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IS PHOTOVOLTAIC CAPABLE TO REPLACE HEAT POWER PLANTS IN THE FUTURE?

CZY FOTOWOLTAIKA JEST W STANIE ZASTĄPIĆ W PRZYSZŁOŚCI ELEKTROWNIE CIEPLNE?

***Summary**: A sudden gain of power installed in Polish photovoltaics during the recent years has been undoubtedly a great surprise for all. From the marginal position few years ago photovoltaics has become the unquestionable leader in respect of the installed power value from among the different types of renewable electric energy sources. It is anticipated that in the current year, the total value of power installed in Polish photovoltaic system will exceed value of 15 GW, leaving far behind – in this respect - wind energetics, even not mentioning other renewable sources of electric energy. Obtaining such high results was mainly possible owing to the state subsidies, developed governmental programs but also to a common enthusiasm which was the share of broad masses of our society – possessing of own power plant on the roof of one's house became, at a certain moment, something fashionable and also, something which the majority of the owners of single family houses wanted to possess (at least to impress the neighbours). A specific euphoria which appeared in connection with the photovoltaics causes that there are announced extremely ambitious plans for its further development and the anticipated future values of the power installed in the photovoltaic panels make you feel dizzy. During the mentioned discussions, we forget that the heat power plants in Poland still constitute the basis of functioning of electric energy system. They produce still more than ca. ¾ of electric energy, produced in our country. Meanwhile, we may often and often meet the publicly announced opinion that heat power plants are no longer necessary because in the nearest future, the decided majority of the electric energy consumed in the country will come only and exclusively from renewable sources; the supreme role will be, of course, played by photovoltaics. Indeed, according to the respective decisions, which were once undertaken by the governmental authorities, most of the Polish coal-fired power plants will cease completely their activity as soon as during the nearest several years.*

The authors of the present paper undertake the attempt to answer the question: whether photovoltaics will be able to replace, in the future, Polish heat power plants, intended for liquidation. The answer to such question is univocally negative and not only due to the seasonality of electric energy production in photovoltaic installations but, first of all, due to the impossibility to introduce a very high power (order of tens of gigawatts) to electric network at the peak moment of its generation in photovoltaic installations. The necessary balancing of such high levels of power in the national electro-energetic system is also impossible. The authors try also to give the answer to the question: where we are now in respect of the degree of advancement of investments in photovoltaics and in connection with it, how much electric power may be additionally installed in Polish photovoltaic power plants. The next problem, undertaken by the authors is the attempt to estimate what percentage of the national demand on electric energy may be covered from photovoltaic installations, with the simultaneous economic justification.

***Keywords**: electric power, heat power plants, renewable energy sources, photovoltaics*

***Streszczenie**: Gwałtowny przyrost w ostatnich latach mocy zainstalowanej w polskiej fotowoltaice był bez wątpienia dla wszystkich sporym zaskoczeniem. Z pozycji jeszcze kilka lat temu wyraźnie marginalnej fotowoltaika wysunęła się obecnie pod względem wartości mocy zainstalowanej na niekwestionowanego lidera spośród różnego rodzaju odnawialnych źródeł energii elektrycznej. Przewiduje się, że w bieżącym roku całkowita wartość mocy zainstalowanej w polskiej fotowoltaice przekroczy wartość 15 GW, daleko dystansując pod tym względem energetykę wiatrową, a o innych odnawialnych źródłach energii elektrycznej nawet nie wspominając. Uzyskanie tak wysokiego wyniku stało się możliwe głównie dzięki dotacjom państwowym, rozbudowanym programom rządowym, ale także poprzez zwykły entuzjazm, który udzielił się szerokim masom naszego społeczeństwa – posiadanie na dachu jednorodzinnego domku własnej elektrowni stało się w pewnym momencie po prostu czymś modnym, a także czymś, co większość właścicieli budynków jednorodzinnych chciałaby koniecznie posiadać, chociażby po to, aby zaimponować swoim sąsiadom. Swoista euforia, która zapanowała wokół fotowoltaiki powoduje, że powszechnie głoszone są niezwykle ambitne plany dalszego jej rozwoju, a przewidywane w przyszłości wartości mocy zainstalowanej w panelach fotowoltaicznych przyprawiają wręcz o zawrót głowy. Podczas tego rodzaju dyskusji zapomina się, że w Polsce elektrownie cieplne nadal stanowią podstawę funkcjonowania systemu elektroenergetycznego i to właśnie w nich wytwarzane jest nadal około trzech czwartych produkowanej w naszym kraju energii elektrycznej. Tymczasem coraz częściej można spotkać się z wygłaszanymi na forum publicznym opiniami, że elektrownie cieplne nie są nam już więcej potrzebne, ponieważ w najbliższej przyszłości zdecydowana większość konsumowanej w kraju energii elektrycznej pochodziła będzie tylko i wyłącznie ze źródeł odnawialnych, gdzie oczywiście nadrzędną rolę odgrywać będzie fotowoltaika. Istotnie, zgodnie z ustaleniami, która zapadły swego czasu na szczeblu rządowym zdecydowana większość polskich elektrowni cieplnych opalanych węglem kamiennym bądź brunatnym ma przestać całkowicie istnieć już w przeciągu najbliższych kilkunastu lat.*

Autorzy artykułu podejmują próbę udzielenia odpowiedzi na pytanie, czy fotowoltaika będzie mogła w przyszłości zastąpić przeznaczone do likwidacji polskie elektrownie cieplne. Odpowiedź na tak postawione pytanie jest jednoznacznie negatywna i to nie tylko z powodu sezonowości produkcji energii elektrycznej w instalacjach fotowoltaicznej, ale przed wszystkim z powodu niemożności wprowadzenia do sieci elektroenergetycznych mocy rzędu dziesiątek gigawatów w szczycie jej produkcji w instalacjach fotowoltaicznych oraz niewykonalności koniecznego zbilansowania tak wielkich poziomów mocy w krajowym systemie elektroenergetycznym. Autorzy usiłują także udzielić odpowiedzi na pytanie, w jakim miejscu pod względem stopnia zaawansowania inwestycji w fotowoltaikę obecnie się znajdujemy i w związku z tym, ile mocy elektrycznej można w polskich elektrowniach fotowoltaicznych jeszcze dodatkowo zainstalować. Kolejną kwestią poruszoną przez autorów, jest próba oszacowania, jaki procent krajowego zapotrzebowania na energię elektryczną można maksymalnie pokryć z instalacji fotowoltaicznych, aby tego rodzaju postępowanie było jeszcze w jakikolwiek sposób uzasadnione ekonomicznie.

***Słowa kluczowe**: elektroenergetyka, elektrownie cieplne, odnawialne źródła energii, fotowoltaika*

Introduction

Undoubtedly, the electric power engineering is not the most important and, simultaneously, the most neuralgic sector of the national economy. Without effectively functioning power energy, it is difficult to imagine functioning of anything in the contemporary world. Power system, as functioning in the reliable way, is absolutely necessary for functioning of the total national industry, transport, trade, service, education, administration, defending system, financial sector and data centres. In general, it is necessary for common people to run normal life in the contemporary reality. Shortly speaking, power engineering is the most important issue!

In connection with the above facts, it seems to be evident that the introduction of any changes of fundamental nature in the domain neuralgic for functioning of the whole economy of the country and total social life must be first very deeply and thoroughly thought out and then, analysed in detail in all possible aspects. Committing any cardinal error as early as in the conception stage may result in the consequences of tragic character and, also, exert the catastrophic impact on the economy of the whole country; such consequences would be painfully sensible to the coming decades.

The stem of Polish electric energy system has been always constituted by black or brown-coal-fired power plants [5]. They are still responsible for the production of ca. ¾ of electric energy, produced in our country. At the same time, they are perceived as extremely reliable and exceptional stable sources of electric power as being almost completely insensitive to any caprices of the weather. In the coming years, it will be, however, subjected to radical changes because after several years, a decided majority of the functioning nowadays heat power plants is going to stop their work. On the other hand, their role will be undertaken, to a great extent, by renewable energy source from among which the photovoltaics is presently found at the first position.

Polish heat power plants

Table 1 contains basic information concerning nine greatest thermal power plants, being found at the territory of Poland. The power installed in each of the mentioned plants exceeds value of 1 GW.

From among the mentioned nine greatest thermal power plants, only two and based on the brown coal and in the remaining eight plants, the black coal is the basic type of fuel (additionally, in some of them, the boilers for burning of biomass have been installed but their meaning is rather marginal). When summing up the data found in Table 1, we may calculate that in the reasonable power plants there was installed total power accounting to 22.402 GW.

As it was earlier mentioned, the direction of the present energetic policy of the state assumes that at the beginning of the thirties of the 21th century, the mentioned above power plants will stop to exist at all – we are leaving carbon forever. By the way, it is worth noticing that in the countries such as China, India and numerous Asia countries, the trend is accurately opposite; besides it, the participation of the EU countries in the emission of $C0_2$ is only ca. 8% of its world emission what constitutes less than ca. 0.5% of its natural emission, connected mainly with the breathing processes of living organisms inhabiting our Globe.

Moreover, when investigating the public opinions of various home-grown or self-proclaimed “experts” in the field of electric energy power (they are most frequently the persons without any technical education) we may get the impression that the wide masses of our nation are convinced that such almost revolutionary energetic transformation will be pass without any pain and may only get much profit because we will possess cheap and pure electric current! So the advantage would be doubled! Why do we need these smoking carbon-based power plants, we will have completely pure (for the environment) photovoltaic at our disposal. By the way, the harmfulness of the total production connected with the manufacture of silicate monocrystals in relation to the environment is not mentioned at all (similarly as in the case of birds and bats which die after the “near meeting” with the rotating sales of windmills).

The impact of geographical latitude on profitability of photovoltaics

The profitability of photovoltaics is dependent first of all on the geographic latitude in which there were placed the semiconductor panels, transforming the energy of solar radiation into electric energy [1]. The most favourable conditions in this respect are found on the Earth’s Equator. More we are going away from the equator towards one of the earth’s poles, more the profitability of photovoltaics becomes decreased because of the seasonality of production; there are greater and greater discrepancies between the period spring-summer and

Table 1. The data concerning the greatest Polish heat power plants

Name	Year of launching	The installed power	Basic type of fueal	Operator
Bełchatów	1981	5,102 GW	Brown coal	PGE
Kozienice	1972	4,016 GW	Black coal	Enea
Opole	1988	3,342 GW	Black coal	PGE
Jaworzno	1979	2,255 GW	Black coal	Tauron
Połaniec	1979	1,882 GW	Black coal	Enea
Rybnik	1972	1,800 GW	Black coal	PGE
Turów	1962	1,488 GW	Brown coal	PGE
Dolna Odra	1974	1,362 GW	Black coal	PGE
Łaziska	1917	1,155 GW	Black coal	Tauron

analogical period autumn-winter. In the case of photovoltaic installations being found in the area between Tropic of Cancer and Tropic of Capricorn we may, in simplification, adopt that the considered production seasonality as a rule does not occur at all – in the discussed site the conditions for work of photovoltaic installations are optimal in this respect. When we, however begin to go away from the mentioned earth poles, the considered seasonality begins to play a more and more meaningful role.

The 50th parallel of the north latitude runs through the southern borders of Cracow. In connection with this fact, a greater part of our country is situated towards north from the mentioned 50th parallel. In the case of the installed photovoltaic panels at the mentioned site, it is difficult to speak about any optimal placement of these installations – in the contrary, the production seasonality there has a very big meaning. In effect, the photovoltaic installations, as being found as the territory of Poland work effectively only in the period of spring-summer where a day is relatively long and a night is short and the sun is suspended for a longer time relatively highly over the horizon. In turn, during the period of autumn-winter, production of electric energy from Polish photovoltaic installations is found, as a rule, on the symbolic level and the electric power plants of this type cannot have, especially in winter period, any significant meaning in the electric energy system.

In the connection with the above facts, we may adopt that value of mean annual indicator of utilization of the power, installed in the case of photovoltaic installations present ast the territory of Poland is equal to ca. 50% because they work effectively as rule for a half of the year. It is not the end, because in the case of photovoltaics – apart from the production seasonality – we have to deal with its daily cyclicality: the installations of this type function only when the sun is shining – in the night, the power generated by photovoltaic panels is equal exactly to zero watts. In connection with this fact, value of mean annual indicator of utilization of the power, installed in Polish photovoltaics panels must remain lowered down to 25%; they work, as a rule, only for a half of the year and moreover, for a half of 24h.

Unfortunately, the mean annual coefficient of utilization of the power installed in the photovoltaic system, as being analysed in practice, has a considerably lower value which does not exceed usually only 10%. Where does so big decline of the value of the considered coefficient come from?

First of all, it comes from the fact of installing the photovoltaic panels as immobile installations which at any rate do not follow the current situation of the sun on the sky. It causes that the angle of arranging the plane of the panels in relation to the spectrum of the bunch of solar radiuses is - for a greater part of their work – found at a very big distance from the value of optimal angle. It causes a considerable decline of the generated electric power. Additionally, the value of the generated power is also affected by cloudiness and, especially by atmospheric precipitation. In this case the decline of the generated power value may be even multiple and the photovoltaic panels covered with the snow, will not generate any electric power.

Final calculations should also consider such factors as decline of the efficiency of the process of transforming the light energy into electric energy, being caused by increased temperature of work of photovoltaic batteries what takes place especially in the summertime [1]. It is estimated that the increase in temperature of photovoltaic batteries by each Celsius centigrade above the nominal temperature of their work results in decline of the efficiency by ca. 0.3% and during the summer heats, photovoltaic panels may become heated up in a full sun shine even to more than 70oC; it results in decline of their efficiency value by as much as ca. 15%. The decline of the effectiveness of photovoltaic installations is also caused by the processes of ageing of the batteries. According to different estimates, the decrease in the effectiveness of work of the energy converting process may reach even to 1% per each successive year of the work of batteries. Therefore, after twenty, or thirty years of utilization of photovoltaic panels, it is not a small value. We cannot also forget about the losses of energy in the inverter which occur during the conversion of the direct current (DC), received directly from the photovoltaic batteries, into alternating current (AC), being sent to the electrical network [7].

As it was already mentioned, in the case of installing the photovoltaic panels in the geographical latitudes typical of our country and after having considered of the discussed above factors, we should not be surprised that value of the mean annual indicator of utilization of the installed power is only ca. 10%. Meanwhile, in the inter-tropical zone, the discussed value is twice higher due to the lack of occurrence of the considered effect fo seasonality of electric energy production. Additionally, when taking the more favourable conditions of solar radiation into account (sun passes there above the horizon considerably higher) and the lower number of cloudy days during the year, the coefficient of utilization of the installed power may reach value even above 30%; therefore, it is significantly more profitable under such conditions [1].

Perspectives for development of photovoltaic installations

The direct consequence of utilization of only 10% of the installed power, in average, in Polish photovoltaics is the fact that in order to replace the heat power plant with power of 1 GW (in respect of annual electric energy production) we should install photovoltaic panels with total power of 10 GW. During the yare of elaborating the present paper, the power installed in Polish photovoltaics should reach value of ca. 15 GW. It is accurately as much as it may be produced by average-size heat power plant with power of 1.5 GM during a year. Meanwhile, the further dynamic increase in the power installed in Polish photovoltaic panels is anticipated what may be supported by Figure 1.

As it results from Table 1, in the perspective of few coming years, the power installed in Polish photovoltaics should be doubled, reaching to value of 30 GW. Unfortunately, it is not sufficient for to replace the greatest brown coal-fired power Polish plant in Bełchatów with the power of more than 5 GW [2]. To obtain such target, it should be necessary to install more than

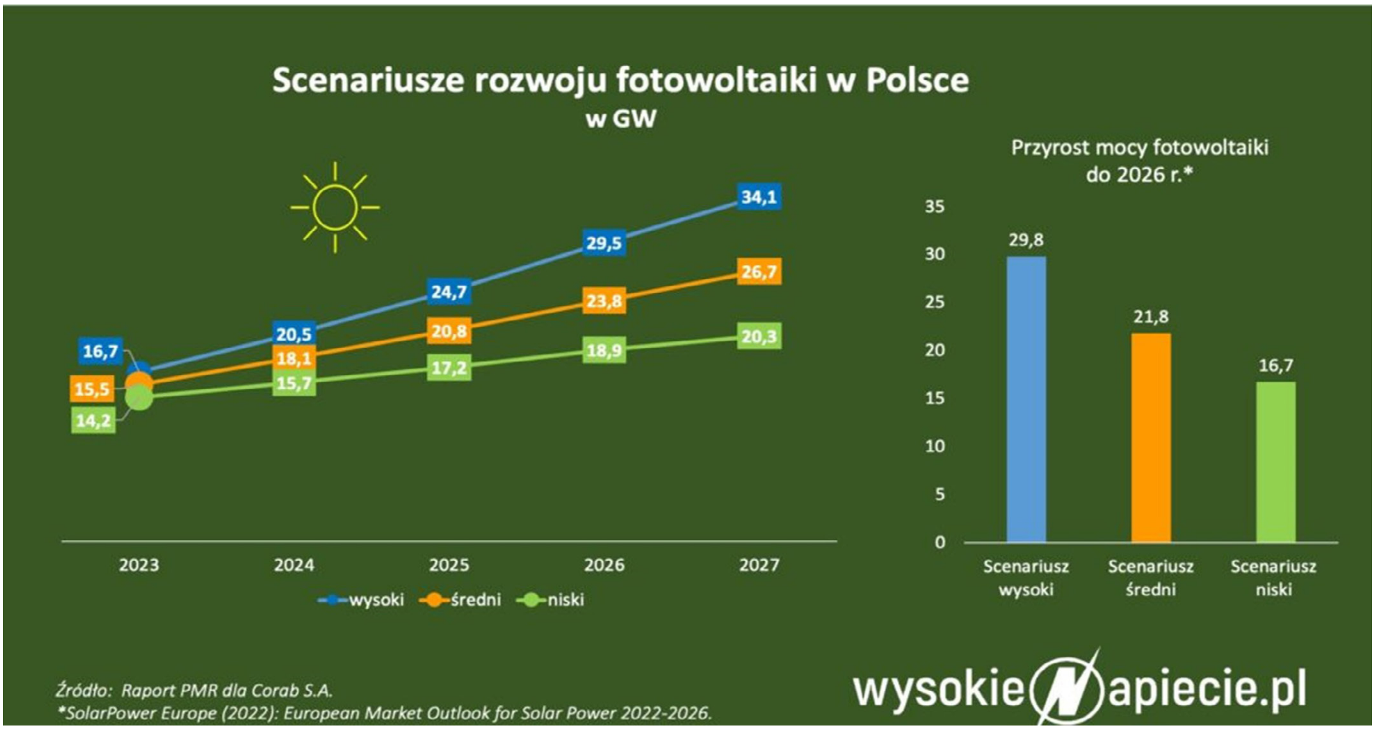

Fig. 1. Different prognoses of the increase of power, installed in Polish photovoltaics (source: https://wysokienapiecie/pl/83071-fotowoltaika-dla-firm-coraz-wazniejsza

50 GW f power in Polish photovoltaics. On the other hand, when we look at diagram, presented in Tab.1, we may expect that the mentioned level will be reached in the successive coming years because the analysed diagram seems to go constantly upwards and, what is more important, any signs of flattening are not visible.

In turn, the replacement of electric energy production coming from all mentioned greatest Polish power plants with the photovoltaic installations would require installing the total power at the level of 220 GW (to this end, *nota bene*, it would be enough to cover the roofs of the half of buildings at the territory of Poland).

Let assume, purely hypothetically that it will be possible in the future to build photovoltaic power plants with the mentioned above power, i.e. more than 200 GW. In such situation, in May, June and July at the peak of production, occurring at the 13th hour of the day (we consider, of course, summer time) photovoltaic should generate at least 100 GW of electric power in total.

We do not need convince – I hope – anybody that at the present technical state in which the national electric energy transmission networks are found, the introduction of power of the order of 100 GW is not possible at all [8]. To this purpose, it should be necessary to build ca. 50 new two-route lines, working under the tension of 400 kV. It would be the investment of almost unimaginable scale. It is enough to say that there is now considered the construction of electric energy transmitting line of direct current (DC) joining the coast of the Baltic sea and the Upper Silesia district as to send the power, generated in the wind power plants installed at the sea. The planned course of the considered line of direct current is given in Figure 2. It is expected to work under the constant tension of at least 500 kV and the implementation of the total project would last for at least ten years and cost many billions PLN. Meanwhile, the maximum transmitting ability of the considered line is to be

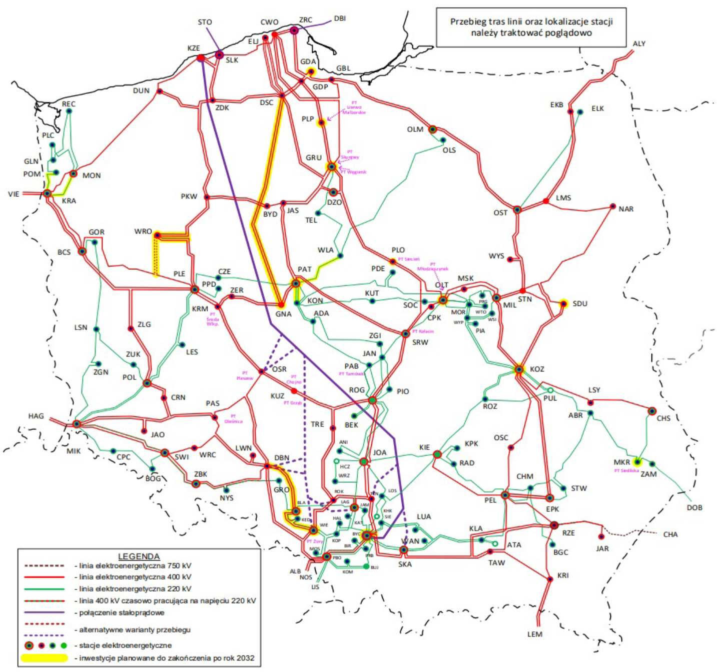

Fig. 2. Map, showing the course of the planned transmitting line of direct current, running from the vicinities of Ustka to the area of the Upper Silesia district (Source: https://swiatoze.pl/autostrada-energetyczna-polaczy-oze-na-polnocy-z-przemyslem-na-poludniu-polski-za-10 lat/)

about 4 GW what would be insignificant value as compared to the considered hypothetic 100 GW of electric power deriving from photovoltaic electric plants.

A brief analysis of Figure 2 shows that Poland has a relatively small number of electric energy transmitting lines of the highest tensions (220 and 400 kV) [4]. Moreover, many of the connections, illustrated in Figure 2, implemented under the tension of 400 kV is now found only in the stage of investment or only preliminary project.

Let's assume, purely hypothetically that in the coming years we would be able to implement the investments in electric energy transmitting lines what would facilitate introduction to them, at the peak moment, the huge powers at the level of 100 GM coming from photovoltaics. Then, we would meet the more serious problem: what we should do with such a gigantic value of the additional power? During the summer months, the demand on electric energy in Poland does not usually exceed (in the noon hours) value of 20 GM in working days and in weekends is it considerably lower. Assuming again the hypothetical situation that the whole demand on the power in the discussed period is covered only and exclusively from the photovoltaic installations (the question may be asked at this moment: so what about the wind plants and water flowing plants?) we will have the unimaginable excess of power of order about 80 GW.

How to store the energy generated in photovoltaic installations?

The first conception coming to my mind is to export the mentioned surplus to the neighbouring countries and perhaps earn on it quite well. Unfortunately, in practice, it is not so simple. In Figure 3 there are given the data made available at the Internet page of polish Electric Energy networks S.A. (PSE) on June, 4, 2023 for 14th hour of the day and night period.

DEMAND [MW]	**15 688**
GENERATION [MW]	**16 256**
Heat power plants	7 481
Water power plants	163
Wind power plants	151
Photovoltaic installations	8 460
Other renewable energy plants	0
BALANCE OF TOTAL EXCHANGE [MW]	**592 EXPORT**
FREQUENCY [Hz]	**49,993**

Fig. 3. Data concerning powers generated in the national electric energy system on June, 4, 2023 (Source: https://pse.pl/home)

As it is followed from Figure 3, during the analysed period of time, the photovoltaic power plants introduced power equal to 8.460 GM to the electric energy system, at the total demand of 15.688 GW (it was Sunday what resulted in a relatively low demand on energy). It is worth noting that at the same time, the power of heat power plants was lowered to only 7.481 GW what constitutes their technical minimum and perhaps a part of the remaining electric energy blocs was shifted to the so-called hot reserve (unfortunately, the data of such type are not published by BSE; it's a pity because it would give a more readable image of the total situation in the Polish power market). It is worthy paying attention to the fact that water flow power plants produced then small energy amount i.e. 163 MW (what is rather typical value) and wind power plants generated 151 MW (the wind was then very rare). If the wind had been strong at the discussed period, the considered power surplus in the system would have exceeded even 90 GW. In Polish wind power plants there are installed more than 9 GM of power in total and the successive investments are planned, including those ones at the area of the Baltic Sea where the velocities of wind are statistically higher.

To get familiarized with the possibilities of electric energy export to the neighbouring countries we may look at Fig.4 where the data published by PSE on the cross-border exchange of power on June 4, 2023 in the 14th hour of day and night period have been presented.

As it results from Figure 4, the power of value of 1.424 GW is introduced to the national electric energy system by two two-route transmitting lines under the tension of 400 kV from the territory of Germany. Then, the discussed electric power is transferred further *via* the territory of Poland and finally it is exported to the neighbouring countries such as Sweden (connection by permanent current cable under the bottom of the Baltic Sea), Lithuania, the Czech Republic, Slovakia and Ukraine.

On the other side, it should be admitted that during the analysed period of time, as it results from Figure 3, we exported to the neighbouring countries 592 MW of electric power in total. It is not especially impressive value; at any rate it does not solve the problem how to get rid of the hypothetic surplus of 80 GW of the power generated from the photovoltaic installations.

Export of energy, produced in photovoltaic power plants is not possible due to the fact that our west neighbour in the past invested very much in the development of photovoltaic installations and the total power of the power plants of such type has exceeded the level of 60 GW in Germany during the moment of writing the present paper; the new successive installations of this type are also constantly developed. Our south neighbours (the Czech people and Slovakians) invest also much in photovoltaics. The conditions for power generation from photovoltaic batteries are somewhat more favourable in these countries as compared to Poland (they are situated somewhat nearer to Equator). Therefore, we will be never able to export the surplus of the energy, generated in photovoltaic system to the mentioned above countries as they will have the same problem: what to do with the excessive gigawatts coming from the photovoltaic installations? The serious problems appear at

Fig. 4. The data concerning the cross-border exchange of power on June, 4, 2023 (Source: https://pse.pl/home)

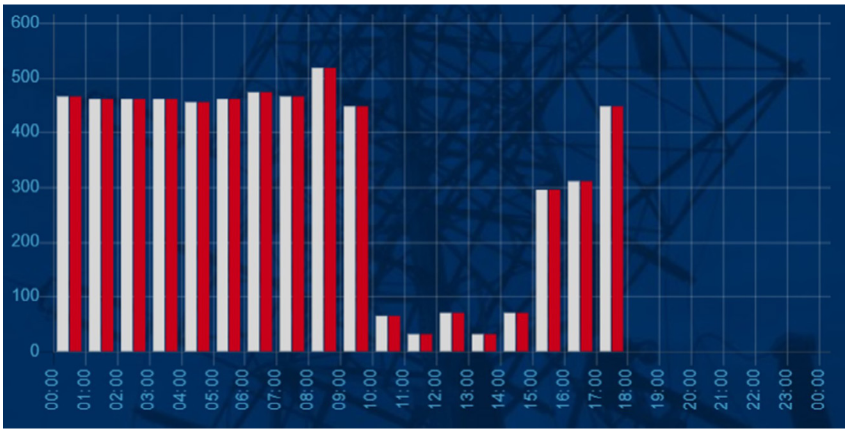

Fig. 5. Information on the gross prices of electric energy in the particular hours of 24h period, on May, 9, 2023 (Source: https://pse.pl/home)

present under the situation when during the peak moment of power generation coming from photovoltaics, the strong winds appear. Such situation occurred, *inter alia*, on May, 9, 2023. Figure 5. illustrates the data, published by PSE concerning the gross prices of energy in the particular hours of day and night period.

As it is followed from Figure 5, in the noon hours, i.e. during the peak of generation of energy from photovoltaic sources, the gross prices of electric energy dropped dramatically to the vicinities of zero (even to ca. 20 PLN per one megawatt hour). At the discussed time, the stability of work of electric power system was rescued by the extraordinary export of electric energy to our south neighbours. In practice, it was, however, giving them the energy produced in the national sources substantially as priceless.

It is worth to take a look at the situation during the so-called evening peak of loading. When dusk falls, all people switch the lights on, the street lamps become also switched and on connection with these facts, the demand on the power in the electric energy system is relatively highest. In Figure 6, there are given the data published at the Internet page of PSE on 6, June, 2023 for the 21st hour of the day and night period.

DEMAND [MW]	**19 602**
GENERATION [MW]	**17 035**
Heat power plants	14 802
Water power plants	1 050
Wind power plants	1 183
Photovoltaic installations	0
Other renewable energy plants	0
BALANCE OF TOTAL EXCHANGE [MW]	**2 529 IMPORT**
FREQUENCY [Hz]	**49,988**

Fig. 6. The data concerning the power generated in the national electric energy system on 6, June, 2023 (Source: https://pse.pl/home)

Fig. 7. The data concerning the cross-border exchange of power on June, 6, 2023 (Source: https://pse.pl/home)

As it is followed from Figure 6, in the analysed period of time, the demand on power in the national electric energy system amounted to 19,602 GW, including 14.802 GW from the heat power plants. Additionally, in the discussed period of time, wind power plants generated 1.183 GW and water power plants made the contribution of 1.050 GW. We should however mention that the recent of the discussed categories includes also pumped-storage power plants which only store (efficiency of ca. 70%) the previously produced electric energy being generated mainly in heat power plants; therefore, their classification in the category of renewable energy sources is rather questionable. From Figure 6, it is followed also that during the mentioned period of evening peak, the photovoltaic plants generated strictly zero watts and moreover we were forced to considerable import of electric energy from the neighbouring countries in amount of 2.529 GW at rather high price. The detailed data of the structure of the considered import of electric energy from the neighbouring countries have been presented in Figure 7.

As it is followed from Figure 7, during the evening peaks of energy loading, we are forced to buy, most probably at high prices, the electric energy from each of our neighbours with whom we have the active cross-border connection. The greatest import is implemented from Germany (1033 MW) and, also from Sweden (516 MW).

When coming back to the problem of disposing the hypothetic 80 GW of power generated by photovoltaic sources, the next idea refers, of course, to the storage of the surplus of the produced energy and then, its recovery with the appropriate efficiency during the evening peak of loading and at night. To these ends, the storage-pumped power plants consisting of two reservoirs (lower and upper) are employed. Water is pumped between these two reservoirs, transforming the electric energy into potential energy of water mass.

The greatest storage-pumped power plant in the world is found at present in China (Fig. 8). It reaches the power of 3.6 GW and, besides it what is more important, facilitates the storage of as much as ca. 40 GWh of electric energy. It may, therefore, work with its full power for the period of more than 10 hours.

Fig. 8. View of the greatest storage-pumped power plant in China (Source: https://swiatoze.pl/elektrownia-szczytowo-pompowa-o-najwiekszej-mocy-zainstalowanej-na-swiecie-juz-dziala-w-chinach/)

As compared to the discussed China giant, Polish storage-pumped power plants are very small. We have 6 objects of such type at our disposal; they are characterized by the following values of the generated power:

- Żarnowiec – 716 MW;
- Porąbka-Zar – 500 MW;
- Solina – 200 MW;
- Żydowo – 167 MW;
- Czorsztyn- Niedzica- Sromowce Wyżne – 94 MW;
- Dychów – 90 MW.

When working in the pumping mode, the Polish storage-pumped power plants collect maximum power of 2 GW from

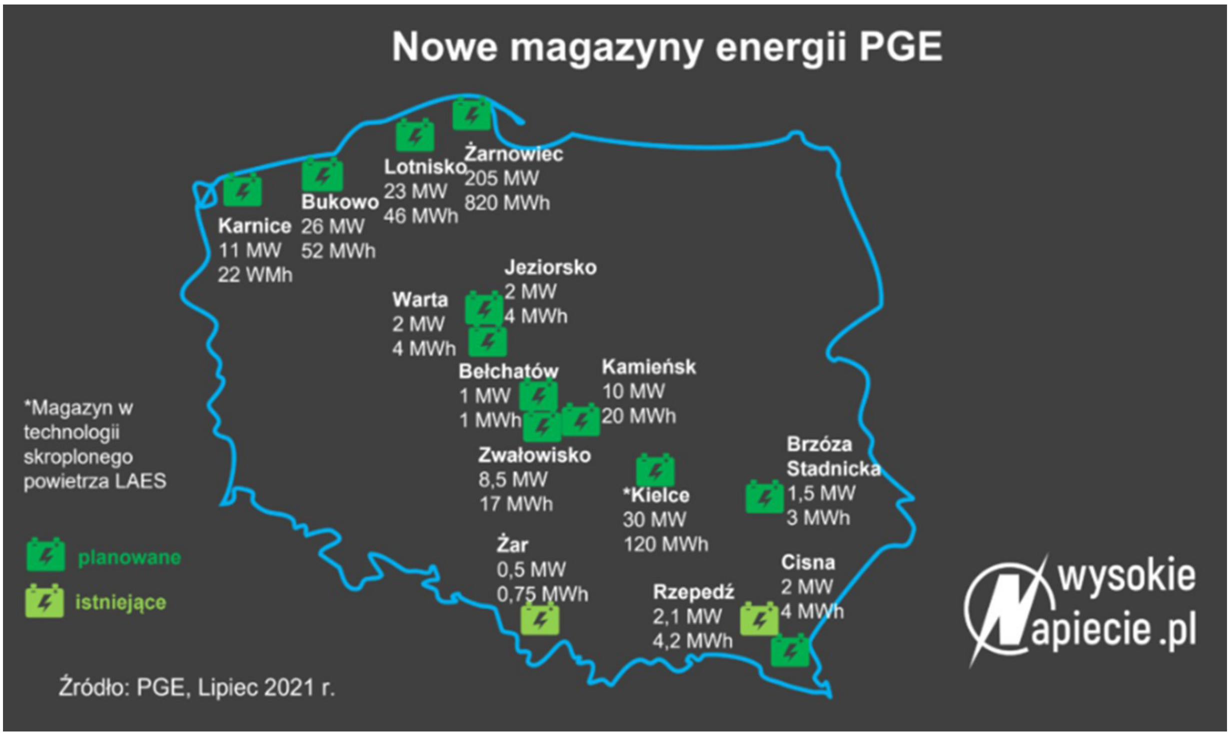

Fig. 9. The distribution of the existing and planned battery storehouses of energy in Poland (Source: https://wysokienaoiecie.pl/84360-magazyny-energii-sa-niezbedne/)

the electric energy system. With the assuming that their upper reservoirs have been previously completely empties, they are able to pump water for the period of maximum 4 hours, collecting the energy equal to 8 GW for this purpose. Meanwhile the management of the surplus of power generated by photovoltaic system in the hypothetically considered amount of 80 GW for the period of, let's say 10 hours per 24h period, it would require the storage of energy in the quantity of 800 GWh. It means that to this end, we should have hundred times more storage-pumped power plants with the same parameters as we have now. It is highly doubtful whether it would be possible to find the sites for their construction at the whole territory of Poland, not mentioning the astronomic costs of such investments [3].

Processing of electric energy in chemical energy, accumulated in batteries is another method for the storage of electric energy. The first installations of such type have been already erected in Poland; the successive ones are planned, as well. Their location has been presented in Figure 9.

If we look, however, more precisely at Figure 9, it may be seen that the question of utilization of battery energy storehouses is not so optimistic as if it could seem at the very beginning. From among the installations, submitted in Figure 9, only one (Żarnowiec) may be recognized as relatively grater as its power is equal to 205 MW and it enables accumulation of electric energy for the period of ca. 4 hours. The remaining battery energy storehouses are the installations nearly microscopic, with power of only few, several or several hundred megawatts; they are able to accumulate energy for the period of around two hours. From the viewpoint of storage of electric energy surplus, generated in photovoltaic system, the battery storehouses do not have any significant meaning.

How much power more may be installed in Polish photovoltaic system?

When I was writing the present paper, the power installed in photovoltaic installations in Poland reached value of 14 GW. At this moment, we may automatically ask the following question: how much more power may be installed with the following effect:

1) its transmission by the existing electric energy network is technically feasible;
2) the energy produced in the mentioned installation is fully utilized.

What is the use of such amount if having even 40 GW installed in photovoltaic panels (that is, almost three times more than now) we will be not able to obtain a half of the generated power in the peak production moment at any rate [2]. Under such situation, it will be necessary to disconnect compulsorily the selected photovoltaic farms from the network in order to ensure the balance of the power in the electric energy system. But just such procedure causes a drastic decline of value of the indicator of mean annual utilization of the power, installed in photovoltaic system which in the assumed case of the total utilization of energy generated in the panels at the territory of Poland is equal to only ca. 10%. If, however it is not possible to obtain a half of the energy at the peak of the photovoltaic generation, value of the mentioned coefficient will fall below only 5%. In such case, the question about any profitability of the voltaic system of this type will be only a kind of rhetoric question.

Figure 10 contains the data published by PSE on April, 22, 2023 in the thirteenth hour of 24h period.

During the considered period of time, the demand on the power in electric energy system amounted to 18.276 GW;

DEMAND [MW]	**18 276**
GENERATION [MW]	**18 044**
Heat power plants	10 009
Water power plants	328
Wind power plants	53
Photovoltaic installations	7 652
Other renewable energy plants	0
BALANCE OF TOTAL EXCHANGE [MW]	**202 IMPORT**
FREQUENCY [Hz]	**50,055**

Fig. 10. The data concerning the powers in the national electric energy system on 22, April, 2023-07-31(Source: https://pse.pl/home)

voltaic generated 7.652 GW and the remaining renewable energy sources gave only 0.381 GW. As usual, heat power plants generated as much as 10.009 GW. The minimal total power at which the national heat power plants may function is equal to ca. 7 GW. The mentioned power plants cannot be, however, completely disconnected due to the fact that when the dusk is commenced, they will be very necessary (simply indispensable) and they will have to increase the generated power considerably as to cover the increasing demand on energy during the evening peak of load.

As it is followed from Figure 10, the heat power plants work with the total power amounting to ca. 10 GW, so there is a certain reserve which could be employed in potential reduction of the power by ca. 3 GW. At the same time, it is worth mentioning that in the discussed day, there was a very weak wind and in connection with this fact, wind power plants generated only 53 MW, most of the windmills did not rotate at all. Meanwhile, as it is followed from Figure 6, Polish windmills generate typically the total power of the order of 1 GW. Simultaneously, as it results from Figure 10, in the discussed ay there was import of electric power in amount of 202 MW; therefore, at the situation of stronger winds, the mentioned import would not occur at all; instead, we could even expect a small export of energy. Reassuming, we may say (with a certain simplification) that the power generated by photovoltaic system would be subjected to decrease to ca. 7 GW what is the absolute minimum in the case of the national electric energy system. As the total power installed in Polish storage-pumped power plants equals to ca. 2 GW, we may assume as follows: if all considered energy plants had pumped water with their full power during the peak of the power generation from photovoltaic system, the photovoltaic plants could deliver the power higher by ca. 2 GW.

It remains, however, debatable question: to what level the upper reservoirs of the mentioned above plants may be emptied because they must constitute always a considerable reserve of the so-called intervention power, having a crucial meaning from the viewpoint of safety of work of electric energy system; sometimes it is the last resort before occurrence of catastrophe in a form of the universal *blackout*. The upper reservoirs of storage-pumped power plants cannot be emptied totally, to zero, what – in practice – limits considerably the time for which the water may be pumped until their complete filling.

Reassuming, after consideration of the admitted reduction of power of heat power plants and the possibilities of the additional work of storage-pumped power plants, connected with the pumping of water to the upper reservoirs, we may assume that the power generated by photovoltaic system could be still by ca. 5 GW higher. It is followed from Figure 10 that Polish photovoltaic power plants in the peak period deliver about 7.5 GW of power, with the total installed power equal to ca 14 GW. Therefore, theoretically, the mentioned installations could generate still 5 GW more; it would be ca 12.5 GW in total. Meanwhile, the prognoses for the coming few years anticipate doubling of the power installed in Polish photovoltaic up to value of ca. 28 GW. Such situation will cause that during the peak of generation, the discussed power plants will deliver about 15 GW in total, i.e. by 2.5 GW more than the calculated previously value of 12.5 GW. Perhaps it would be possible to export the mentioned additional 2.5 GW to the neighbouring countries (probably at a very low price, perhaps even of negative value) but it can be clearly seen that the value of power installed in Polish photovoltaic at the level of ca. 25 GW is principally the limit value, the exceeding of which has not any sense; it would result in compulsory switching on of photovoltaic installations during the period of peak power generation. Meanwhile when looking at Figure 1, we may conclude that the ambitions concerning the development of Polish photovoltaic system go considerably further, ignoring completely the elementary economic calculus and analysis of profitability of further development of the discussed sector of electric power system.

How much energy coming from photovoltaic may be produced in Poland?

Let's try to answer the following question: how high percentage (maximum) of electric energy produced in Poland during one year may come from photovoltaics system when assuming that the whole energy generated in Photovoltaics panels would be completely utilized. Table 2 contains the data concerning generation of energy from photovoltaic sources on 12, June, 2023.

As it is followed from Table 2, the highest value of the power, generated from the photovoltaic sources had place at the 14^{th} hour of the 24h period and was equal to 7.565 GM, in average. In order to simplify the further considerations, let's assume that the demand on electric energy in Poland is constant and amounts strictly to 20 GW at each hour of the day-and-night period during the whole year. To cover fully the demand of the customers, 480

Table 2. The data concerning generation of power from photovoltaic sources in the particular hours of 24h period on June, 12, 2023 (Source: https://pse.pl/home)

Hour of 24h period	Power generated from photovoltaic sources [GW]
1	0
2	0
3	0
4	0
5	0.067
6	0.442
7	1.437
8	3.284
9	5.320
10	6.637
11	6.914
12	7.400
13	7.534
14	7.565
15	7.374
16	6.580
17	5.226
18	3.695
19	2.079
20	0.849
21	0.274

GW should be produced during 24 h period; during the whole year, it would be necessary to generate 175.2 TWh of electric energy. Let's assume – purely theoretically – that we do not have at all any coal-fired power plants in Poland, only gas turbines, so we cannot be flexibly adjusted to the current performance of photovoltaic installations in respect of the generated power. It follows that in the 14th hour of the day photovoltaic system should supply power in amount of ca 20 GW and, in connection with this fact, cover totally the demand of the users. During the remaining hours of 24-h period, gas turbines must additionally perform their work because the power supplied by photovoltaic system will be, unfortunately, lower than the required 20 GW.

At the present level of power installed in photovoltaic system amounting to 14 GW at the peak of production in the 14th hour of the day, the mentioned panels generate 7.565 GW of electric power in total, so the increase of the level of generated power up to 20 G would require the increase of the installed power by 264 times (up to the level of ca. 37 GW). Then, the values contained in Table 2 should be also multiplied by coefficient 2,.64. It would allow determining the amount of energy produced by photovoltaic system in the particular hours of day-and-night period.

The considered values are as follows:

- hour 5 - 0.177 GWh,
- hour 6 - 1.167 GWh,
- hour 7 - 3.794 GWh,
- hour 8 - 8.670 GWh,
- hour 9 - 14.045 GWh,
- hour 10 - 17.522 GWh,
- hour 11 - 18.253 GWh,
- hour 12 - 19.536 GWh,
- hour 13 - 19.890 GWh,
- hour 14 - 19.972 GWh,
- hour 15 - 19.467 GWh,
- hour 16 - 17.371 GWh,
- hour 17 - 13.770 GWh,
- hour 18 - 9.755 GWh,
- hour 19 - 5.489 GWh,
- hour 20 - 2.241 GWh,
- hour 21 - 0.723 GWh,
- hour 22 - 0.063 GWh.

In total, photovoltaic system would produce 191.9 GWh of electric energy during the day and night period (24 h). Let's assume again, in order to simplify the conducted considerations that photovoltaic system works with the indicated above hourly values of power for the period of a half of the year i.e. after rounding for 182 days (it is of course, a very optimistic scenario). In such situation, all Polish photovoltaic installations would produce 34.9 TWh of electric energy during the year what would constitute 19.9% of the whole electric energy produced in Poland during the year.

During the conducted calculations, the possibilities of storing the energy in storage-pumped power plants were not taken into account. The number of such installations in Poland is relatively small, so their consideration would not change much. On the other hand, generation of power from other renewable sources, especially from windmills and water power plants were not taken into account; it compensates, to a certain extent, the effect connected with the lack of consideration of the possibilities of storing the energy.

As it is followed from the presented calculations, geographic latitude typical of the location of our country does not allow generating by the photovoltaic system more than ca. 20% of the total energy produced in Poland. Moreover, the mentioned result was achieved with very optimistic assumptions: the produced photovoltaic energy will be always utilized in 100%. Such solution would, however, make the cooperation of photovoltaics with the coal-fired heat power plants impossible, and especially with nuclear energetics. On the other hand, it would be potentially possible to occur in the case of application of gas turbines. It is rather completely excluded at the present geopolitical situation, not mentioning the threat of a serious danger to the safety of our energetic system [6].

Therefore, when looking at the whole problem from the realistic viewpoint, we should univocally state that we are able to produce from photovoltaics perhaps ca. 10% of the total electric energy generated in Poland. In the case of building many

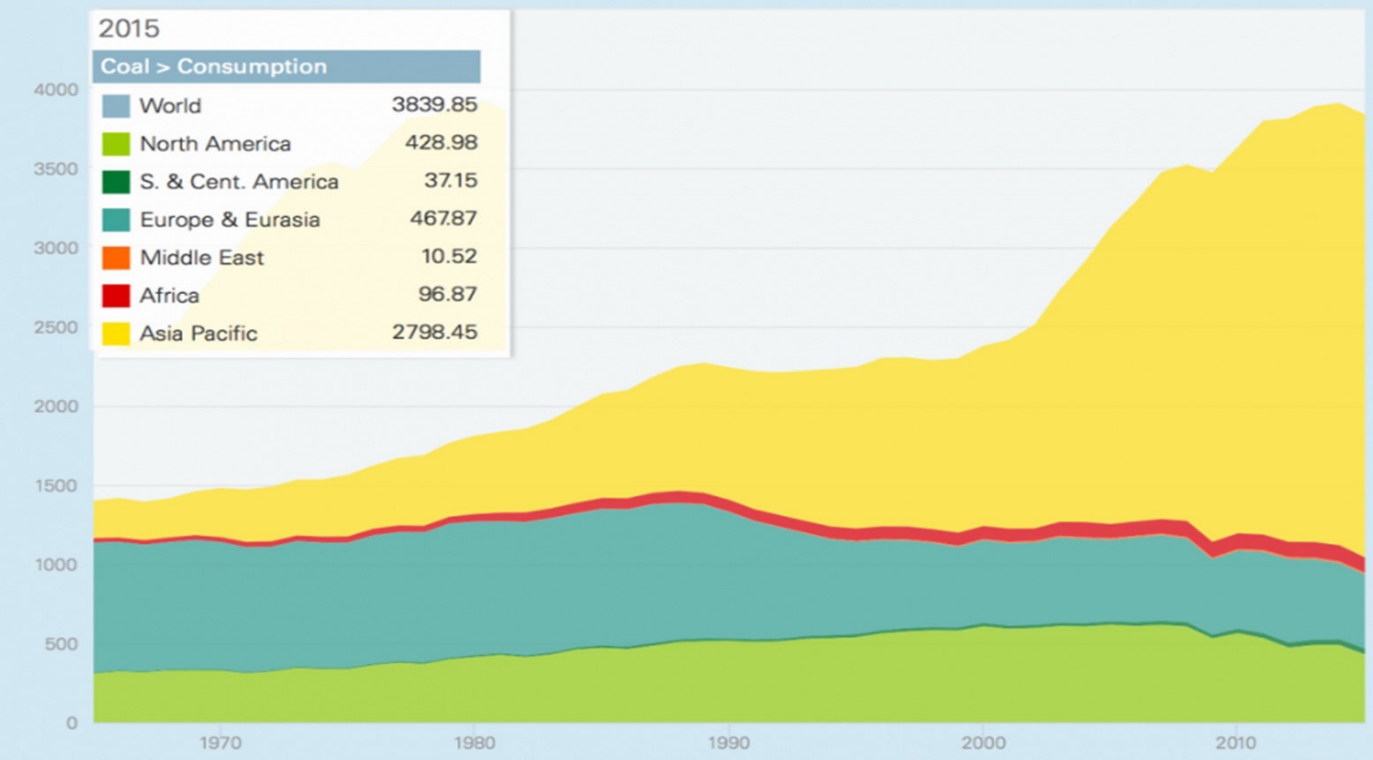

Fig. 11. Diagram, illustrating the increase ibn coal consumption all over the world during the recent few decades (Source: https://independenttardes.pl/swiatelko-w-tunelu-dla-wegla.html)

pumped-storage power plants it may amount to few percent more, let's say within the limits of 15%. The question arises: is it worth to bear enormous costs (many billions PLN) connected with the erection of successive pumped-storage power plants what would undoubtedly cause the furious reaction of ecologists and wide social protests of the people, displaced from the areas intended for construction of water reservoirs.

The analogical question may be asked even in the context of the mentioned 10% of electric energy which may be annually gained from photovoltaic system in Poland in the case of its cooperation with heat power plants or future nuclear power plants. Whether the discussed 10% only of the total electric energy produced in Poland is worth bearing the so-far and future enormous costs of all those governmental programmes and nearly gigantic subsidies for the prosuments? What may the discussed fact change in a final calculation when Poland is, anyway, responsible for less than 1% of the world emission of CO_2? If we even will contribute to the fact that the world emission

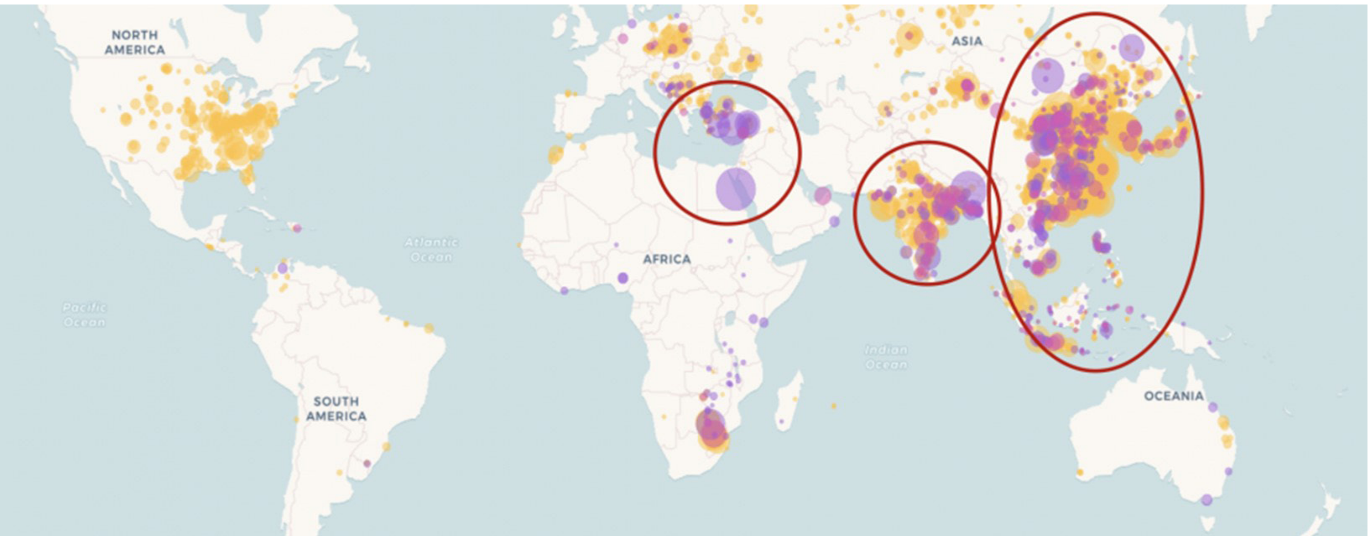

Fig. 12. Geographic distribution of functioning, being constructed and being planned coal mines (Source: https://independenttrade.pl/w-jakie-surowce-warto-inwestowac.html)

of carbon dioxide is decreased by one per mille owing to Polish photovoltaic system, it will be "compensated" with the surplus by many Asia countries which are not worried with such limitations and do not have any intentions to introduce them in this respect. To be convinced of this, it is enough to analyse the diagram, presented in Figure 11. It is distinctly clear that relatively small decline in carbon consumption in Europe and the North America is systematically compensated with a quite great surplus in Asian countries where coal mining is constantly increasing.

It is also worth to get familiarized with the map, presented in Figure 12, where yellow colour means the existing now coal mines whereas the new launched mines and those ones in the course of building or those only planned are marked with darker colours. As is can be seen (Fig. 12), the world does not give up the coal at all – in the contrary, there are planned gigantic investments connected with building of many new mines. We may distinguish here especially three areas: region of the Near East, area of India and region of China and South-East Asia. The construction of new coal mines is also planned in the South Africa and in Australia.

Summing up

With each second, the enormous quantities of radiant energy coming directly from the Sun, arrives to the surface of the Earth. Apparently, it seems that its utilization and effective management could contribute for always to the definitive solution of all energetic problems of humanity. Unfortunately, in practice, overcoming of the natural forces and employment them in work with the aim to satisfy the energetic needs of our technical civilisation is not as simple as it could seem at the first sight.

Photovoltaics may constitute a certain additional source of energy, the utilization of which in reasonable limits may be economically justified. Nevertheless, photovoltaics will never be the fundamental source of electric energy and definitely it will not enable the complete elimination of heat power plants. Moreover, only the power plants equipped with gas turbines are suitable for the most effective cooperation with photovoltaics; they may be quickly detached and then, again started up as quickly as during several dozen minutes (for comparison, re-ignition of the coal bloc takes even 8 hours). The transformation of the national electric energy system into gas fuel seems nowadays highly problematic – it would be difficult – at the existing transmission difficulties – to ensure the quantities of fuel for gas power plants, not mentioning even the energetic safety of such undertaking (almost complete dependence on the unstable foreign deliveries).

On the other hand, nuclear power plants are not suitable for cooperation with photovoltaic at all, as in such case there are no practical possibilities of regulating their power in a 24g period cycle (not mentioning their periodical switching out from work). Simply speaking, nuclear reactor must work all the time with its nominal power and any changes of it are a very slow and highly undesirable process (increase of the risk of failure). It generates the next question: the justification of constructing many nuclear power plants in Poland in the coming ten years (three bigger and a considerable number of small modular reactors) at the situation when we so strongly bet on development of photovoltaic installations. It seems that there is a distinct contradiction between the discussed two types of electric energy sources which will be difficult to make reconciled in the future [6].

Finally, it is worth mentioning that photovoltaic system is not the only one known method for conversion of solar radiation energy into electric energy. There have been already constructed experimental installations, composed of many thousands of mirrors, focusing rays of sunlight in a relatively small area as to heat up a liquid in a closed system to a very high temperature (for example, liquid sodium or brine). Then, the mentioned liquid is used for production of water vapour, driving the turbine connected with the current generator [5]. In such case, naturally stored energy of sun radiation is converted into heat energy of the liquid, heated up to a very high temperature.

We cannot also forget about "natural" photovoltaics that is, about green plants which replace the energy of solar radiation into biomass [1]. It is also the effective method for energy storage as the biomass in a dry state may be as a rule stored for any time; then, it may be burned in order to transform it into electric energy at the moment when there is the greatest demand on it.

Perhaps the discussed above problems are the appropriate directions of the studies on the effective utilization of the Sun energy, coming to our Globe whereas, at present, we speak practically and exclusively about photovoltaics.

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