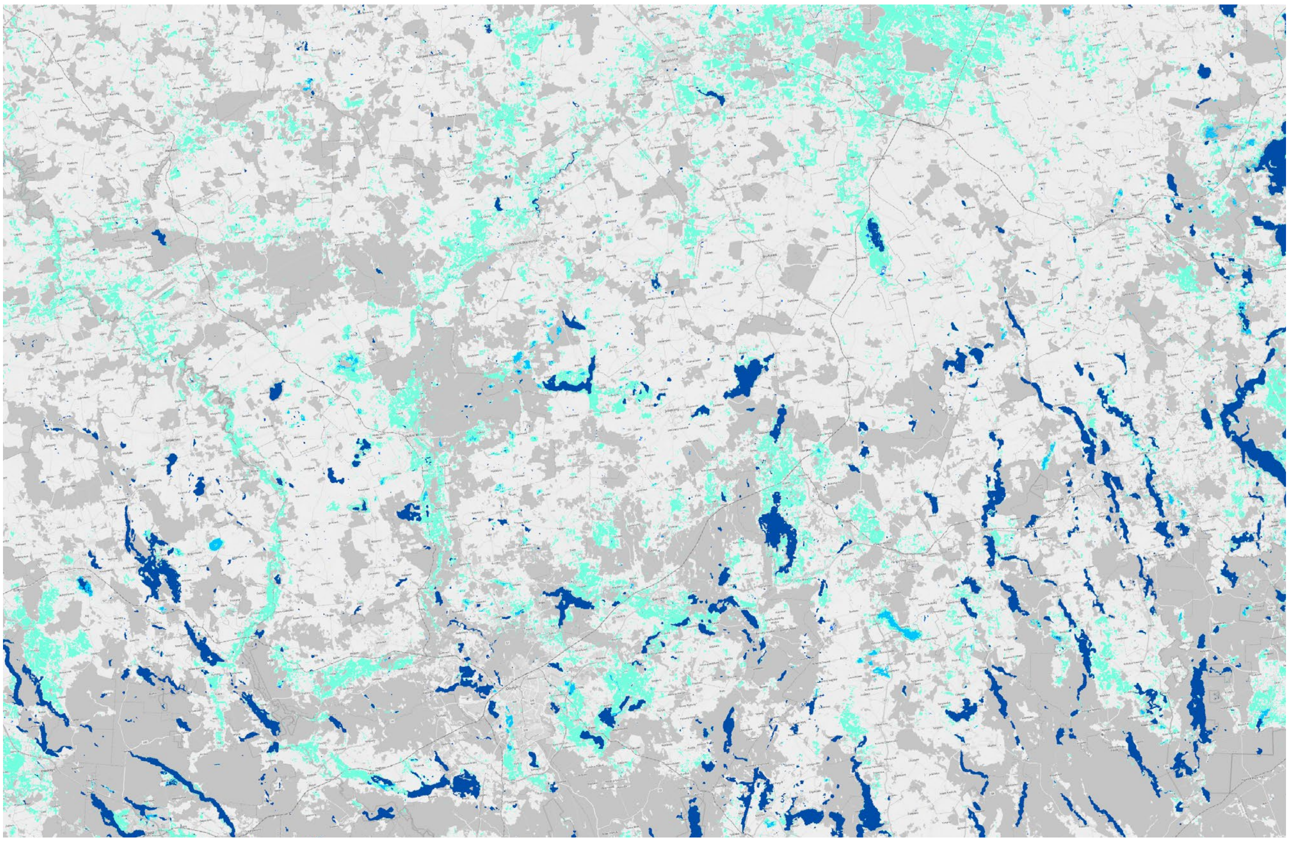
Figure 13. Map of floodplains for the example area

Wetlands – permanent

Water – permanent area

Wetlands – temporary

Water – temporary area



Source: Internal analysis based on Copernicus Water & Wetness data

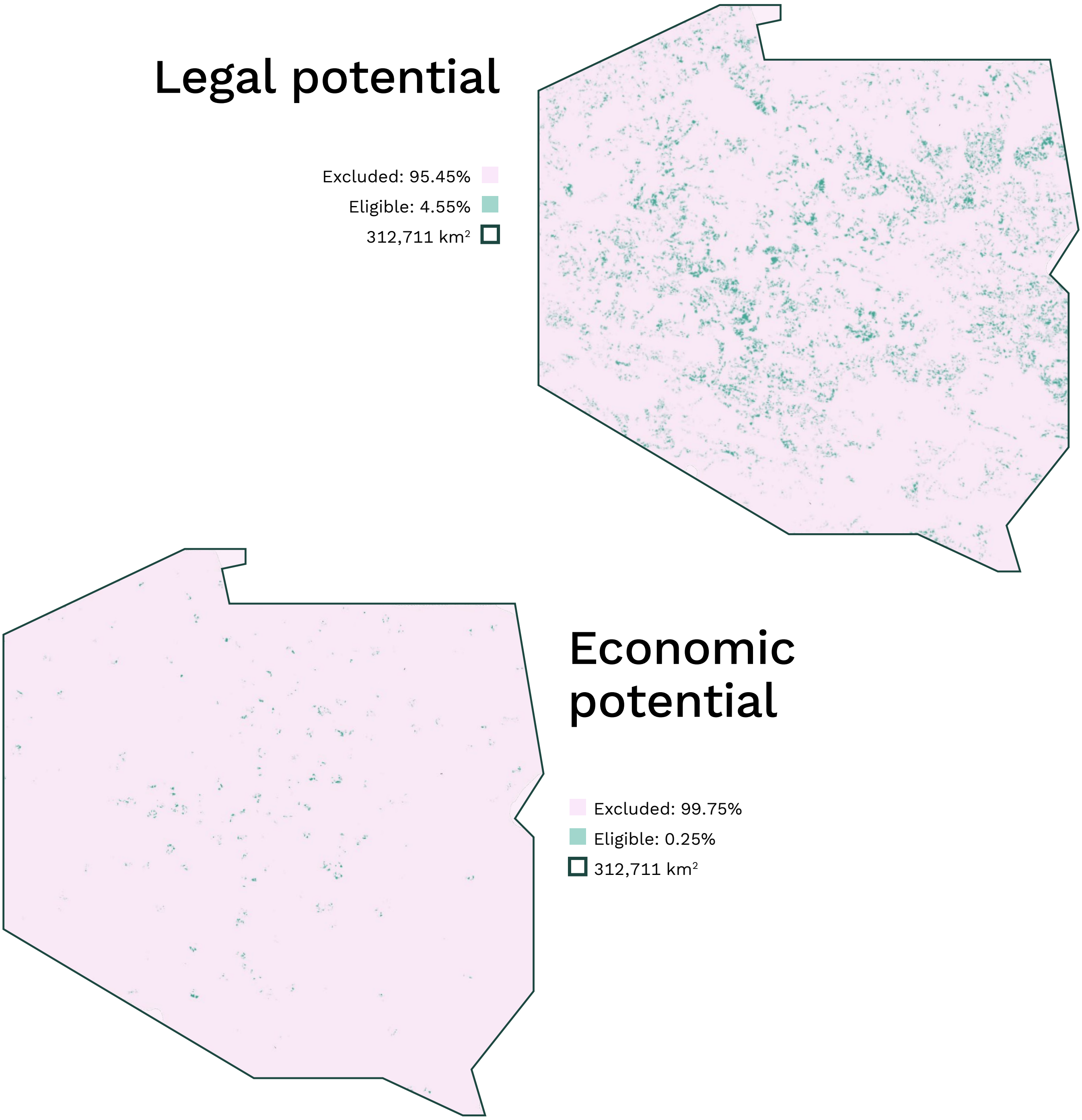
Finally, the analysis addressed factors influencing the profitability of PV systems. One of the important components of the overall investment cost are the costs of connection to the power grid (Fig. 14). The greater the distance from the connection point, the higher the cost of routing a new medium or high voltage line, which must be covered by the investor. In case of medium-scale and larger farms, the connection is typically made to a high/medium-voltage substation (Chmarzyński, 2021). For the purpose of this analysis, the station locations available in the OSM database (OpenStreetMap, 2021) were used. Based on the information obtained from industry investors, the distance of 5 km to the grid connection point was assumed as the distance ensuring sufficient profitability for medium-large PV projects. For the largest projects (>50-100 MW), the maximum distance may be higher and the abovementioned assumption should be treated as conservative.

Figure 14. Map of the power system, including HV/MV substations for the example area

Source: Instrat's internal analysis based on OpenInfraMap data

Application of the above criteria caused the available investment area to drop to 0.25% of the total area of Poland (approx. 782 km^2) – Fig. 15. To convert the available area figure to the potential installed capacity of ground-mounted solar farms, the actual density of PV panels installed in one of Poland's largest solar power plants currently constructed (Brudzew – ZE PAK, 2020), was used. This project foresees installation of 70 MW solar power plant on a plot of land of approx. 100 ha. Therefore, the 70 MWp/km^2 land development factor was assumed in the calculations. Under such assumptions, solar farms with the total capacity of 47.4 GWp can be built in Poland.

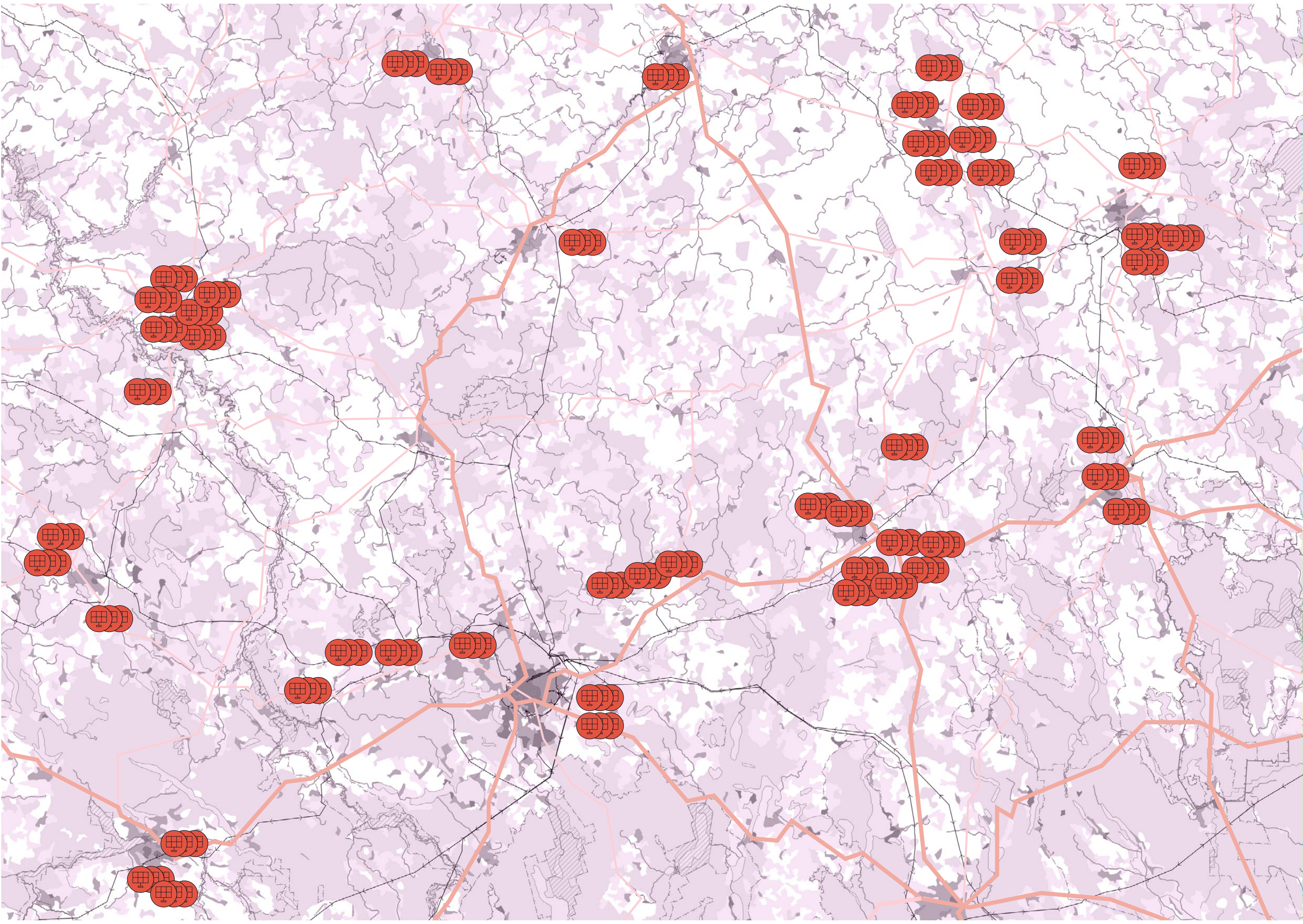
Figure 15. Availability of areas for PV farms



Source: Instrat's internal analysis

Fig. 16 shows an example of the arrangement of solar farms in a selected area of Poland. Clustering of investment projects in the vicinity of substations is visible – these projects will have the highest chance to be profitable. Along with the decrease in investment costs and development of network infrastructure, it might be possible to build cost-effective solar power plants in more and more areas.

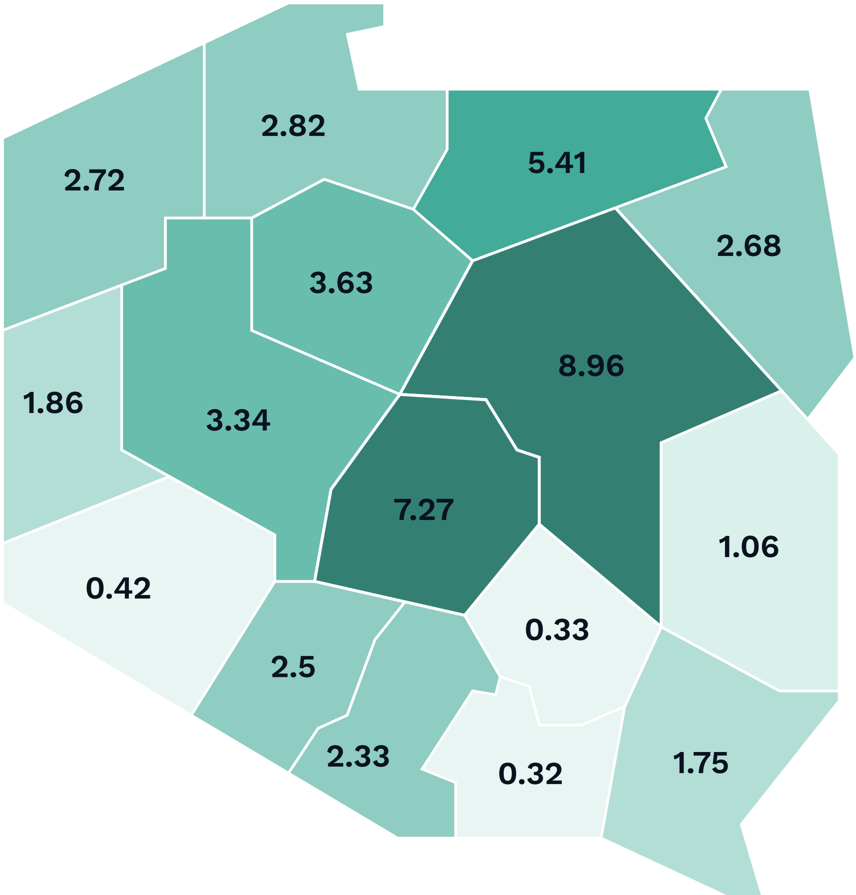
Figure 16. Example of the placement of solar farms



Source: Instrat's internal analysis

The total installed capacity in individual voivodeships is shown in Fig. 17. The largest number of solar farms can be developed in the Mazowieckie and Łódzkie voivodeships – up to 7–8 GW, due to relatively flat topography, large surface area, small afforestation, low humidity and low-class soils, followed by the Warmińsko-Mazurskie voivodeship – approx. 5 GW. The smallest potential is demonstrated by the Małopolskie, Świętokrzyskie and Dolnośląskie voivodeships, among others due to the mountainous topography of the area.

Figure 17. Installed capacity of ground-mounted solar farms in individual voivodeships



Source: Instrat's internal analysis

3.4. Rooftop PV systems

Rooftop PV systems, in particular micro-systems in single-family houses, have become the driving force of the Polish RES sector in recent years. However, as it will be demonstrated, their potential is still far from being exhausted.

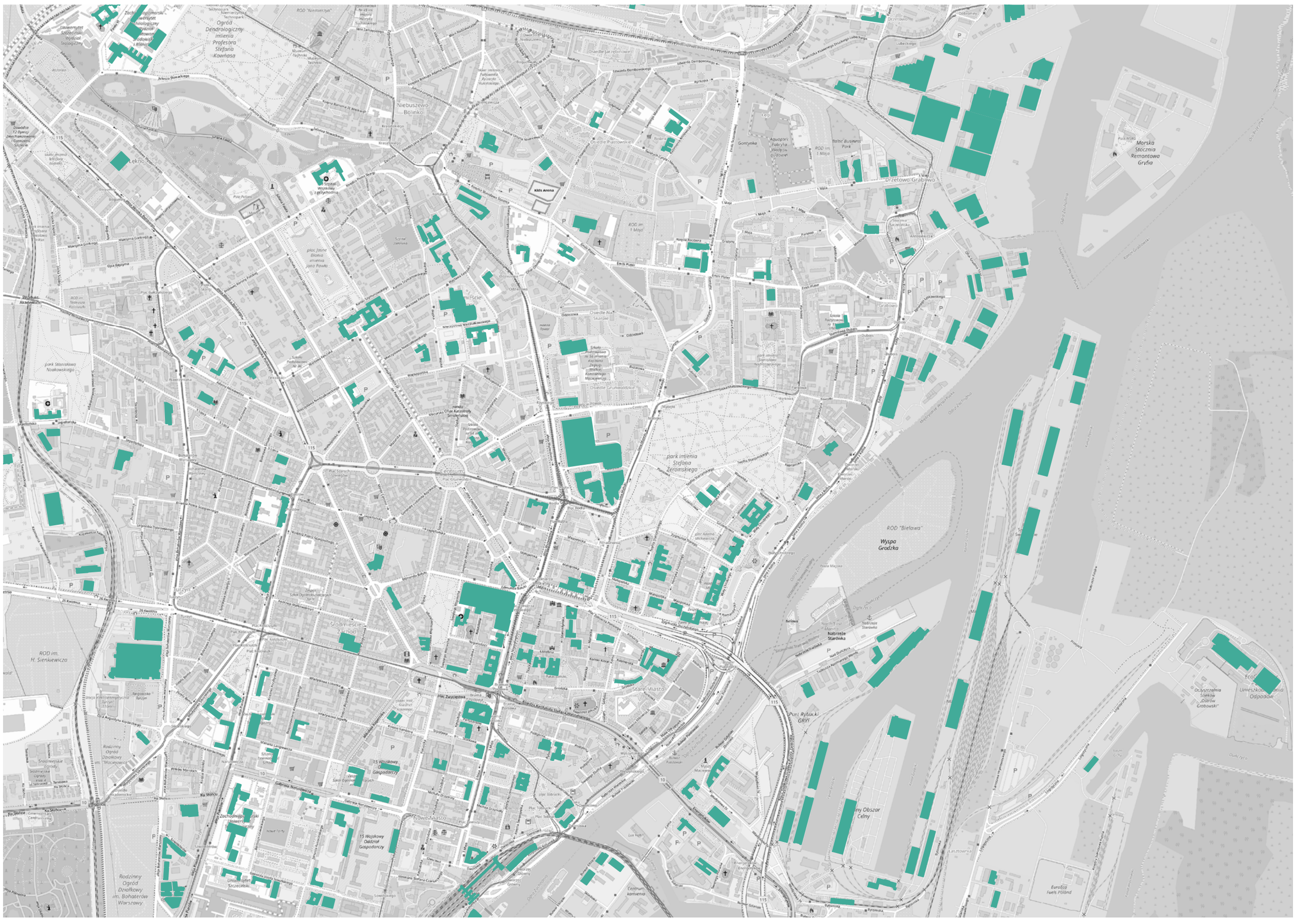
The calculations are divided into two categories. The first one – covering single-family buildings and the second one – covering large non-residential buildings. Multi-family buildings were excluded from the potential calculations because the current legislation on power cooperatives does not allow for their efficient utilization[24], and they cannot be treated as prosumer

24 In the coming months, this may change – the amendment to the Energy Law and the RES Act containing, i.a., improvements concerning power cooperatives: https://legislacja.gov.pl/projekt/12347450/katalog/12792164#12792164 is being discussed.

systems (capacity above 50 kW). The roof structure of multi-family buildings is more complicated than that of, e.g., storage halls and shops. However, this means that the potential of rooftop PV systems may increase in the future to include the segment of multi-family buildings.

The statistics of the Statistics Poland (GUS, 2013) were used to calculate the PV potential in residential buildings. According to GUS data, there are at least 5 million residential single-family buildings and 0.5 million multi-family buildings in Poland. The residents of single-family buildings may benefit from the aid for photovoltaic systems offered under the “My electricity” program. So far (May 2021) more than 200 thousand households have used the co-financing (National Fund for Environmental Protection and Water Management, 2021). The installed capacity was 1.15 GW. The average size of a single system is 5.7 kW. By applying this factor to the number of single-family buildings, a technical potential of 28.5 GW was obtained. According to the latest surveys (Sunday Polska, 2021), 67% of owners of single-family houses plan to invest in solar energy in the next three years. Assuming that these investments will be technically feasible, this provides a potential of approx. 19.1 GW of capacity in PV micro-systems in single-family houses.

Figure 18. Non-residential buildings potentially available for PV systems



Source: Instrat’s internal analysis based on OpenStreetMap data

The OpenStreetMap data (Geofabrik, 2021), containing over 15 million buildings located in Poland was used to calculate the PV potential of non-residential facilities. Only buildings with an outline area of more than 1000 m^2 were taken into account – the threshold was assumed as a typical area of medium-sized shops, e.g. Biedronka chain. This reduced the number of buildings taken into account at a later stage to approx. 150 thousand with a total surface area of 381 km^2. The following buildings were excluded at the next stage:

- **residential buildings (for reasons discussed above),**
- **sacral buildings,**
- **military buildings,**
- **agricultural buildings not suitable for mounting of PV systems (e.g. greenhouses and biogas plants),**
- **stadiums,**
- **buildings under construction,**
- **ruins.**

This resulted in 135 thousand buildings with a total surface area of 310 km^2. An example of marking of potentially available roofs for PV systems is shown in Fig. 18. It is estimated that on average approx. half (49–64%) of the roofs in the EU is suitable for installation of PV systems, e.g. due to their load-bearing capacity, technical condition of the building, roof structure, orientation of the building (Bódis, 2019).

Even in such a reduced pool of buildings, not the entire surface area can be used for the purposes of the photovoltaic system. On large buildings with flat roofs, it is assumed to apply mounting spacing from the roof edge of approx. 20% of the building height (Szymański, 2019) – typically 1–2 m, which reduces the available area by even a few percent (approx. 6% for a building with a surface area of 1000 m^2). It is also necessary to exclude structural elements of the roof – stacks, ventilation shafts, elements of the air conditioning system, roof windows. However, since the PV modules must be installed with some spacing between rows, a certain flexibility in their arrangement is permitted, taking into account the structural elements. It was assumed that the above structural factors will exclude approx. 20% of the roof surface. The greatest impact on estimating the actual capacity achievable in a PV system on a flat roof is the spacing between rows of PV modules resulting from their inclination (and thus shading of subsequent rows). Under Polish conditions, the optimum inclination of modules is up to 30–35 degrees, but due to limited surface availability, the inclination of rooftop systems is below 20 degrees. In this case, an inclination of 10 degrees was assumed, which means that the utilization factor for the mounting surface is 60% (Szymański, 2019). Taking into account all the above criteria, 24 percent of the 310 km^2 indicated above – 73 km^2 – are available for the PV system. When using panels with a capacity of 180 W/m^2 [25] this provides a potential of 13.2 GW of installed capacity on roofs of non-residential buildings.

25 Factor used by the European Commission (Kapetaki, 2020). In practice, the widely available monocrystalline panels with a capacity above 400 W obtain factors above 200 W/m2,, so the potential capacity may increase in the future.

3.5. Biomass and biogas

Biomass and biogas power plants have so far played a limited role in the Polish energy mix, and the installed capacity has not changed in principle for several years.

According to the analyses conducted by the Soil Science and Plant Cultivation – State Research Institute in Puławy (IUNG, 2015), the technical potential of biomass in Poland is:

- **12.6 million tons of straw from cereals,**
- **295 thousand tons of straw from oil plants,**
- **199 thousand tons of hay,**
- **20 million tons of energy plants (mainly willow, silvergrass and Virginia mallow).**

It is worth noting that no wood biomass is indicated among the sustainable biomass sources. Subsequent analyses, including those of the European Commission, indicate the risks related to forest clearing for energy purposes (Camia et al., 2021). The European Union recommends that Member States apply increasingly stringent standards for the sustainable sourcing of biomass raw materials. Therefore, the analysis assumes that only substrates from the above list will be used and that wood biomass will be completely abandoned.

Assuming the net calorific value at the level of 15 MJ/kg (Krawczyk, 2011; Terlikowski, 2012)[26] and electricity generation efficiency at the level of 30% (according to PEP2040), Poland could produce up to 41.4 TWh of electricity from biomass per year – nearly ten times more than currently (4.8 TWh in 2020, excluding co-firing with coal). Biomass combustion plants in Poland operate with load factors of only approx. 40%; it is theoretically possible to increase it significantly. With loads of 90%, the installed capacity corresponding to the technical potential is 5,2 GW.

It should be noted that the potential of biomass, in particular from energy plants, does not distribute uniformly on the national scale (Fig. 19). In the Kujawsko-Pomorskie, Wielkopolskie and Małopolskie voivodeships, this potential is practically not present. The possibility of obtaining substrates is the largest in the Podlaskie, Łódzkie, Opolskie and Zachodniopomorskie voivodeships. The planned arrangement of the biogas plant must take into account the availability of fuel, which is heavily diversified in Poland.

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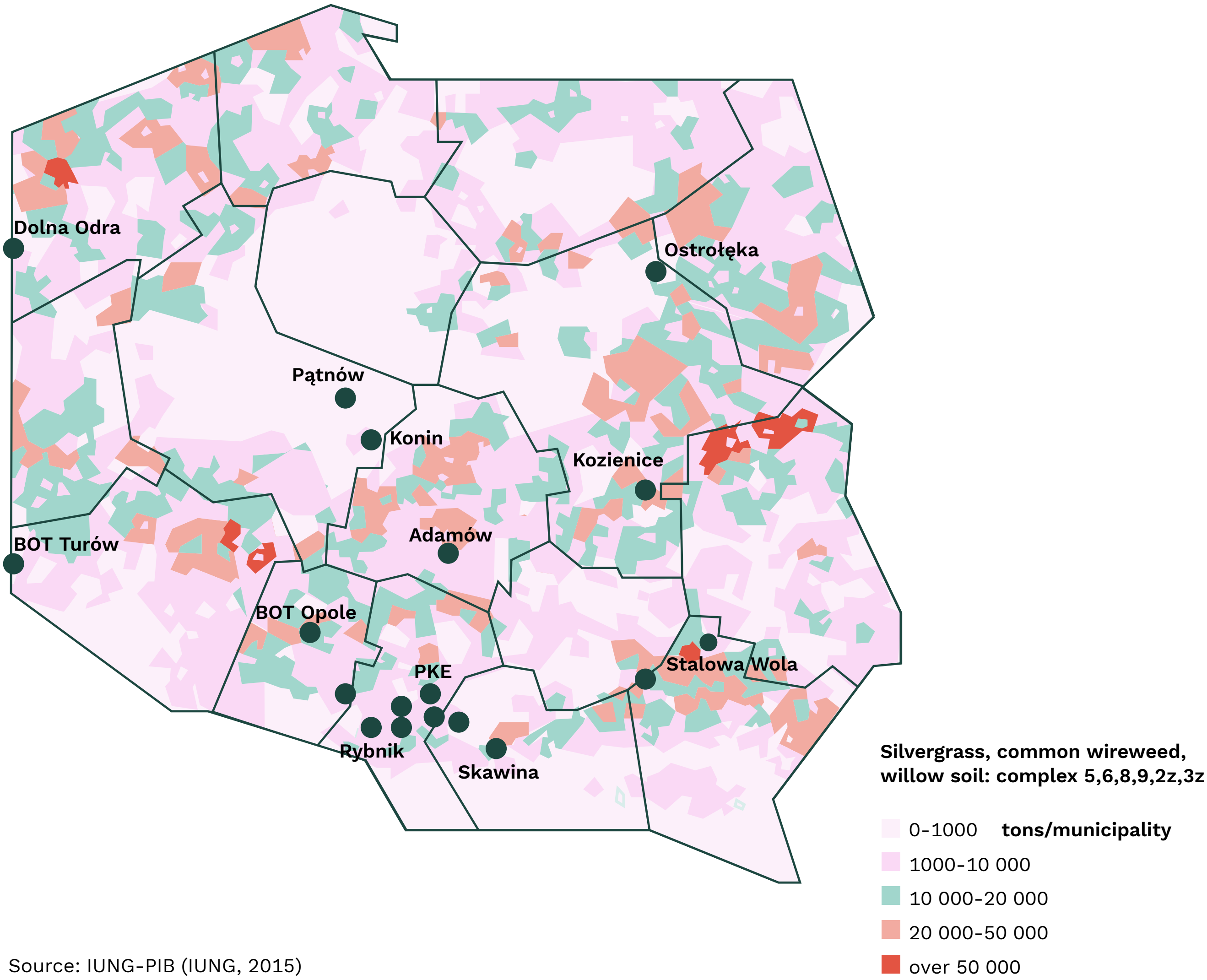
26 The net calorific values differ slightly, however, for the referenced materials they are typically within the range of 14–16 MJ/kg.

Figure 19. Potential of energy biomass in individual municipalities



Source: IUNG-PIB (IUNG, 2015)

Due to doubts concerning wood biomass and high emission of the combustion process, approx. 0.403 tCO_2/MWth (EPA, 2014), increasing restrictions are expected on the financing of biomass power plants. At the same time, investment costs per 1 MW are several times higher than for solar and wind systems. Therefore, a strong increase in the installed capacity of biomass power plants in Poland should not be expected. Increasing the load factor in the existing power plants could increase production to up to 10–11 TWh per year while maintaining the current installed capacity.

The above doubts do not apply to biogas plants with much lower emissions – 0.178 tCO_2/MWth (EPA, 2014). The fuel used in biogas plants also has a smaller negative impact on the use of cultivated land – mainly waste is used, not energy plants planted specifically for this purpose.

According to the analysis of the scientists of the Ecotechnologies Laboratory of the Institute of Biosystems Engineering, Poznań University of Life Sciences, the sustainable potential of biogas production in Poland is 13.5 billion m3 of biogas per year (Magazyn Biomasa, 2018). This potential was calculated on the basis of the biogas plant efficiency analysis for over 1.5 thousand different types of substrates and availability of individual waste materials, which amounts to:

- **approx. 90 million tons of manure, pig slurry and poultry litter,**
- **8 million tons of straw, cereals and rape,**
- **4 million tons of maize straw.**

The calculations also take into account the use of:

- **waste plant biomass (e.g. from protected areas, valuable natural areas, etc.)**
- **waste from food processing, sugar plants, slaughterhouses, dairies, distilleries, etc.;**
- **refood, i.e. expired and spoiled food.**

The authors of the analysis estimate the annual electricity generation potential at 30.5 TWh for the installed capacity of 3,6 GW[27].

Due to the high emissivity of both biogas and biomass, their significant role in shaping the future energy mix should not be assumed. Of the two technologies, the emissivity of biogas being twice lower suggests that the potential development of bioenergy will take place in this area. At the same time, however, the increasingly numerous analyses draw attention to the decreasing consumption of meat and dairy, which will translate into a decrease in the availability of zoonotic substrates (European Commission, 2020) and thus reduce the long-term potential of biogas.

3.6. Hydropower

The hydropower sector has not played a significant role in Poland for many years. In 2020, hydropower plants generated 1.62 TWh of electricity, which constitutes only 1% of domestic production. Such a small share of this technology in the energy mix is caused by specific economic and technical factors. The cost-effectiveness of the hydropower plant projects depends on the geographical conditions of the country – the availability of rivers with

27 This corresponds to the capacity utilization factor of 96%. Currently it is 57%.

a high grade translates into a greater potential of the hydropower sector. In countries using this technology, such as Switzerland, the grades of hydropower plants are of hundreds of meters, whereas in Poland, the nominal grade, e.g. in Włocławek hydropower plant, is only 8.8 meters. Therefore, the costs of electricity generation in Polish hydropower plants are higher than the revenues from its sale, and their survival is possible only through high subsidies. The maximum guaranteed prices for hydropower plants amount to PLN 535/MWh for facilities with a capacity above 1 MW and up to PLN 620/MWh for power plants with a capacity below 0.5 MW.

Another problem is the impact of the power plants on the natural environment, because water dams are a significant interference in the ecosystem, worsen the problem of drought and are also a source of emission of methane – a greenhouse gas with a higher harmfulness than carbon dioxide.

Damage caused by once-through hydropower plants has been noticed by the European Commission, which, under the EU Water Framework Directive, requires all countries to bring all the rivers to good condition by 2027 at the latest, forcing elimination of dams on rivers (WysokieNapięcie.pl, 2021). Therefore, the reduction in the installed capacity of hydropower plants in Poland should be expected.

The exception are pumped storage power plants that provide energy storage capabilities, which are of key importance with increasing RES share in the energy mix. These power plants can be built in, e.g., excavations of decommissioned brown coal mines, and thus without interference to the natural environment. The Achieving the goal report proposed the construction of this type of unit on the premises of the Turów Mine, using the project of the Zgorzelec Cluster for Development of Renewable Energy Sources (ZKlaster), the Warsaw University of Technology and the National Chamber of Energy Clusters (Węgrzyn et al., 2020). The would have a capacity of 2300 MW with 165 GWh of storage. A similar solution could be applied on the premises of the Bełchatów Mine.

4. Expected rate of development of selected energy generation and storage technologies

The previous chapter focused on the maximum achievable installed capacity for individual types of renewable energy sources. This point discusses the rate of capacity increase in the 2040 perspective. In practice, it seems it will not be possible to exploit all the potential in any of the technologies presented by 2040, mainly due to legislative barriers (chapter 2). However, the rate of RES development is crucial in the context of meeting the climate targets for 2030, accelerating shutdowns of unprofitable coal-fired power units, increasing prices and import of energy, delays in the implementation of the nuclear energy program.

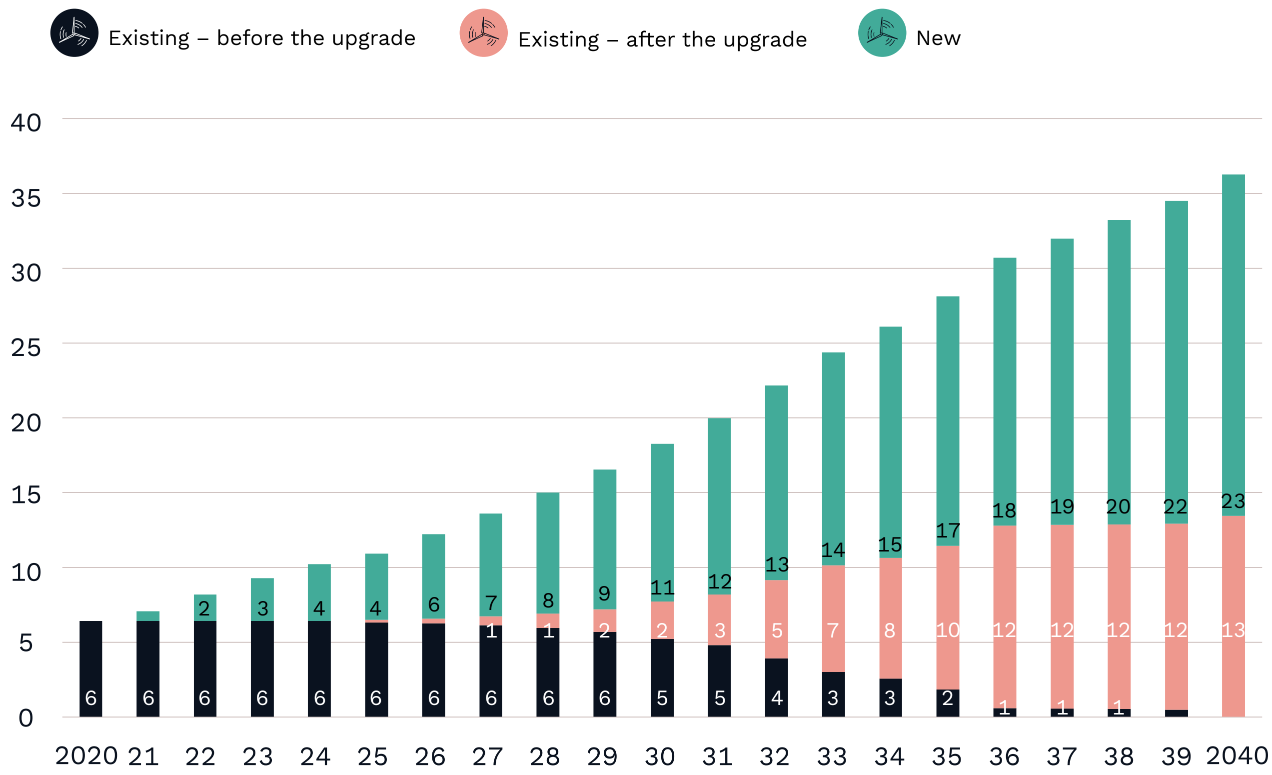
4.1. Wind energy

Onshore wind energy developed dynamically until 2016, when the yearly capacity increase reached as much as 1.23 GW. Since 2018, investment projects with a building permit obtained before 2016 could participate in RES auctions. As a result of the auctions in 2018–2020, it is expected that the capacity of wind turbines will increase to approx. 10 GW in 2024[28]. In the auction settled in June 2021, the pool for wind turbines is 600 MW, if fully used, the installed capacity will increase to 10.8 GW by 2025.

The future of wind power is subject to uncertainty related to the amendment of the "Anti-Wind Law" (Czyżak, Sikorski, Wrona, 2021). The proposed increase in the administrative burden may cause delays in projects by the end of the 2020s. However, the model assumes that the amendment will take into account the urgency of meeting the climate targets for 2030, and the time of implementation of investment projects will not be extended compared to the current 3–5 years. If the amendment comes into force in 2022, a rapid development of wind turbines can be expected already in 2026. The model assumes that it will then be possible to achieve an increase at the historic level of 1.23 GW per year – which, on the one hand, is an ambitious value, on the other hand, has already been achieved 10 years

28 Provided that projects are handed over for operation three years after winning the auction.

Figure 20. Forecast of the installed capacity increase of onshore wind turbines [GW]



Źródło: Opracowanie własne Instrat

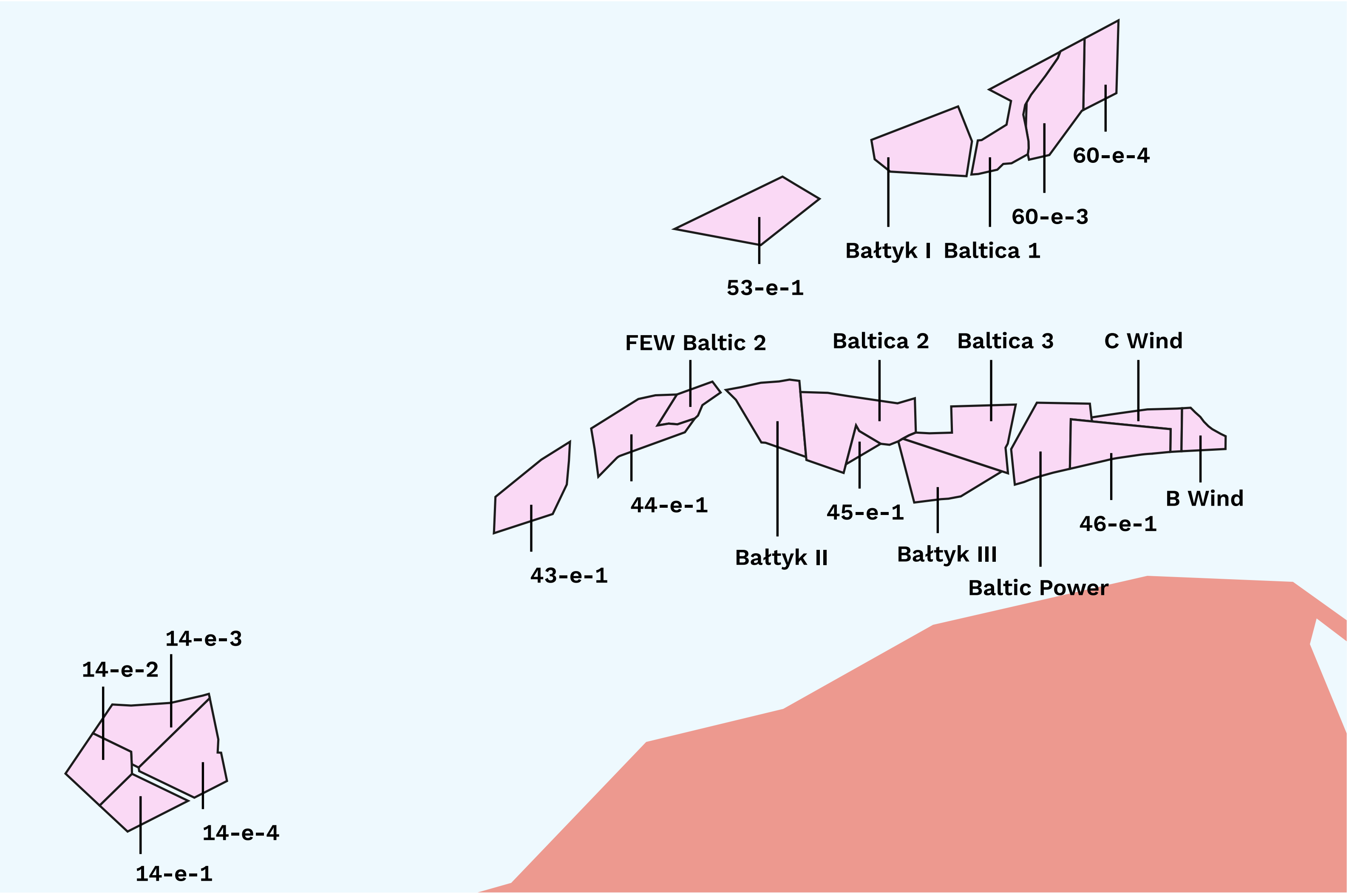
earlier, with a lower level of technology and higher investment costs. Therefore, it is highly probable that after the removal of legislative barriers, the rate of development of the wind power will be even quicker.

The model includes the upgrade of the existing turbines. The draft amendment to the "Anti-Wind Energy Law" does not propose legislative facilitations in this respect, which means that the rate of the so-called repowering (increase in the capacity of the existing power plant by, e.g., replacement of the turbine) would be slowed down. However, it is assumed that a solution will be developed to enable efficient repowering of the existing turbines, necessary to achieve the required installed capacity. The model assumes that in the existing turbines the capacity will be increased on average 2.1 times[29] after 20 years after their construction. This will result in a gradual fleet replacement in 2025–2040 and an additional capacity increase of 6–7 GW.

29 Assuming a replacement of typical Vestas V80/90 turbines with a capacity of 2 MW with, e.g., Vestas V117 turbines with a similar total height, but with a capacity of 4.2 MW. Obviously, for smaller turbines, the capacity increase will be higher.

Based on the above assumptions, a scenario of development of onshore wind turbines was prepared – Fig. 20. The installed capacity will increase from 6.4 GW at the end of 2020 to nearly 11 GW in 2025, 18 GW in 2030, 28 GW in 2035 and 36 GW in 2040. The value obtained in 2040 does not exploit the full potential indicated in Chapter 3 (Tab. 1), however, further growth opportunities are lower than in the case of other technologies (as much as 82% of the onshore wind power potential is used).

Figure 21. Map of the planned offshore wind farms [GW]



Source: Instrat's internal analysis based on energy.instrat.pl data

Table 6. Executed and planned offshore wind farm projects

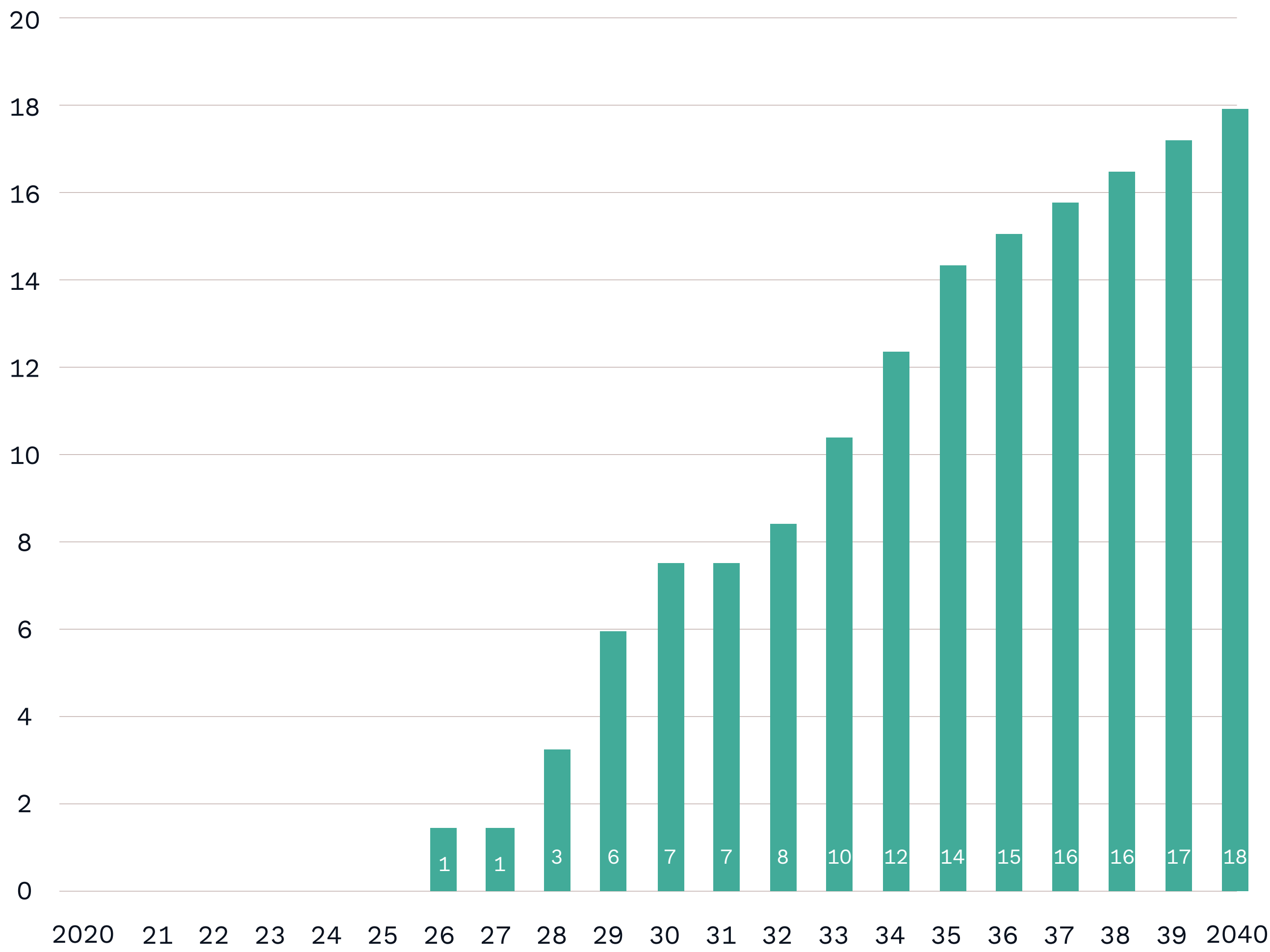
Project	Owner	Installed capacity [MW]	Potential of the area [MW]	Commissioning date*
Bałtyk III	Polenergia / Equinor	720		2026
Bałtyk II	Polenergia / Equinor	720		2026
B Wind	EDP Renewables	200		2028
C Wind	EDP Renewables	200		2028
Baltica 3	PGE / Orsted	1045		2028
FEW Baltic 2	RWE	350		2028
Baltic Power	PKN Orlen	1200		2029
Baltica 2	PGE / Orsted	1498		2029
Bałtyk I	Polenergia / Equinor	1560		2030
Baltica 1	PGE / Orsted	896		2032
60-e-4			620	before 2035
60-e-3			1143	before 2035
53-e-1			1202	before 2035
46-e-1			895	before 2035
45-e-1			138	before 2035
44-e-1			971	before 2035
43-e-1			947	before 2035
14-e-4			1181	before 2040
14-e-3			1008	before 2040
14-e-2			729	before 2040
14-e-1			659	before 2040

* The first full year of operation in accordance with the connection agreement. In the case of the Bałtyk I, the year of commissioning has been preponed from 2031 to 2029 compared to the Achieving the goal report, in accordance with the documentation updated in May 2021 (PSE, 2021). The maximum dates of 2035 (projects connected in Słupsk and Żarnowiec) and 2040 (projects connected near Koszalin and Świnoujście – e.g. Dunowo MTS and Recław MTS) were adopted for the undeveloped areas.

Source: Instrat's internal analysis on the basis of energy.instrat.pl data and the List of entities applying for connection to the National Transmission Network (PSE, 2021). Status as of May 31, 2021

The rate of development of offshore wind farms can be estimated on the basis of the projects already being developed (Fig. 21 and Tab. 6), many of which have already signed connection agreements with Polskie Sieci Elektroenergetyczne (the TSO). The first offshore power plants are to be commissioned already at the end of 2025. In compliance with PEP2040, the installed capacity is to reach 5.9 GW in 2030, a similar value was adopted in the Achieving the goal report on the basis of the dates resulting from the connection agreements. However, the *List of entities applying for connection to the National Transmission Network* (PSE, 2021) updated in May 2021 indicates that the Bałtyk I commissioning date has been preponed from 2031 to November 2029. This means that the capacity of offshore wind farms may reach up to 7.5 GW in 2030 (Fig. 22). In the 2040 perspective, the development of the remaining areas included in the Offshore Act and the Spatial Development Plan for Polish Marine Areas (PZPPOM) with a linear increase in the installed capacity up to 18 GW in 2040 was assumed. Still, this means using only 58% of the potential indicated in Chapter 3 (Tab. 1).

Figure 22. Forecast of the installed capacity increase of offshore wind turbines [GW]



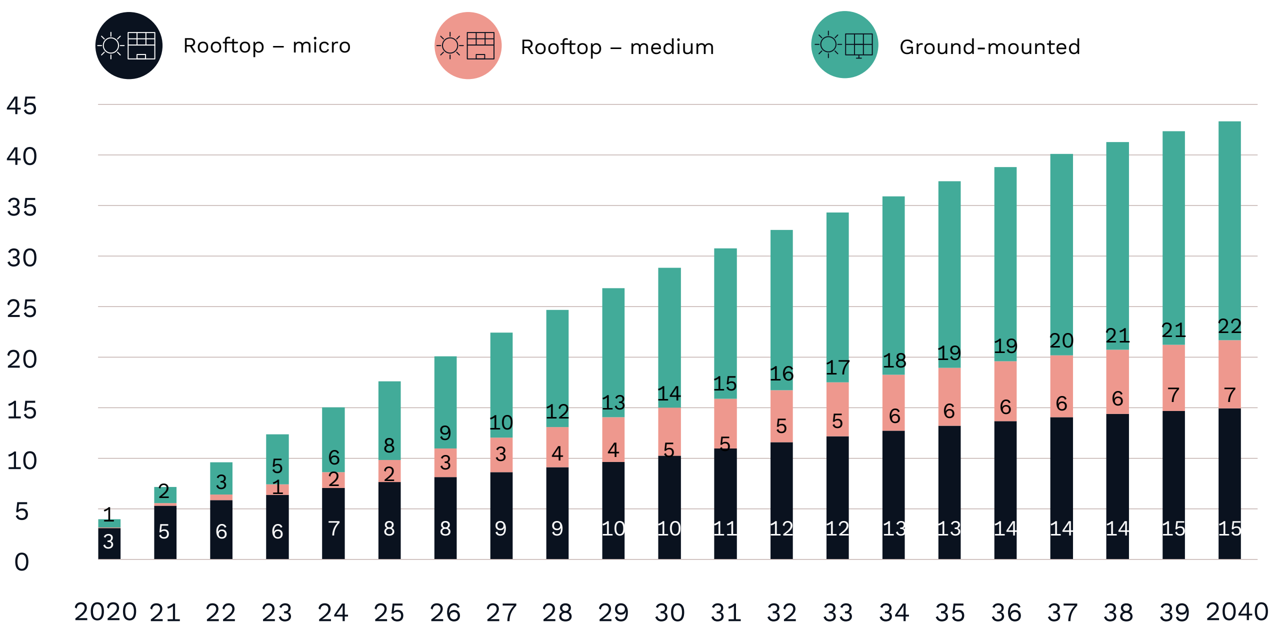
Source: Instrat's internal analysis on the basis of energy.instrat.pl data and the List of entities applying for connection to the National Transmission Network (PSE, 2021). Status as of May 31, 2021

4.2. Solar energy

The development of solar energy has been extremely dynamic in the recent years – both in the area of micro-systems through the "My electricity" program and in the area of large PV farms supported by the RES auctions. In 2020, the capacity of the former increased by 1.8 GW up to 3.1 GW, the latter by 0.6 GW up to 0.8 GW. In total, a record-breaking 2.4 GW of new solar power plants were commissioned in 2020.

In the light of the current events, the forecast concerning the development of photovoltaics was updated with reference to the scenario from the Achieving the goal report. In particular, the structure of the division of power into rooftop and ground-mounted systems was revised. In the RES auctions settled in June 2021, an impressive pool of solar power plant capacity of 1.8 GW is to be contracted. At the same time, controversial changes concerning the settlement system for prosumers (Chapter 2) are being consulted, which, even in its mild form, will reduce the pace of development of PV micro-systems. Therefore, we expect that the structure of solar power plants will change from one dominated by micro-systems to one with a predominance of large PV farms (IEO, 2021). It is worth noting that the legislative uncertainty and the proposed changes to the prosumer support system since January 2022 are likely to cause an increased demand for micro-systems until the end of 2021. Data from the first months of 2021 already indicate that the increase in PV capacity is likely to exceed the record value from 2020. By the end of April 2021, as much as 730 MW solar power plants were commissioned. In the same period of 2020 this equaled 537 MW. The rate of capacity increase typically accelerates in the second half of the year, so the total increase in PV installed capacity in 2021 is estimated at 3.2–3.3 GW.

Figure 23. Forecast of the installed capacity increase of solar power plants [GW]



Source: Instrat's internal analysis

The conservative forecast from the Achieving the goal report was updated on the basis of the trends and legislative changes observed in the first half of 2021, as well as taking into consideration the recently published update of the “Photovoltaic market in Poland” report by the Institute for Renewable Energy (IEO, 2021). Apart from micro-systems and solar farms, the model now includes small photovoltaic systems (50–500 kW) – mainly on commercial buildings. Their potential has been practically untapped until 2020, however, the introduction of the capacity market fee and growing electricity bills for companies resulted in a sharp increase in the popularity of this group of PV systems. It is estimated that in 2021 alone, the power increase in this sector will amount to 200 MW and it will accelerate in the coming years (IEO, 2021).

Similarly to the Achieving the goal report, the forecast for the years 2022–2040 assumes a declining pace of solar capacity development, from 3.2 GW in 2021 to approx. 1 GW annually in 2040. There will probably be a significant slowdown in the sector of micro-systems beginning in 2022 – from approx. 2 GW in 2020 and 2021 to approx. 0.5 GW per year. Commissioning of solar farms from the record auctions in 2020 and 2021 will partially reduce the negative effects of the slowdown in the area of prosumer systems. RES auctions in their current form will function at least until the end of 2027, however, a continuous decrease in investment costs and an increase in the wholesale electricity prices means that an increasing pool of projects operating outside the auction system can be expected – e.g. in the PPA formula. Therefore, it is assumed that the share of large solar power plants in the annual increase will remain at a level of approx. 50%.

In total, by 2030, solar power plants should be expected to reach the level of 29 GW, in 2040 it will be approx. 43 GW, (Fig. 23) – as has been mentioned, this is slightly more than in the Achieving the goal report due to the trends and events from the first half of 2021 taken into account. The forecasted values for 2040 are far from exhausting the potential – 78% of the potential will be implemented in the micro-system sector, 51% in the sector of medium rooftop systems (mainly business ones) and 46% in the sector of large PV farms. Therefore, further development of the solar energy should be expected after 2040.

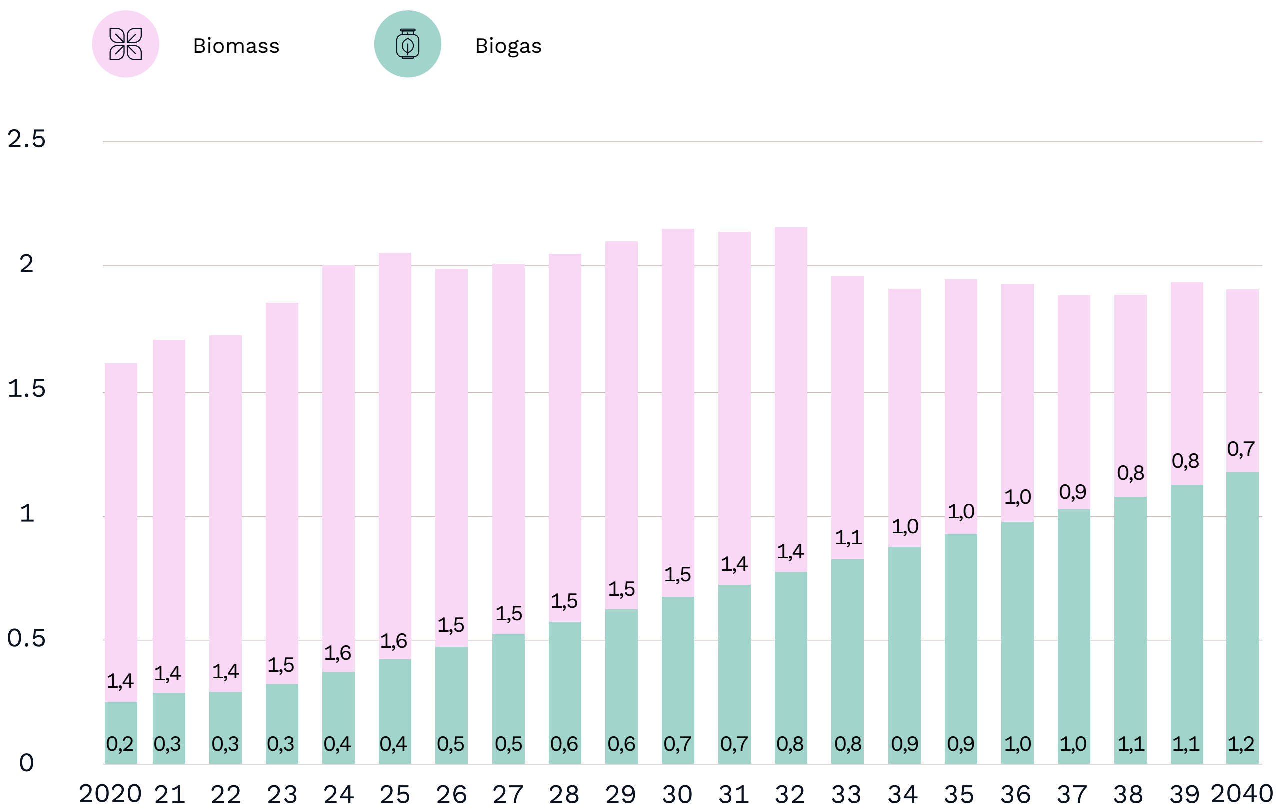
4.3. Biomass and biogas

The *Achieving the goal* report assumes a significant increase in the significance of bioenergy in electricity generation. An ambitious pace of biogas plant development was adopted, based, among others, on the declarations of the government, PGNiG, PKN Orlen. Leaving aside the ecological controversy concerning the extraction of biomass or the decreasing supply of raw materials for biogas (p. 3.5.), the high emissivity of both technologies would lead to a situation in which in 2040, bioenergy would account for 54% of CO_2 emissions in power generation, making a full decarbonization of the sector difficult to achieve.

Therefore, a scenario with a reduced share of bioenergy was prepared. Only a slight increase in the capacity of the biomass combustion plants is assumed (in accordance with the outcomes of this year's RES auction) in the short-term perspective, followed by a gradual decrease in the power output caused by the shutdown of the existing power plants after 20 years of operation. Such a scenario leads to a reduction of the installed biomass combustion plant capacity to 731 MW in 2040, most of which are large biomass power units in combined heat and power plants. The forecast concerning biogas plant development was also reduced compared to the one proposed in the Achieving the goal report, assuming a growth rate of approx. 50 MW per year, in accordance with the estimates presented in a publication of "Biomass Magazine" and the Polish Development Fund on the basis of trends from 2005–2016 (Magazyn Biomasa, 2020). Such a scenario means reaching a biogas plant capacity of 600–700 MW in 2030 and nearly 1200 MW in 2040.

Of course, the development of biomass and biogas power plants will be heavily determined by the government's actions in this respect, since high investment costs will prevent the industry from operating without dedicated national support schemes.

Figure 24. Change in the installed capacity of biomass and biogas power plants [GW]



Source: Instrat's internal analysis

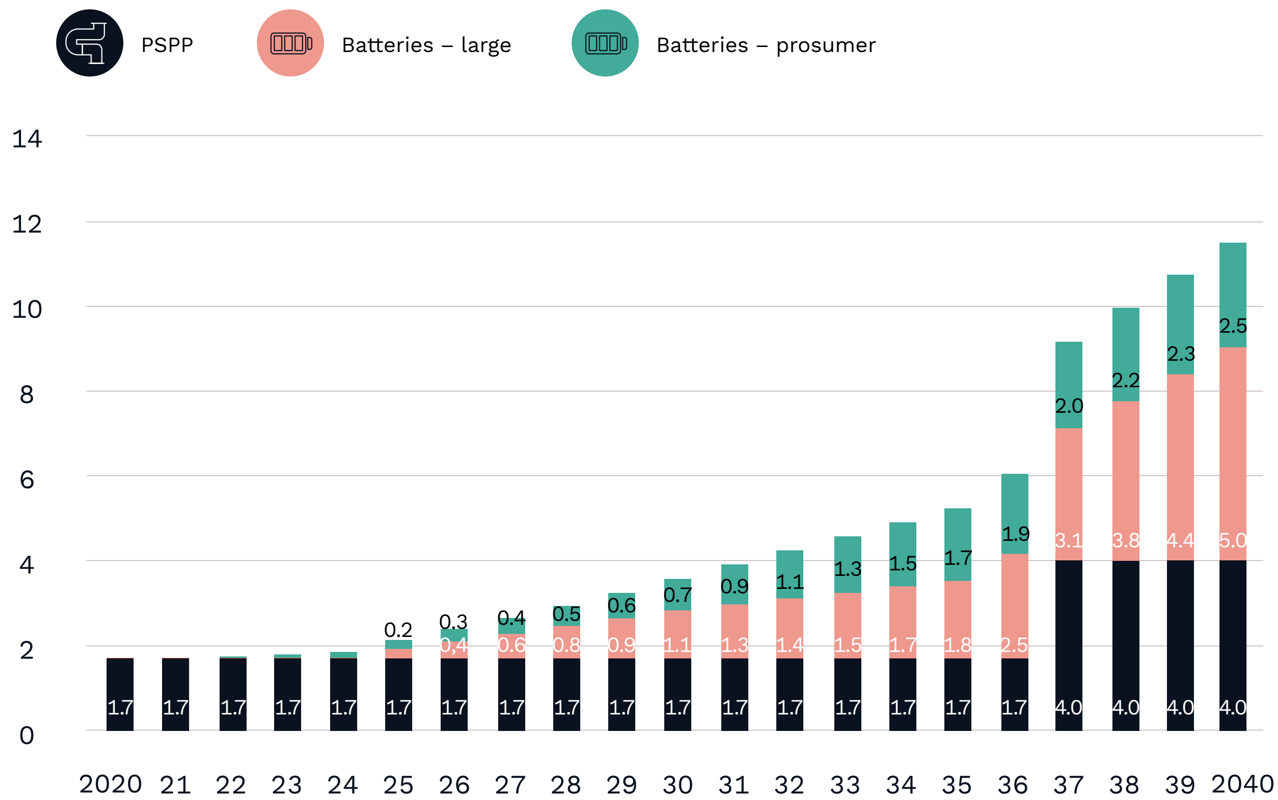
4.4. Energy storage facilities and other

Ensuring the stability of energy supplies in the face of planned shutdowns of coal-fired power units requires not only an increase in the RES capacity, but also the development of storage technologies. Currently, there are 5 pumped storage power plants and several small battery energy storage facilities in Poland. The total installed capacity of the former is 1.7 GW, the storage capacity of the largest power plant in Żarnowiec is 3.6 GWh. According to the scenario described in the *Achieving the goal* report, the commissioning of a new pumped storage power plant with an installed capacity of 2.3 GW and a storage capacity of 165 GWh in the location of the Turów Mine in 2037 has been assumed (Węgrzyn, 2020). The PSPP efficiency of 75% was assumed.

A strong development of large battery energy storage facilities is also expected. PGE itself plans to commission 800 MW of the above-mentioned by 2030 (PGE, 2020) and a number of projects are already being developed. There are discussions concerning the broadening of the RES auction with the so-called hybrid systems containing energy storage, 2 GW of energy storage facilities were also submitted to this year's capacity market auction with the commissioning date in 2026 (BiznesAlert.pl, 2021). At the same time, the investment costs of battery energy storage facilities are dropping extremely quickly, effectively competing with gas units as a tool for satisfying the peak power demand in situations of low RES generation (energy-storage.news, 2021). In Great Britain, the installed capacity of large battery storage facilities is 1.1 GW, another 10.5 GW is already under construction or with building permits already issued (edie.net, 2021). In Poland, with additional support from the RES auction and/or the capacity market, a quick development in this area should be expected – even up to 5 GW of installed capacity in 2040. For new projects, a 4:1 capacity-to-power ratio was assumed, typical for large batteries, e.g. Tesla Powerpack, and an efficiency of 90%.

In a response to a number of recent developments, the scenario was broadened to include the home energy storage facilities that complement micro-PV systems. The legislative changes in the support scheme for prosumers currently discussed will result in a sharp drop in the profitability of photovoltaic micro-systems, and the only way to avoid this will be to supplement investment projects with a battery storage system. At the same time, with the announcement about the broadening of the "My electricity" program to include energy storage, the investment costs will decrease, which will constitute an additional purchase incentive. Therefore, the scenario assumes that from 2022 (after the modification of the prosumer support scheme), 10% of the new PV micro-systems will also contain an energy storage. The percentage of storage penetration will increase linearly to 100% in 2040 (with the conservative assumption that this applies only to new projects). It is worth noting that in Germany even 70% of new PV systems contained energy storage already in 2020 and their storage capacity amounted to 2.3 GWh (energy-storage.news, 2021a). It was assumed that in the home batteries, the capacity-to-power ratio is 2:1 on average (according to the parameters of the most popular products). Based on the scenario of the PV micro-system development as well as the above assumptions, the installed capacity in home energy storage facilities may amount to 0.7 GW in 2030 and 2.5 GW in 2040.

Figure 25. Change in the installed capacity of energy storage facilities [GW]



Source: Instrat's internal analysis

The total capacity of all types of energy storage facilities may amount to 3.5 GW in 2030 and 11.5 GW in 2040. After 2040, a further increase in the capacity of battery energy storage facilities, as well as potentially construction of new pumped storage power plants, should be expected. It should be emphasized that the development of local energy storage facilities eliminates to some extent the challenges related to the connection of PV micro-systems, allowing for power balancing within individual homes, with a much smaller volume of energy released to the NPS.

Among the technologies used in the model, the Demand Side Response (DSR) has been included. According to the results of the capacity market auction, the current availability of DSR at a level of 800 MW should increase to approx. 1 GW in 2025. Ultimately, DSR potential is estimated at 2.5 GW and it is assumed that it will be achieved in 2040 (gramwzielone.pl, 2019). The DSR service price is very high (PLN 1000/MWh and more), which means that it is activated only in critical situations and it should be treated as a safety buffer. As part of the model, it is therefore one of the elements of ensuring the required overcapacity, but it is assumed that the system can be balanced in each hour of the year without the DSR involvement.

Finally, in the long run (since 2035), the model takes into consideration the application of green hydrogen in electricity generation. In accordance with the recommendations of the Team for Development of the RES Industry and Benefits for the Polish Economy at the Ministry of Climate (Kupecki et al., 2020), green hydrogen may be used, among others, for combustion in CCGT power plants instead of/besides natural gas as well as in the production of energy in fuel cells. The production of green hydrogen in the electrolysis process enables the use of surplus energy from RES, which in the 2040 perspective are a significant factor threatening the profitability of investments into solar and wind power plants. The combustion of such generated green hydrogen in CCGT units enables the reduction of natural gas import, reduction of CO_2 emissions and, finally, profitability of the constructed CCGT units under conditions of increasing CO_2 prices and competition from RES and batteries. On the other hand, green hydrogen fueled cells can be tested as peak power sources, providing the required overcapacity. The first large-scale projects of this type, providing continuous green energy, are planned to be launched even before 2030 (e.g. RechargeNews.com, 2021). After 2030, co-combustion of hydrogen may also be possible in gas-fired combined heat and power plants, which, however, has not been taken into account in the proposed scenario.

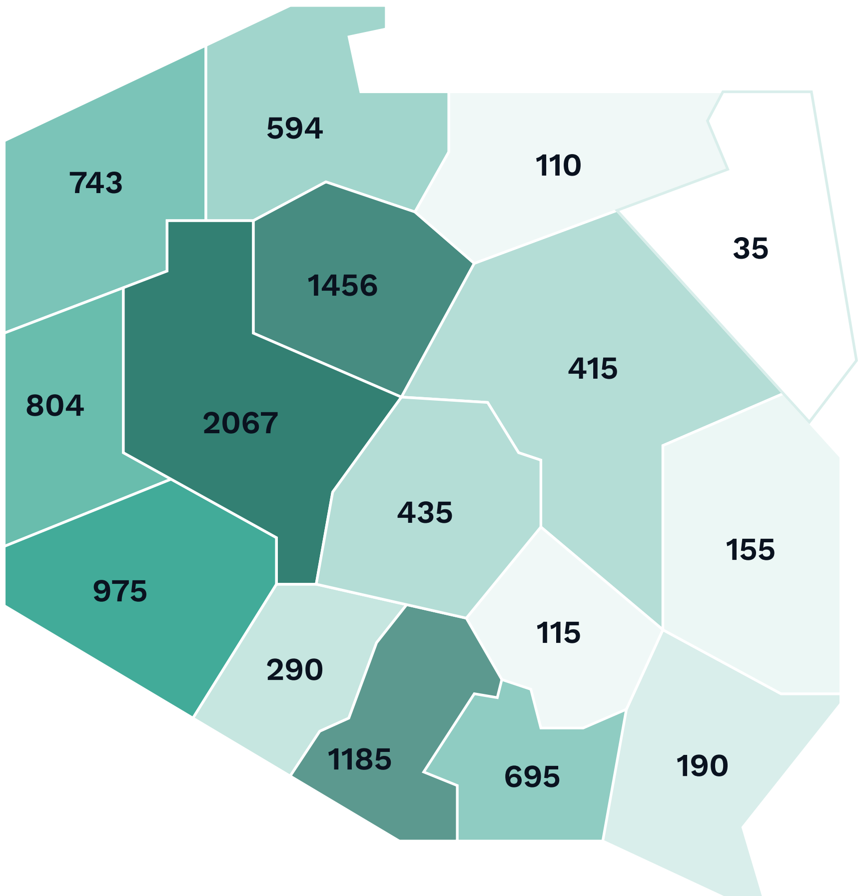
The draft *Polish Hydrogen Strategy* (MKiŚ, 2021a) assumes the construction of 2 GW of electrolysers already in the 2030 perspective. This is expected to enable the production of approximately 193643 tons of green hydrogen. According to the EU hydrogen strategy (European Commission, 2020a), by 2030, the construction of 40 GW electrolysers is assumed, and up to 500 GW by 2050. Poland could ultimately have even more than 20 GW of electrolysers. On the demand side, hydrogen is combusted in two CCGT units in Ostrołęka and Dolna Odra, as well as in peak-load power plants with a total capacity of 3 GW in 2040[30]. It is worth noting that the surplus of energy from RES in the discussed scenario allows to produce a quantity of hydrogen significantly exceeding the demand (Chapter 5). This therefore opens up the potential for future export of green hydrogen as well as its use in other sectors of economy – e.g. transport and industry.

30 Modeled as OCGT units with an efficiency of 40%

4.5. Connection capacity

The above considerations did not discuss the issue of the connection capacity availability on the side of the Distribution Network Operators and the Transmission System Operator. According to the forecast of the Institute for Renewable Energy (IEO, 2021), the connection capacity available for new electricity sources is currently 11.6 GW. Its increase up to 14.2 GW in 2025, by a maximum of 1.1 GW per year is planned. By 2025, the total capacity increase of onshore photovoltaic and wind systems is 18 GW, which would mean that the available connection capacity would be exceeded by approx. 4 GW. On the other hand, even in the conservative *Transmission Network Development Plan for the years 2021–2030*, it is expected that 4.9 GW of centrally dispatched generating units in the horizon 2025 (PSE, 2020) will be switched off, in 2021 alone this will be 2.1 GW (whereas a new power unit in Turów with a capacity of 0.5 GW has been put into operation). In the Instrat scenario, the shutdowns of coal-fired power units in 2021–2025 amount even to as much as 12 GW. Additional exclusions will cover coal-fired combined heat and power plants, however, these will be systematically replaced with gas units, so they have been omitted in these considerations.

Figure 26. Availability of connection capacity in individual voivodeships [MW]



Source: Internal analysis based on the IEO data

In subsequent years, the increase in connection capacity at the level of approx. 1 GW per year may not be sufficient for the required rate of RES development, even after taking into account the shutdowns of coal-fired power units. Additionally, in 2026–2027, offshore wind farms (for which, in fact, a dedicated network infrastructure is planned) and potentially new gas-fired power units (which, however, will be connected instead of coal--fired power units) will be connected to the energy mix. High hopes can be placed on the development of energy storage facilities, which will reduce the network load and the flows from the prosumers, potentially increasing the connection capacity available for other technologies.

The spatial distribution of the available connection capacity is a major challenge – it is currently very uneven (Fig. 26) and only partially overlaps with the potential of wind and solar energy (Fig. 8 and Fig. 17). While the western part of the country has good conditions for connection of the RES systems, e.g. in Warmińsko-Mazurskie Voivodeship, characterized by a huge RES potential, it is almost impossible to connect new capacities.

Therefore, the investment expenditures at the level of transmission and distribution networks must be increased and the achievement of the required rate of RES development, and thus EU climate targets, will require a huge mobilization on the part of network operators. The issue of the transmission networks modernization costs was discussed in more detail in the third publication from the cycle: The missing element. Energy security considerations.

5. Impact of the RES development on the National Power System

The assumptions concerning the development of individual technologies were used to create a coal phase-out scenario, and subsequently to carry out an optimization using the PyPSA-PL model described in the Achieving the goal report (after: Brown, Hörsch, Schlachtberger, 2018). This study proposes to update the scenario from March 2021 and compares the results with the PEP2040 adopted in February 2021[31].

The summary of the analysis results is presented in Tab. 7 and discussed in detail in the following subchapters. With a conservative pace of commissioning new wind and solar plants, the RES share in electricity generation may exceed 70% in 2030. At the same time, the share of coal will decrease to 12%, and after 2030, the coal-fired power units shall be used only occasionally, functioning as back-up units. Interestingly, if the PEP2040 scenario permitted the use of energy imports (in accordance with the EU law), the share of coal in electricity generation would decrease from the declared 37% to only 22% in 2030. This results from the high cost of energy generation in PEP2040, which stimulates the import from the neighboring countries, where energy may be even twice as cheap. By negating the RES development, the PEP2040 scenario may lead to an almost fourfold increase in the import volume within a decade. The application of the RES development scenario proposed by Instrat may reduce the cost of energy generation by 31–50% in relation to PEP2040 in 2030, ultimately reducing the import to half of the 2020 value. At the same time, a reduction of CO_2 emissions in the power sector is achieved in accordance with the EU's GHG-55% target – by 65% compared to 2015, and the emissions in 2030 will be more than two times lower than it has been declared in PEP2040, that is not compliant with the climate targets.

31 Obwieszczenie Ministra Klimatu i Środowiska z dnia 2 marca 2021 r. w sprawie polityki energetycznej państwa do 2040 [Announcement of the Minister of Climate and Environment of March 2, 2021 on the state energy policy until 2040].

Table 7. Comparison of the PEP2040* and Instrat scenarios against the EU 2030 climate targets

	2030				
	GHG–55% — target	GHG–55% — consequence for Poland	PEP2040 – no import	PEP2040 – with impor	Instrat
Reduction of CO2 emissions compared to 2015	-70%		-25%		-65%
CO2 emissions [mln tonnes]		40	100		46
Share of coal in electricity generation	2%		37%	22%	12%
Gross electricity generation from coal [TWh]		22	75	34	20
RES share in electricity generation	68%		32%	44%	71%
Average cost of energy generation [PLN/MWh]			554	404	279
Energy import [TWh]			0	48	28

*High CO2 price scenario

Source: Instrat's internal analysis on the basis of modeling results, PEP2040, (European Commission, 2020) and (Ecologic, 2020)

5.1. Update of the Instrat scenario

The *Achieving the goal* report scenario has been updated, taking into account the current events: legislative changes, sudden increase in CO_2 prices, RES development in Poland in the first half of 2021, investment announcements of companies, latest scientific and industry publications. The role of bioenergy has been also reduced, which translated into a deeper reduction of CO_2 emissions after 2030.

Table 8 presents the cost parameters, which have changed in relation to the Achieving the goal report (Tab. Z.1. ibidem). As the price of CO_2 emission allowances exceeded 50 EUR/t in May 2021 (energy.instrat.pl, 2021a) and the analysts predict its increase even to 65 EUR/t in the fourth quarter of 2021 (Montel, 2021), the previous assumptions have been updated in accordance with the latest BNEF forecast (BNEF, 2021) – up to 69.1 EUR/t in 2025 and 109.3 EUR/t since 2030. It is worth noting that in a longer perspective, an increase even up to 150–200 EUR/t (Pietzcker, Osorio, Rodrigues, 2021) is possible, however, due to high uncertainty of the long-term forecasts, the model conservatively assumes a stabilization of the CO_2 prices at the level from 2030. The forecasts for the green hydrogen prices have been also updated, since the latest BNEF data indicate a decrease in prices even below 1.5 EUR/kg in 2030 and below 1 EUR/kg in 2050 (cf.: RechargeNews.com, 2021). Therefore, the minimum value indicated in the EU *Hydrogen Strategy* (European Commission, 2020a) has been adopted for 2040 – 1.1 EUR/kg. Other cost parameters – prices of coal, gas, etc. remain in accordance with the *Achieving the goal report* (Tab. Z.1).

Table 8. Updated cost parameters used in modeling

Parameter	Unit	2020	2025	2030	2035	2040	Source
Price of CO2 emissions allowances	EUR/t	26.5	69.1	108.3	108.3	108.3	(BNEF, 2021)
Green hydrogen price	EUR/kg				1.5	1.1	(Renew Economy, 2021; RechargeNews, 2021 za: BNEF)

Source: internal analysis

With reference to the Achieving the goal report, the fleet of the planned gas-fired combined heat and power plants has been updated in accordance with the latest investment plans, which slightly reduced the capacity in the segment of coal-fired combined heat and power plants by 0.8 GW in 2040, at the same time, increasing the capacity of gas-fired CHP units by 1.2 GW in 2040.

Finally, the rate of development of photovoltaics and the battery energy storage facilities has been updated on the basis of the trends from the first half of 2021 as well as the legislative changes (in accordance with point 4.2. and point 4.4.), and the latest commissioning dates of offshore wind farm projects have been taken into account (point 4.1.). Also, it has been proposed to significantly reduce the role of bioenergy in favor of green hydrogen peak load units (point 4.4). It is worth mentioning that the OCGT power units were used as green hydrogen peak generators, however, they could also be implemented as power units operating on the basis of fuel cells if this technology becomes competitive in terms of costs.

5.2. Impact of RES development on the power sector

The described scenario was implemented in the PyPSA-PL model, optimizing variable costs of power generation. The power system is balanced at any hour throughout the year without the application of the DSR service, which shall constitute an additional security buffer of up to 2.5 GW in 2040. As it has been mentioned, the model also uses hydrogen peak generators to achieve the required overcapacity. Detailed considerations concerning the power balance and energy security, also in the context of PEP2040, have been included in the third publication of the cycle: *The missing element.*

Similarly to the Achieving the goal report, the assumptions concerning the annual energy and power demand were taken from PEP2040/TNDP – Tab. 9, however, the hourly demand profile for 2019 was used (energy.instrat.pl, 2021d). The difference between the net and gross demands equaled +10%.

Table 9. Forecast of the net electricity and net power demands in the annual peak [GW]

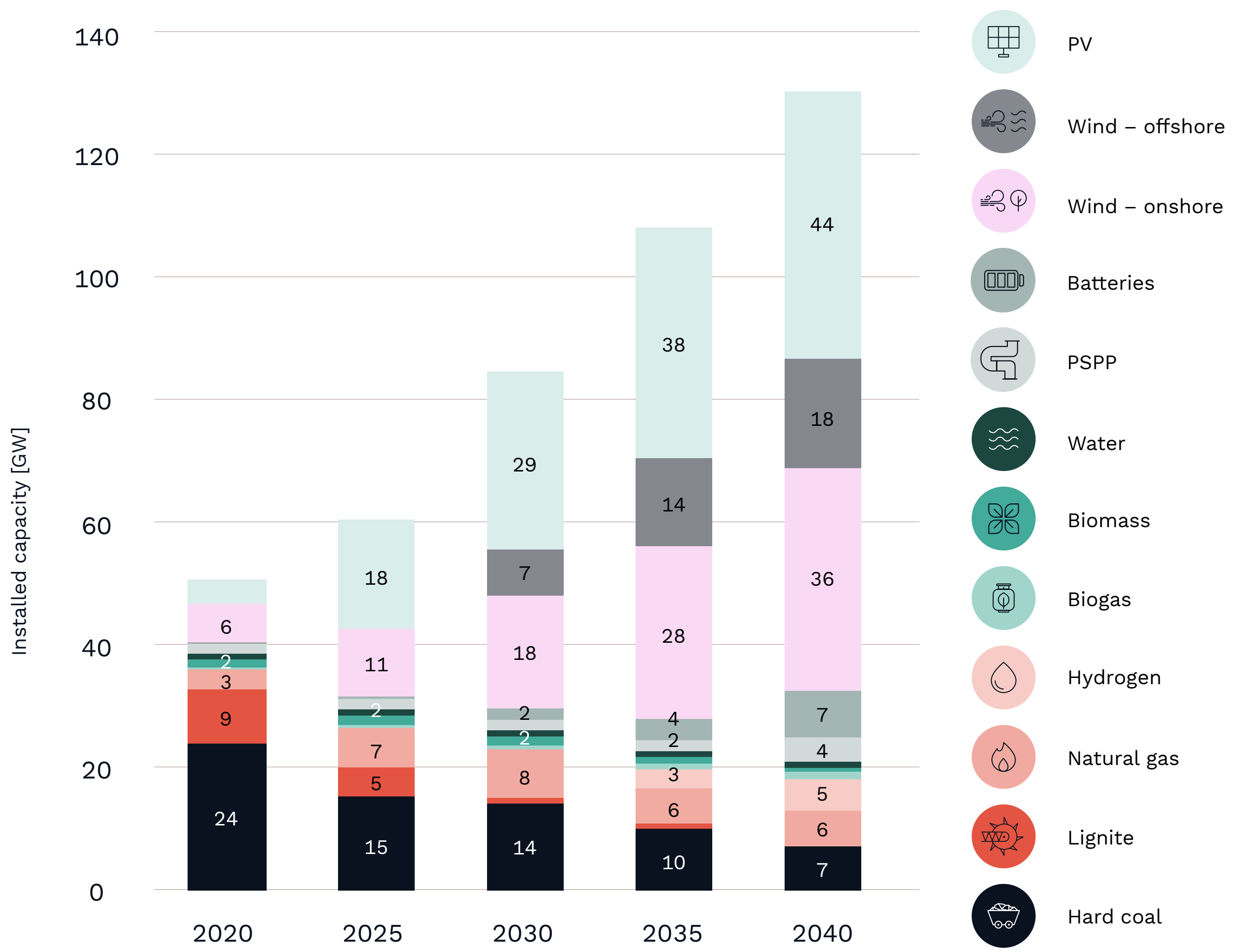
	2020	2025	2030	2035	2040
Net electricity demand [TWh]	159.9	170.1	181.1	191.9	204.2
Net power demand in the annual peak [GW]	24.5	25.9	27.7	29.5	31.3

Source: PEP2040 cf.: (PSE, 2020)

The structure of the installed capacity for the generating units and energy storage facilities is shown in Fig. 27. The change of the coal-fired power unit capacity results from the shutdown scenario described in the *Achieving the goal report*. Apart from the capacities included in Fig. 27, the operation of the DSR service is assumed at a level from the current 800–900 MW to 2500 MW in 2040. The conservative forecast of the development of cross-border connections described in the *Achieving the goal* was upheld – from the current 4.6 GW to 7.3 GW in 2030.

In 2040, the dispatchable capacity will be 35 GW – this value is almost identical as in PEP2040 (35.8 GW), despite the fact that in the latter 4.4 GW of nuclear power plants is assumed to be constructed by that time. The proposed power structure allows safe balancing in the yearly peak demand, even under complete loss of wind and solar production or unavailability of cross-border power connections. Balancing based solely on national sources is possible in the PEP2040 scenario but only if the nuclear power plant is implemented in a timely manner. Further delays in PNPP would therefore cause a long-term dependence of Poland on energy imports (described in more detail in the publication: *The missing element*).

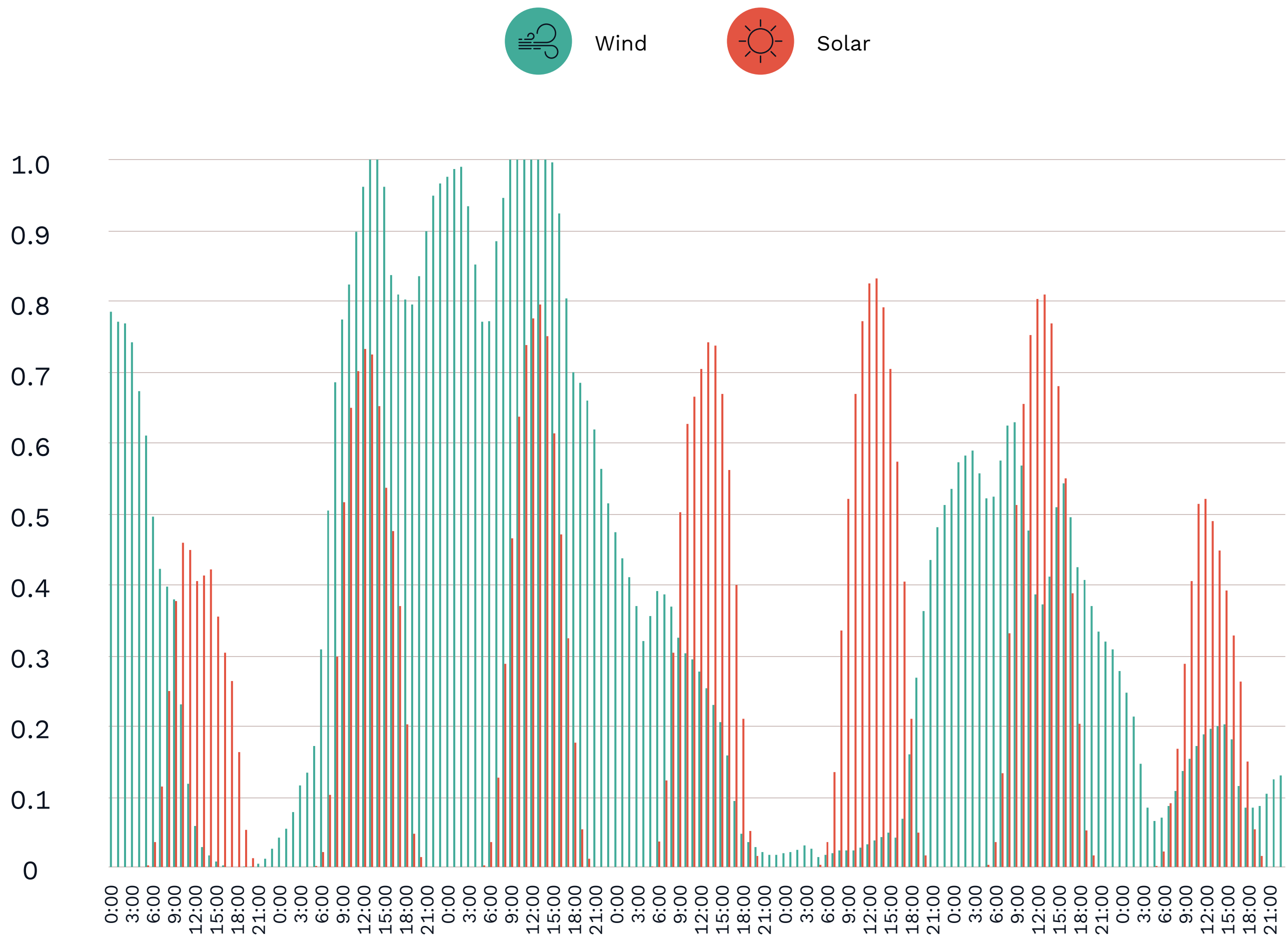
Figure 27. Installed capacity for individual technologies [GW]



Źródło: opracowanie własne Instrat, dla roku 2020 dane ARE za: energy.instrat.pl

Similarly to the Achieving the goal report, wind and solar energy generation profiles from the European Commission EMHIRES database (Energy.instrat.pl, 2021b) and the renewables.ninja project (Pfenninger & Staffell, 2016; Pfenninger & Staffell, 2016a) have been used. Also, the profile of electricity generation in combined heat and power plants, based on actual averaged values for 2019 (Energy.instrat.pl, 2021c), has not changed. The wind and solar energy generation profile for an exemplary summer week is shown in Fig. 28.

Figure 28. Hourly wind and solar generation profile in summer week



Source: internal analysis based on EMHIRES data cf.: energy.instrat.pl

The forecast of the electricity generation structure in the 2040 perspective is presented in Fig. 29. Compared to the *Achieving the goal* report, favorable changes resulting from the update of the assumptions can be observed. Due to the conversion of more combined heat and power plants into gas plants, the production of electricity from coal is being reduced in favor of natural gas. In 2030, coal is only responsible for 20 TWh of electricity – it is a value consistent with the trajectory resulting from the EU's GHG-55% target (Czyżak & Wrona, 2021). The production of energy from biomass and biogas was significantly reduced, to 12 TWh in 2040. Preponing of the Bałtyk I offshore wind farm commissioning enables the reduction of import in 2030. The RES development contributes to the reduction of import in the long run – in 2040 to almost half of the 2020 value. Of course, in the medium term, import increases due to the high costs of energy generation from coal. After 2035, green hydrogen appears in the energy mix – it could ultimately replace the entirety of natural gas and coal (after the conversion of all combined heat and power plants and industrial units).

As a reference point, the PyPSA-PL model implements the “High CO2 price” scenario from PEP2040, based on the installed capacities from Appendix. 2 to PEP2040 (in the version adopted in February 2021). Two possible situations have been investigated – with the energy import blockage (in accordance with the generation structure included in the government document) and with import enabled (in accordance with EU law). The capacity of cross-border links and import costs were left at the same level as in the Instrat scenario, similarly to basic price assumptions, technical assumptions, etc.

In 2030, the RES share in electricity generation exceeds 70%. (Fig. 30). This is slightly less than in the Achieving the goal scenario, due to the reduction in the use of biomass and biogas. It should be emphasized that a 71% RES share is obtained despite the conservative assumptions concerning the pace of construction of new wind and solar turbines. In PEP2040, the RES share is to amount to 32% in 2030, however, this value is completely unrealistic – obtained only in the conditions of energy import blockage, which is not possible in the European Union. If import was allowed on market terms in the PEP2040 scenario, it would increase rapidly – even up to 48 TWh in 2030. (Fig. 31)[32]. This in turn would push the coal-fired power sector out of the mix, increasing the RES share in domestic production to 44% and reducing the share of coal to 22% in 2030. In the light of these considerations, the share of coal at the level of 12% in the Instrat scenario becomes much less controversial.

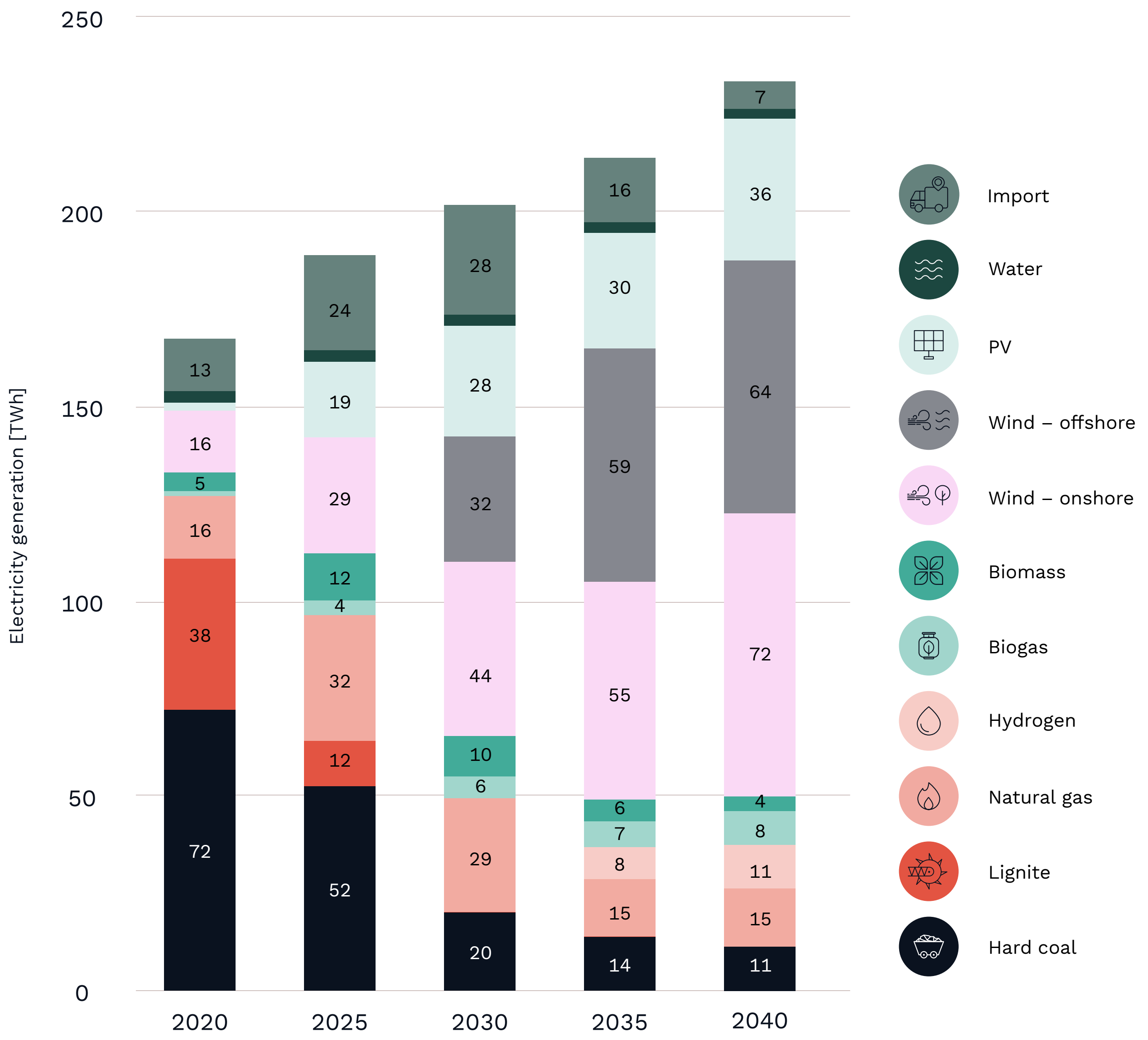
Dramatically low ambitions concerning the development of RES in PEP2040 lead not only to the dependence of Poland on energy import, but also to a sudden increase in the costs of energy generation. In the “High CO_2 price” scenario without import, the average Short-Run Marginal Cost of electricity production[33] by 2030 increases more than twofold (by 123%) in relation to the values from the end of 2020 and is twice as high as in the Instrat scenario. It should be mentioned that the increase in the prices of CO_2 emission allowances in the first half of 2021 means that already now the cost of generation is closer to the values from 2025 – at ETS prices of 50 EUR/t it amounts to approx. 344 PLN/MWh. Even with such a reference point, the PEP2040 scenario will lead to a further SRMC increase in the 2025 and 2030 perspectives. In the years 2030–2040, the SRMC for the PEP2040 scenario

32

33 SRMC – marginal cost of electricity generation, it does not directly translate into energy prices in households, but it should be treated as a value below which the wholesale energy price/energy price on the forward market cannot fall. These in turn shape the tariffs (which may take place with a certain delay, as it requires approval by the Energy Regulatory Office). The subject is discussed in more detail in the publication: The missing element.

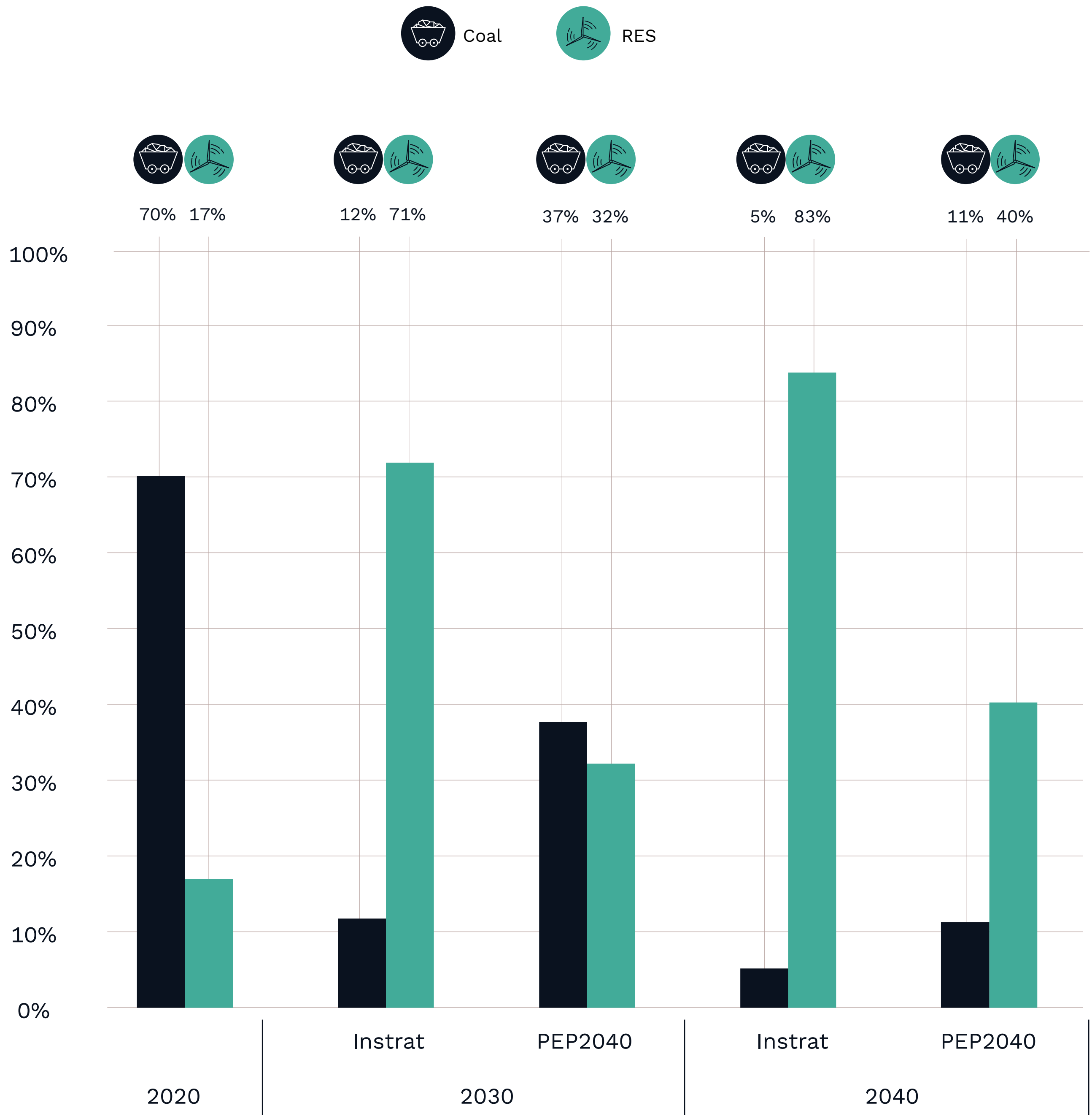
with import shall amount to 44%, 96% and 146% more than in the Instrat scenario. For the PEP2040 scenario without import, already in 2030 SRMC is 98% higher than in the Instrat scenario, and in later years, this difference may even amount to 218%. In the Instrat scenario, already in 2030, the generation cost drops below the value from the first half of 2021, and in 2040 it is 44% lower than in 2020, which also reduces the import by 48% compared to 2020. In the PEP2040 scenario, SRMC is slightly decreasing since 2035 due to the planned commissioning of a nuclear power plant, but even the values in 2040 exceed the values of 2020. This means that Poland would still have a more expensive energy mix than the neighboring countries and would be forced to become a net importer.

Figure 29. Gross electricity generation for individual technologies [TWh]



Source: Instrat's internal analysis based on modeling results, 2020 ARE data cf.: energy.instrat.pl

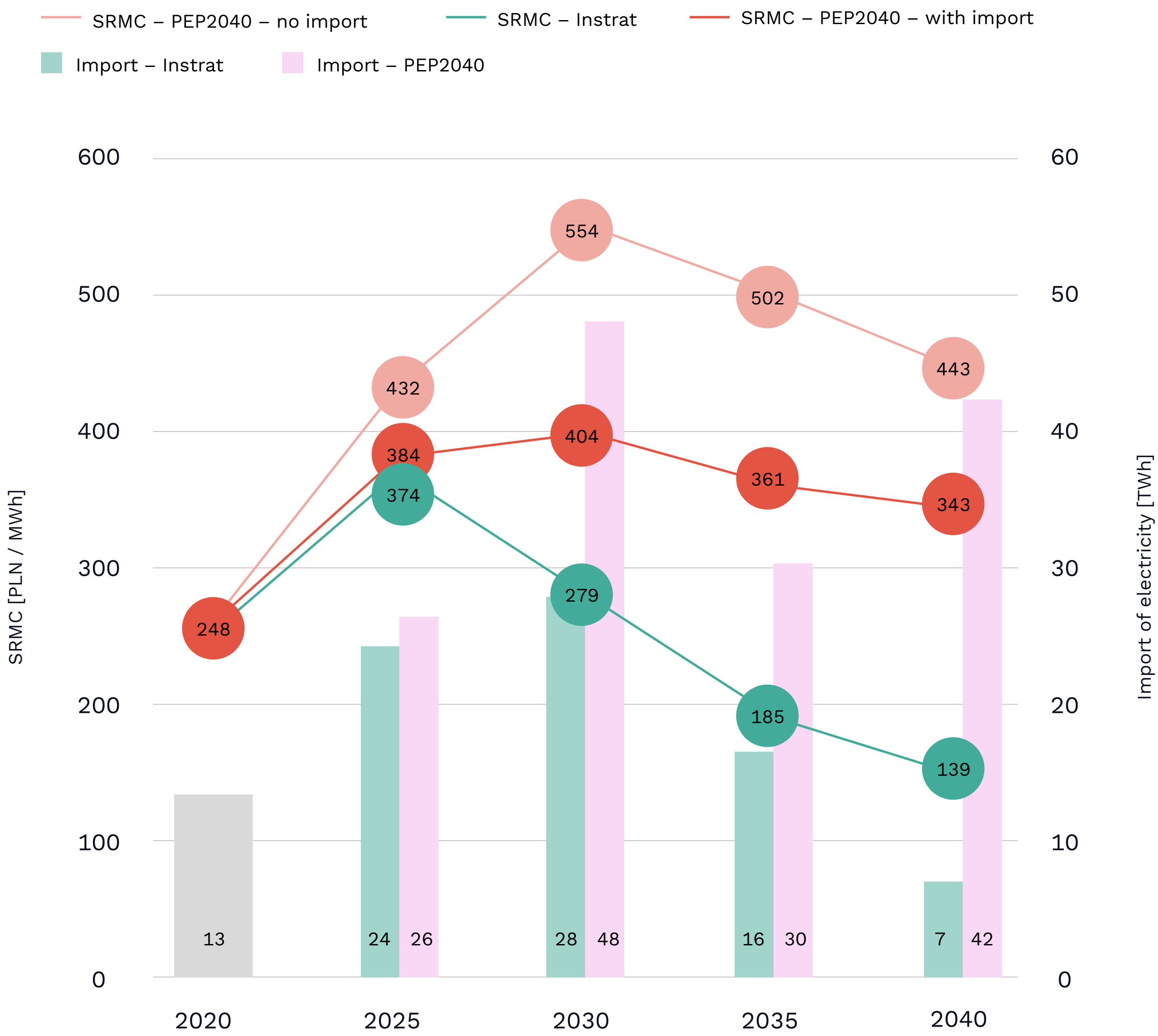
Figure 30. Share of fossil fuels and RES in domestic electricity generation



Source: Instrat's internal analysis based on modeling results and PEP2040, for 2020 ARE data cf.: energy.instrat.pl

It should be noted that in the Instrat scenario, the load of cross-border connections does not increase significantly in relation to 2020 – in 2020 it amounted to 33%, and in 2030 it would increase to 43%. This means that the implementation of import values resulting from cost optimization should not pose a technical challenge. According to the EU regulations, since 2025, the Transmission System Operator is obliged to make available 70% of the technical capacity of cross-border links for market flow needs. High SRMC of the PEP2040 scenario will therefore lead to a sudden increase in import, which in 2030 will reach as much as 75% of the technical capacity of the links. Such a value may not be feasible, which would involve the necessity to activate more coal-fired generating units than the optimum number, and thus increasing the SRMC. Full availability of energy supply is also assumed from the neighboring countries, which is an obvious simplification. However, in the PEP2040 scenario, import is utilized not only in times of peak demand and limited supply of wind/solar energy (as in the Instrat scenario), but mainly instead of the expensive Polish coal-fired power units. This means that import takes place also in times of huge energy surplus in other countries, which may sell them to Poland at higher prices than on their domestic market, still competing effectively with the Polish power plants.

Figure 31. Average Short-Run Marginal Cost of electricity generation



Source: Instrat's internal analysis

Obviously, considerations on the average cost of energy generation do not give a full picture of price formation on the energy market, in particular due to the application of regulated tariffs for households. The subject is discussed in more detail in the publication: The missing element. However, it is worth mentioning one of the important aspects of the RES development – the occurrence of surplus energy. The variability of wind and solar energy generation profiles and a mismatch with the demand profile means that there is a shortage or surplus of generation in individual hours throughout the year. This phenomenon can be partially mitigated by the use of energy storage facilities or dynamic demand control. However, in the majority of scenarios with a high RES share in the energy mix, the surplus amounts to even several dozen percent of production capacity, which in turn poses a risk to the profitability of the RES systems and/or the necessity to implement of additional compensation of lost profits by the state. One way to respond to this challenge is to use surplus RES energy to produce green hydrogen in the electrolysis process.

Installing 10 GW of electrolysers by 2040 would allow to produce 0.97 million tons of green hydrogen[34]. This is significantly higher than the hydrogen demand in the proposed CCGT and OCGT power units – 0.62 million tons in 2040. Hydrogen production for transport or industry would therefore also be possible. Producing these 0.97 million tons of green hydrogen would absorb approx. 50.4 TWh of electricity[35] – almost all the surplus energy from RES in 2040 (57 TWh)[36]. According to Aurora Energy Research (2021) estimates, the use of electrolysers may reduce the unused solar energy ratio to 1 percent and onshore wind to 5 percent in 2040. The use of electrolysers would also increase the power utilization rate in a potential nuclear power plant. It is worth noting that, in the scenario being discussed, the total efficiency of using green hydrogen is very low (approx. 30%) due to its combustion, among other things, in OCGT power units. In the future, the higher efficiency of electrolysers and the widespread use of fuel cells should be expected, which would increase the efficiency of the entire process (electricity – > hydrogen – > electricity) to as much as 50%.

The updated Instrat scenario leads to a higher reduction of CO_2 emissions in the power sector – by as much as 65.5% in 2030 compared to 2015 (Fig. 32), which corresponds nearly to the value planned for the entire EU – 70% (European Commission, 2020). After 2030, it is possible to further reduce emissions to 27 million tons in 2040 – this is 40% less than in the Achieving the goal report, which results mainly from the reduction of high-emission combustion of biomass and biogas. The value achieved in 2030 and 2040 is

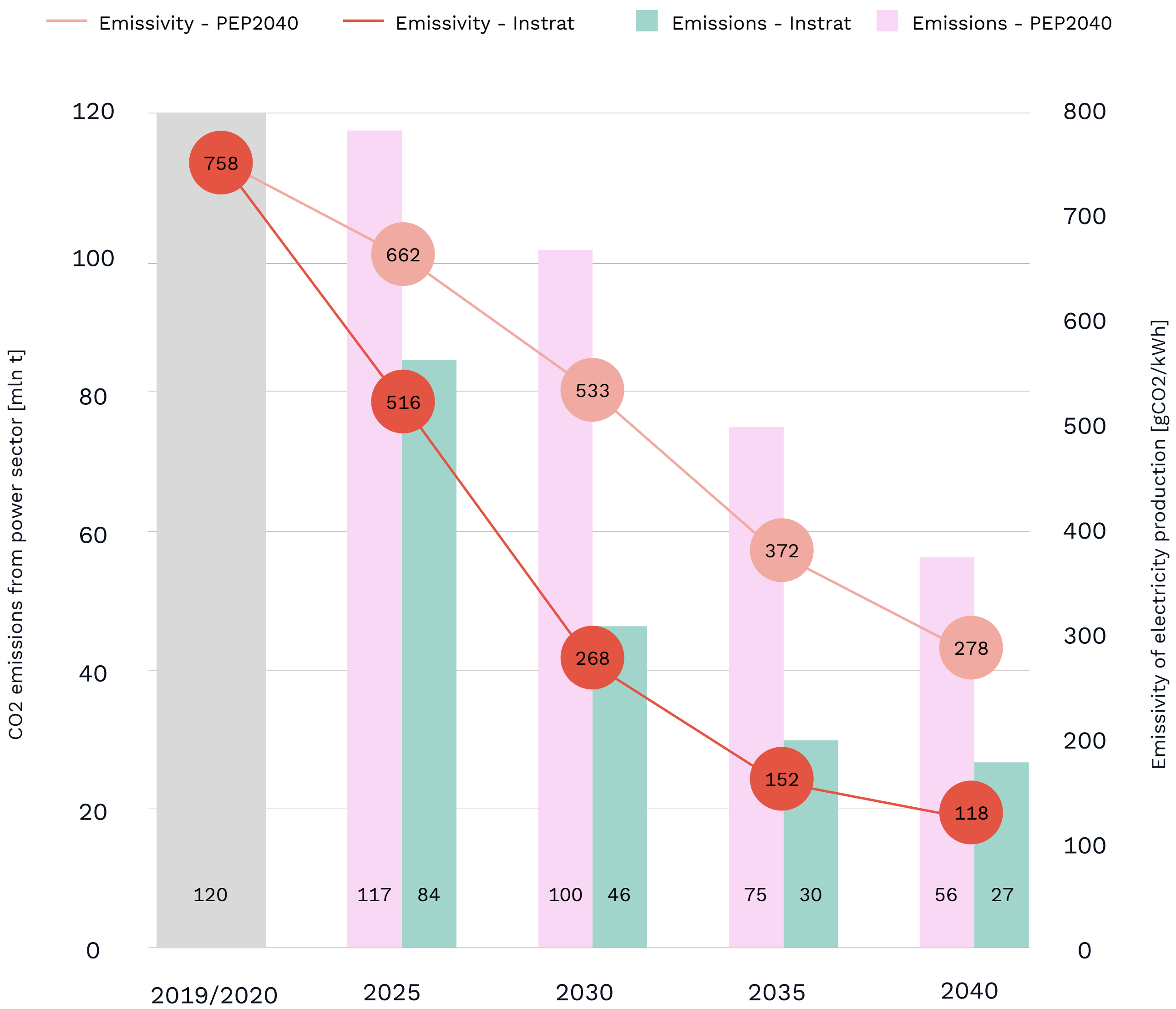
34 Assuming 5000 operating hours per year and 70% efficiency – in accordance with the draft of the Polish Hydrogen Strategy (MKiŚ, 2021a).

35 As above, at 70% efficiency and 130 MJ/kg calorific value.

36 A detailed analysis of the issue would require the implementation of electrolysers in the model, which is beyond the scope of this document. If hydrogen production profiles were not optimized and energy was consumed only when surplus RES occurs, electrolysers with the power output of 10 GW could consume 28 TWh of this surplus. However, hydrogen production is expected to be controlled dynamically, including adjusting the electrolyser load to the national energy demand, production from individual sources, import profile, etc., therefore allowing for their optimized use and maximum reduction of surplus energy from RES.

more than 50% lower than in the PEP2040 scenario, which is not compatible with the EU's GHG-55% target. In the Instrat scenario, the emissivity per unit of electricity produced drops to 268 gCO_2 / kWh in 2030 and 118 gCO_2 / kWh in 2040 – it is almost ten times less than in some units of the Bełchatów or Pątnów Power Plants. The best hard coal units achieve an emissivity of 700 gCO_2 / kWh (Jaworzno 2 B7, Kozienice B11, Opole B5-6, Łagisza B10). In PEP2040, the emissivity in 2030-2040 is more or less twice as high as in the Instrat scenario, in 2035 it still exceeds the value typically assumed for gas energy – 300-350 gCO_2 / kWh, which would mean that in the 30s Poland would still have the most emissive electricity mix in the European Union.

Figure 32. CO2 emissions from the power sector



Source: Instrat's internal analysis on the basis of modeling results and data from Eurostat, ARE, EEA, KOBiZE, energy.instrat.pl, PEP2040

In 2040, the breakdown of emissions is dominated by combined heat and power plants – 38.5%, then industrial power plants – 24.2%, biogas and biomass – 22.1% and other conventional units – 12%. Efforts to fully decarbonize the power sector must therefore focus on the heat sector in which coal-fired power units should be replaced with gas-fired ones with hydrogen co-combustion. A similar transformation should be carried out among industrial plants. By 2050, biogas and biomass combustion plants will probably have to be equipped with carbon capture and storage systems. However, it should be emphasized that the scenario proposed by Instrat leads to a four-fold reduction of CO2 emissions in the years 2020–2040, allowing not only to meet the EU targets for 2030, but also moving the Polish power sector close to the climate neutrality target in 2050.

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