Energy Transition in Power, Heating and Transport Sectors, based on the Majority of RES and Energy Storage

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Abstract: The world is facing problems that are related to climate change and pollution, which are partially caused by the emission of toxic compounds and CO_2, from the combustion of fossil fuels. The natural resource of fossil fuels, have been exploited for many years, such resources have also been depleted dramatically. The above-mentioned facts determine the need to conduct research that will demonstrate the technological and socio-economical possibilities of transforming energy systems and parts of transport systems from fossil fuels to renewable energy. This paper presents the idea of supplying a selected region, 100% with RES, accounting for costs and environmental efficiencies, for the entire energy system. Further, the analysis of the subject indicated a need to conduct research on correlations derived from integrating collective heating, transport systems with high V2G energy storage capacity and power systems, in order to optimize the functioning of the entire energy market. Furthermore, the above considerations suggest that there is a need to propose a new model for electrical systems, different than the one based on the classical concept of producer-recipient. This research was carried out through a combination of quantitative and qualitative methods. The quantitative analysis applied agent-based modelling; A method supported by extensive qualitative research. The conducted research indicates that renewable energy systems demonstrate greater cost and environmental competitiveness, than conventional energy systems. Furthermore, it has been shown that the integration of collective heating and transport systems, with the energy system has a positive impact on the efficiency of the entire system, by reducing primary energy demand and decreasing carbon dioxide emissions. Finally, the conducted research revealed that the reduction of energy demand, has a positive effect on the transformation of a conventional energy system, into a RES system

Keywords: grid planning; V2G energy storage; smart EV transportation; renewable energy; optimization; energy transition; decarbonization; smart buildings heating

1 Introduction and Literature Review

Currently, most of the energy systems in the world are based on fossil fuels. However, the possibilities of supplying the energy system with renewable energy sources have been discussed in the literature for many years [1-3]. At the beginning of this century, a lot of researchers were of the opinion that renewable energy sources could cover only a few percent of the energy needs of a country the size of Germany. Afterward, when renewable energy sources became constantly present on the day-ahead markets, it was examined whether wind energy could take part in balancing markets (following the day-ahead markets) [4] [5]. Nowadays, the participation of this energy source is becoming reality [6]. Many regions, not only in Europe, are currently introducing plans to modernize energy systems in order to cover most of the demand for electricity by RES within several or several dozens of years (Costa Rica 100% until 2021, Denmark 100% until 2050, Sri Lanka until 2030) [7].

The use of renewable sources in classical energy systems does not always imply that the entire system needs to be reconstructed. It is possible to supply the system with up to 25% of energy coming from fluctuating renewable sources without major system modifications. However, problems arise only if one wants to create a system powered almost 100% from renewable sources in which the majority of energy comes from fluctuating sources of renewable energy, such as solar, wind, or wave energy [8-10]. From the system operator's point of view, what is the ideal source of renewable energy are hydroelectric power plants the power of which can be freely modulated. In countries such as Norway, Brazil, and Venezuela, more than 65% of energy comes from hydroelectric power plants [11]. Unfortunately, most countries, due to their geographical location and climate, are forced to seek other renewable energy sources which are not as stable as hydroelectric power plants. Systems powered mostly by fluctuating sources require the system operator to search for methods to compensate power fluctuations. These considerations raise a number of questions related to the impact of modern technologies used to obtain electricity from RES on the nature and structure of the electricity market, both in Europe and worldwide. These questions formed the basis for conducting research on the idea of supplying a selected region with high-RES participation, taking into account cost and environmental efficiencies for the entire energy system. Further, the analysis of the subject indicated the need to conduct research on correlations that derive from integrating collective heating and transport systems with an electricity system in order to optimize the functioning of the entire energy market.

The issue, as outlined above, determines the objectives of this research, i.e., exploring the possibility of supplying a selected region with high renewable energy sources participation, identifying correlations between the integration of a supply system powered by RSE with collective heating and transport sector. The spatial scope refers primarily to the empirical part of the research and concerns Poland, however, supported by data from all over Europe. The conducted research focuses on the economic analysis from the perspective of electricity end-users and does not encompass legal and political aspects. In particular, it encompasses data from national energy operators, materials made available by statistical offices, and the International Renewable Energy Agency.

2 Research Methods and Calculation Parameters

This research was carried out through a combination of quantitative and qualitative methods. The quantitative analysis applied agent-based modeling; a method supported by extensive qualitative research. In order to forecast the input data for the model, such as demand or variable environmental parameters on the basis of historical data, Idat-Matlab functions based on inter alia ARIMA models were used. Model simulations were carried out with the application of the multilayered Danish algorithm, used by the state Danish operator and research institutes for modeling the impact of RES on the whole energy system. Simulations and the process of designing the new system structure were performed in the MATLAB environment, and with the use of Energy Plan, Idat and Simulink (UniPR Tools) software, on a yearly basis, in hourly steps, reflecting the typical day-ahead market. Based on the related literature [12-15], the following dependencies were adopted for model simulations:

Definition of demand in the model:

Electricity demand is defined as the difference between total demand and heat demand and is broken down into hourly parts of the whole year.

$$dE' = De - dEH \qquad (1)$$

$$\text{if } dE' < 0 \text{ then } dE' = 0$$

$$DE' = \sum dE'$$

where: DE'- total annual electricity demand, dEH – heat demand, dE' – demand for electricity at a selected time of the year

Production of thermal energy

The demand for thermal energy from the sun is supported by production from cogeneration, heat pumps, and thermal heating plants. Conventional heat energy is defined as the difference between total production and thermal energy produced from solar energy.

$$qM\text{-}Oil = hM\text{-}Oil - q'\,Solar\text{-}M\text{-}Oil \qquad (2)$$

where: $qM\text{-}Oil$ – conventional heat energy, $hM\text{-}Oil$ – total heat demand

Production from renewable energy sources

$$eRes' = eRes * 1 / [1 - FACRes * (1- e\ Res)] \quad (3)$$

were: *eRes* - energy produced in *RES, FACRes* - production factor for a given hour

Fuel demand in heating plants

$$f\ M\text{-}Oil = QM\text{-}Oil / \mu M\text{-}Oil \quad (4)$$

where: heat energy in collective heating, *µM-Oil* - efficiency of the turbine/boiler, *QM-Oil* – heat demand

Generating hydrogen:

The hydrogen production per hour is defined as follows:

$$f\ ElcM = f\ M\text{-}H2CHP\text{-}Average = FM\text{-}H2CHP / 8784 \quad (5)$$

then the content of the hydrogen tank is calculated for each hour *SElcM(x)*

$$SElcM(X) = SElcM(X\text{-}1) + f\ M\text{-}H2CHP\text{-}Average - fM\text{-}H2CHP\ (X) \quad (6)$$

If the capacity of the tank is exceeded in a given hour, the hydrogen production will be limited

$$If\ SElcM > SElcM\ then\ f\ ElcM = f\ ElcM - (\ SElcM - SElcM) \quad (7)$$

$$CElc\text{-}MIN = Hour\ max(\ f\ ElcM\ ) / \alpha ElcM \quad (8)$$

where: *SElcM*- the amount of hydrogen in the tank, *f ElcM* – hydrogen produced, *f M-H2CHP-Average* – average demand for hydrogen in a condensing turbine

Geothermal energy:

Electricity production by geothermal power plants:

$$Geothermal=FACGeothermal*CGeothermal*dGeothermal/Max(dGeothermal) \quad (9)$$

$$f\ Geothermal = eGeothermal / \mu Geothermal$$

where: *eGeothermal* - energy production from geothermal sources, *Cgeothermal* - installed capacity of geothermal power plant MW, *µGeothermal* – efficiency, *dGeothermal* - distribution of production in hourly intervals/year, *FACGeothermal* - production-to-installed capacity coefficient f, *FGeothermal* - fuel demand for a geothermal power plant, *eGeothermal* - production of geothermal energy

Water energy, Electricity production through hydropower plants

$$eHydro\text{-}ave = \mu Hydro * WHydro / 8784 \quad (10)$$

where: *µHydro* - turbine efficiency, *WHydro* - water available

Input data in the conducted simulations come from, among others, the bases of national energy operators and European bases:

EU: International Renewable Energy Agency (IRENA 2021), European Statistical Office (Eurostat 2021), Agency for the Cooperation of Energy Regulators (ACER

2021), Council of European Energy Regulators (Ceer 2021). Spain: Red Eléctrica de España (Red Eléctrica 2021), [16, 17, 18]

Poland: Urząd Regulacji Energetyki (Energy Regulatory Office, ure.gov.pl 2021), Główny Urząd Statystyczny (Main Statistical Office, GUS 2021), Instytut Meteorologii i Gospodarki Wodnej (Institute of Meteorology and Water Management, IMGW 2021) [19, 20, 21]

Calculation parameters were selected on the basis of the binding standards in the years 2015-2017 in the Danish and German energy systems, mainly based on the Danish model of the energy system transformation [22].

3 The System with High V2G Energy Storage Capacity, Wind Energy, PV and Non-Renewable Energy Sources Methodology

Simulation 1

The subject of the analysis is a system enriched by large battery capacities in V2G. The battery capacity corresponds to 15 million urban cars driven in the V2G with the battery capacity of 25 KWh and the value of 375 GWh. It should be noted here that the adopted capacity of KWh is much lower than that in the new cars now offered in the market. For example, new Tesla cars have a battery with the capacity of over 80KWh [23], which reduces the number of necessary cars in the storage system of the same capacity to five million vehicles. In the selected simulation, the provider of stored energy can earn in two ways: through the sale and purchase of energy from the network or through the sale of their own energy produced in power peak times. The energy system operator shares 30% of the costs of photovoltaic panels; thus, the annual cost of electricity also takes into account the depreciation of PV. As regards the storage system, the changing market price of energy should be a motivation to use the additional option of each modern EV. For example, energy prices in the Spanish day-ahead market may fluctuate from 0 to 150 euros [24]. Owing to the significant increase in the capacity of electricity storage, the import of energy decreased by almost 2 TWh, while its export practically remained constant and is on the level of 46.43 TWh, which accounts for about 35% of the overall demand of Poland in 2015.

The high installed capacity of wind power plants and a few-day long continuous wind in February allowed powering the energy system with RES in 100%, with the significant advantage of wind turbines (blue color). In real conditions, electricity prices could stay on level zero or have negative values [20]. In Figure 1 (from the right), we can notice a small area in yellow color, which reflects conventional energy sources.

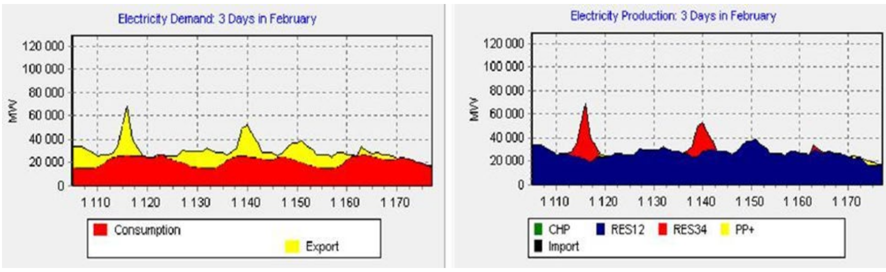


Figure 1
Three-day electricity production in February, with a breakdown by the production technology (the chart on the right), the three-day demand for electricity with the export of production surpluses in February (the chart on the left)
Source: Authors' own work

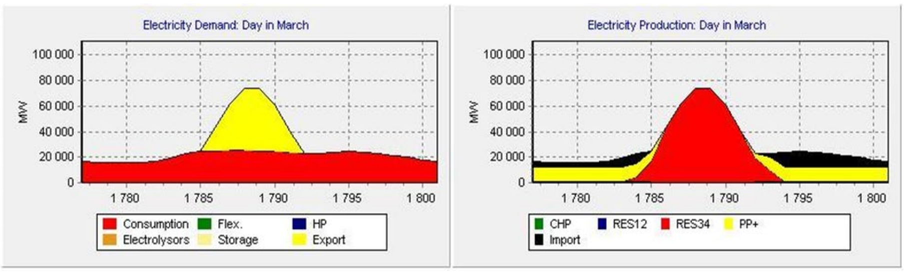


Figure 2
One-day electricity production in March with a breakdown by the production technology (the chart on the right), the one-day demand for electricity with the export of production surpluses in March (the chart on the left)
Source: Authors' own work

It is solar power (red color) that is the dominant energy source (the chart on the right). It can be a source of energy only during the day. Because there was no wind on the day of the analysis, electricity is supplied from NO-RES and, from the V2G battery (yellow). The remaining shortage is compensated by imports. We can see that the batteries are used practically during the whole period of lack of solar radiation and they play an important role in supplying the power system.

The excess of export over the import of energy may play a key role from the economic point of view. In Figure 3, navy blue color refers to the export of electricity generated by PV, while import is marked with green. The selected day is quite characteristic and shows the huge variability of some RES, in this case - sun and wind. Electricity import is caused by the lack of wind and NO-RES limited production capacity, as well as limited storage possibilities. It should be noted here that it is an exceptional day because excess production in the examined year represents 35% of the annual demand for energy.

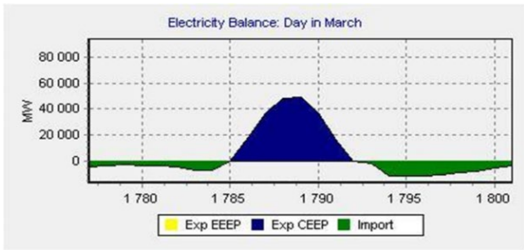


Figure 3
Import and export on the selected day in March
Source: Authors' own work

4 The Increasing Share of Electric Vehicles in the Integrated Energy System Results

The increased share of electric vehicles in transport entails a rise in demand for electricity to be used for transport. Owing to energy storage capability, electric vehicles contribute to the improved efficiency of systems with significant RES dominance (simulation 1). V2G systems have a positive impact on the economy thanks to the excess production of energy and partly compensate for energy shortages, which are usually filled with imports in non-storage systems. What is another important aspect of the change in the structure of transport is a drop in the emission of carbon dioxide and other substances which are a product of the combustion of fossil fuels.

Simulation 2

The assumption is an increase in the share of electric vehicles in satisfying the demand for electricity in the integrated energy system. In 2015, were 20723000 passenger cars registered in Poland [25]. For the sake of the simulation, we assumed the share of electric passenger vehicles from 0 to 100%, the average annual mileage 20000 km, with the demand of 1l of petrol per 14 km for internal combustion cars and 1 kWh for 6 km for electric vehicles, which corresponds to European statistics.

In Figure 4, the vertical axis refers to the demand for electricity in TWh over a year, while the horizontal axis shows the number of passenger cars. Red color represents the relationship between the number of vehicles and EV's demand for energy, while yellow color shows the same relationship for combustion vehicles.

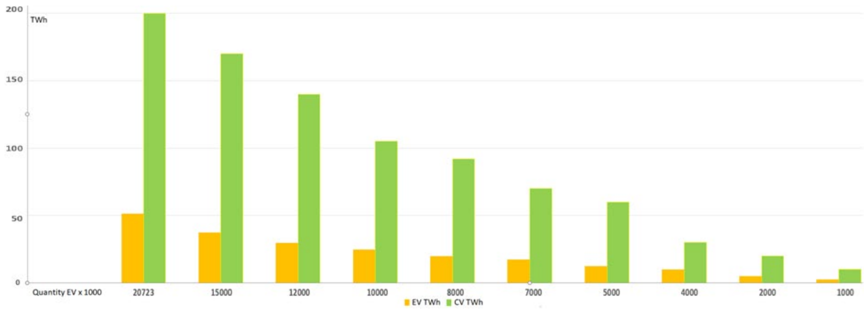


Figure 4

The relationship between the number of electric and combustion vehicles and the demand for energy

Source: Authors' own work

The analysis of the chart shows that electric vehicles have a significantly lower demand for energy than cars with internal combustion engines. This is mainly due to the efficiency of both engine types, which is about 90% for an electric engine, and about 30% in the case of internal combustion engines [13]. Owing to the use of energy from RES, electric vehicles will be powered in an entirely ecological way, while the batteries of parked cars may optimize the efficiency of energy consumption in accordance with the simulation from point 1.

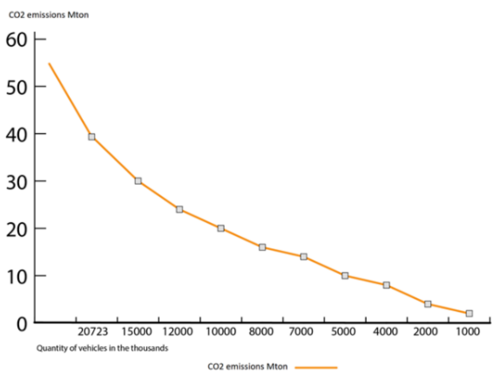


Figure 5

The relationship between the number of internal combustion cars and carbon dioxide emission

Source: Authors' own work

The reduction of carbon dioxide emission and of other substances produced by burning fossil fuels is an increasingly important issue in Europe (Willenbacher 2017). In Figure 5, the vertical axis refers to carbon dioxide emission in millions of tons, while the horizontal axis represents the number of vehicles in the analyzed system, which, in the initial phase, corresponds to the number of passenger cars in Poland in 2015. In that year, passenger cars emitted about 511 million tons of carbon dioxide. At the same time, it must be emphasized that emission standards for combustion vehicles are the same as for new cars from 2015 [27]. The simulation results show that the transformation of the transport system dominated by fossil fuels, into the one with a significant share of electric vehicles, significantly contributes to the elimination of carbon dioxide emissions.

5 The Integrated Electricity and Heating System

As far as cogeneration (the generation of electricity and heating power within a single process) is concerned, the Polish district heating system looks quite good in comparison to the rest of Europe. In 2015, over 63% of thermal energy came from thermoelectric power stations. The situation is worse when it comes to the type of fuels used by energy producers. About 75% of the energy used in district heating came from coal, while only 7.4% came from RES. The other fuels used in district heating include natural gas, fuel oil, and biomass. In 2015, the demand for thermal energy in district heating systems in Poland was 94.937 TWh [20], while the consumption of energy in individual, household heating systems amounted to 129.6 TWh.

Simulation 3

For the sake of the simulation, we assumed the installed capacity of licensed thermal energy producers at the level of 56048 MW and the demand for system heat of 94937 TWh, while the demand of individual heating systems in households was assumed at the level of 129.6 TWh, which corresponds to the actual parameters of thermal energy systems in

Poland in 2015. In accordance with simulations concerning the increased share of EV in transport and simulation 1 presenting the optimum energy system, we may conclude that:

a) The carbon dioxide emission of passenger cars for the state close to the year 2015 is 51.1 Mt, but it may be reduced down to zero by introducing into transport all-electric vehicles powered by non-emission RES.

b) In the electricity sector, CO2 emission in 2015 was about 109 Mt, but, through the reduction of the consumption of fossil fuels and introducing non-emission RES, it could be reduced down to 37.6 Mt.

c) The volume of carbon dioxide emission in the district heating sector for the system reflecting the Polish energy system of 2015 was 61.2 Mt.

In order to reduce CO2 emission and improve the use of the excess production from RES, the integrated systems of electricity and heating will be integrated into the current simulation. The energy system will be the same as in simulation 1, while the heating system will reflect the actual Polish heating system from 2015 in the first steps of the simulation. The overall sum of CO_2 emissions for these systems is 98.853 Mt. It is possible to reduce the emitted pollution owing to replacing some of the coal-fired power plants with heat pumps, which in particular are powered by the excess production of energy from RES.

When comparing Figures 7 and 8, one might notice that by replacing a part of coal-fired power plants of the installed capacity of 10000 MW with heat pumps of the same capacity we can significantly reduce the export of energy, with only a slight increase of import. On a yearly basis, export decreased by 22.2 TWh, while imports increased by 2.3 TWh. Savings from the better use of electricity production surpluses thanks to the utilization of heat pumps result not only from the reduction of export but first of all from the replacement of expensive fossil fuels used in district heating. What is of significance is also the characteristics of a heat pump which can produce three times as much energy as it consumes [22]. By increasing the share of RES in the heating system, we could reduce carbon dioxide emission by about 10 Mt. As heat pumps can be used both in individual and district heating systems, it is important to select the proper types of RES in the system of heating and electricity generation.

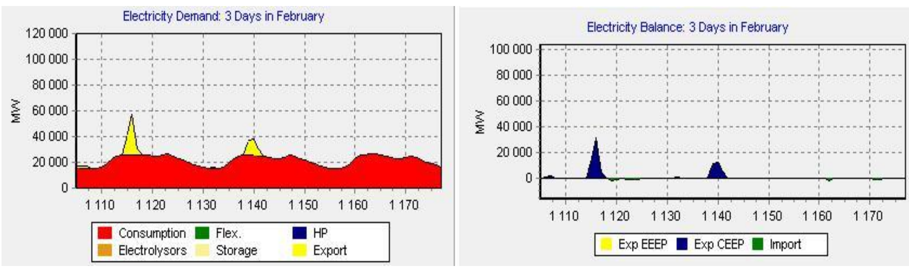


Figure 6
District heating demand in 2015
Source:(GUS 2021), (URE 2021), Authors' own work

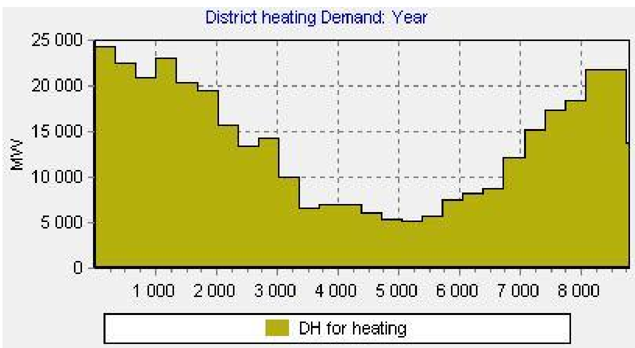
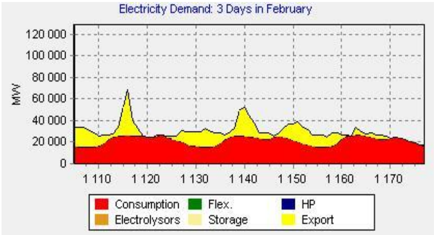


Figure 7
Three-day demand for electricity along with the export of production surpluses in February (the chart on the left), three-day export/import of electricity in February (the chart on the right), in the integrated system of electricity and heating generation without the share of heat pumps
Source: Authors' own work



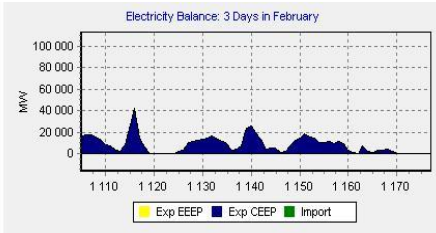


Figure 8

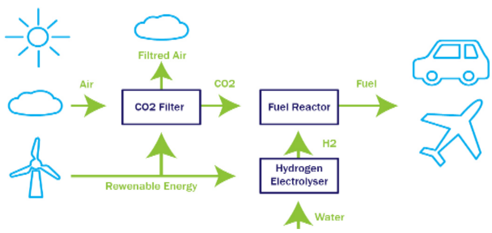
Three-day demand for electricity along with the export of production surpluses in February (the chart on the left), three-day export/import of electricity in February (the chart on the right), in the integrated system of electricity and heating generation with the share of heat pumps

Source: Authors' own work

6 The Production of Biofuels and Synthetic Fuels on the Basis of the Excess Production of Electricity from RES

Simulation 4

The production of synthetic fuels and biofuels based on electrical energy from RES is a lot more complex process than the use of heat pumps in the heating system described in simulation 3. The main advantage of the production of synthetic fuels is the use of the existing carbon dioxide already in the natural environment or when it is produced in industrial processes.



Schem1

The simplified scheme of the production of synthetic fuel based on RES

Source: Authors' own work

Synthetic fuels or biofuels may be used in industry or transport, which, due to their characteristics, makes use of internal combustion engines. Because of the high cost of the process itself, the production of the abovementioned fuels plays a secondary role in the simulation. Energy from the excess production of RES is first used in heat pumps and then transferred to the production of fuels. One of the assumptions of the simulation is the minimization of import and export, and in the case of crisis situations/energy peak times, synthetic fuels may also be used for the production of electricity.

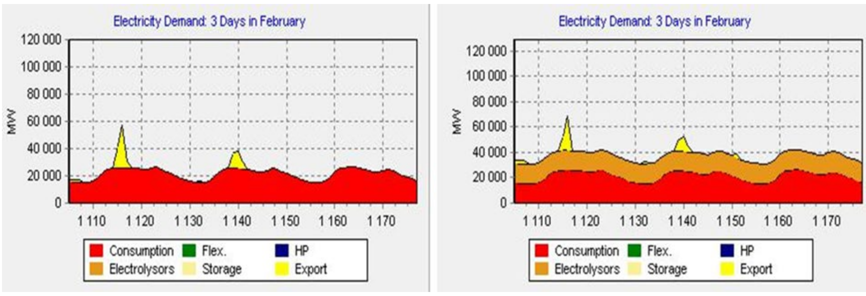


Figure 9
Three-day demand for electricity along with the export of production surpluses in February in the integrated system of the production of electricity and heating power and electricity with the share of heat pumps (the chart on the left). The chart on the right presents the system enriched with the possibility of the production of synthetic fuels and biofuels
Source: Authors' own work

Owing to adding heat pumps to the energy system and the possibility of the production of synthetic fuels and biofuels based on the available sources (Figure 9), export was reduced. On a yearly basis, there was a drop in export by another 8 TWh, while the demand for electricity rose because of the need to use electrical energy in the production of synthetic fuels and biofuels. The production of fuels was established at the level of 150 TWh annually.

Conclusions

This research paper presents the diverse aspects of the energy system transformation, within the context of the increasing share of renewable energy sources and V2G energy storage. The main criterion of the study was the cost and environmental efficiency of the whole energy system. The detailed analysis of energy systems revealed the need to undertake research into the dependencies resulting from the integration of the energy system with the transport system and the district heating system in order to optimize the functioning of the whole energy market.

The first simulation shows that increasing the capacity of battery storage significantly enables the system to be powered by photovoltaic energy stored in batteries during periods of no solar radiation. Using electric vehicles in the energy system as energy storage opens up new possibilities for decentralized energy storage.

The analysis of the model (simulation 2) which assumes an increase in the share of electric vehicles in transport shows that as the number of combustion vehicles in the system decreases, carbon dioxide emission decreases. In the examined model, internal combustion cars are replaced with electric ones, which are powered by non-emission renewable energy. Following the reduction of the emission of carbon dioxide and other substances produced by burning fossil fuels, the environmental efficiency of the system increases. When the share of electric vehicles in the transport system reaches 100%, carbon dioxide emission amounts to zero.

A change in the method of powering passenger vehicles not only results in the reduction of environmental pollution, but it also decreases the demand for energy in transport. Owing to the introduction of electric vehicles in the transport system model, it is possible to reduce the consumption of energy from the level of 280 TWh to the level of 70 TWh on an annual basis. This brings enormous financial and environmental benefits. The advantage of electric vehicles is to a large degree the result of the higher efficiency of the electric engine, which is about 90%, as compared to the efficiency of the combustion engine (25-30%).

The concept of combining a power plant with a thermal energy plant is quite a common practice, but the increasing share of RES in the energy market provides new opportunities to use production surpluses from fluctuating renewable sources in heating. The simulation of the integrated model of district heating and electricity (simulation 3) clearly shows that by replacing the production of heating energy coming from thermal energy plants with the energy from heat pumps, we can significantly reduce carbon dioxide emissions. Energy used in heat pumps is derived from the RES excess production, owing to which there is no need to burn expensive and high-emission fossil fuels. The integration of both systems and a change in the technology of power generation raises the cost and environmental efficiency of the whole energy system.

Taking into consideration the integration of the electrical energy and transport systems through the production of synthetic fuels and biofuels from the RES excess electricity production (simulation 4), it is possible to integrate the heavy transport systems and other systems in which petroleum products are used, thanks to which, the share of RES increases in other sectors of the economy.

To conclude, owing to the integration of the systems of electrical energy, heating, and transport, the volume of carbon dioxide emission in the whole system has dropped by a half and the demand for energy produced by burning fossil fuels has gone down by almost 210 TWh, which accounts for about 40% of the classical primary demand, in the coal-based energy system, for a country the size of Poland.

Further research should focus on proposing alternative structures of the electrical energy market and on the analysis of relationships between professional and individual energy producers.

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