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ENERGY TRANSITION IN THE POWER, HEATING AND TRANSPORT SECTORS BASED ON A MAJORITY OF RES AND ENERGY STORAGE

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ABSTRACT. Climate change and environmental pollution are partly driven by fossil fuel emissions of hazardous chemicals like CO2. Due to years of exploitation, fossil fuel natural resources have been drastically decreased. The following data show the necessity for research on the technological and socioeconomic possibilities of converting energy systems and elements of the transportation system to renewable energy. This article proposes supplying an entire region with RES while considering cost and environmental efficiencies. The subject study also showed the need to research correlations between collective heating, transport systems with high V2G energy storage capacity, and power systems to optimize the total energy market. Moreover, the aforesaid reasons suggest that a new model of the power system, different from the standard producer-recipient paradigm, is needed. This research was quantitative and qualitative. Agent-based modeling, underpinned by qualitative research, was used in quantitative analysis. Renewable energy systems are more cost- and environmentally-competitive, according to study. Integration of community heating and transport systems with the energy system reduces primary energy consumption and carbon dioxide emissions, improving system efficiency. Research shows that reducing energy consumption helps transition 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

The majority of the world's energy systems rely on fossil fuels. The possibility of feeding the energy grid with renewable energy has been explored for decades. At the turn of the century, many academics thought renewable energy could meet just a small portion of Germany's energy demands. After renewable energy sources became regulars on day-ahead markets, it was explored if the wind might help balance markets (following the day-ahead markets). Using this energy source is now a reality. Many areas, not just in Europe, are actively developing plans to upgrade energy infrastructure to satisfy most of the demand for power by RES within a few or several dozens of years (Costa Rica 100% by 2021, Denmark 100% by 2050, Sri Lanka 2030).

Using renewable sources in traditional energy systems doesn't always mean rebuilding. Up to 25% of the system's energy can come from renewable sources without substantial changes. However, complications occur if one tries to design a system powered nearly entirely by renewable sources, such as solar, wind, or wave energy. From a system operator's perspective, freely modulating hydroelectric power plants are the perfect renewable energy source. In Norway, Brazil, and Venezuela, hydroelectric facilities provide over 65% of electricity (Riahi et al., 2012). Most nations, owing to their location and climate, must explore alternate renewable energy sources that are not as dependable as hydroelectric power facilities. Variable-power systems need the operator to accommodate for power variations.

These factors raise issues about the influence of current technology used to get power from RES on the character and structure of the electricity market in Europe and internationally.

These problems prompted a study on the notion of providing a designated region with high RES participation, taking economic and environmental efficiency for the overall energy system into consideration. Further, the analysis showed the necessity to explore correlations derived from merging communal heating and transport systems with an electrical system to optimize the total energy market. The issue mentioned above sets the aims of this research, namely evaluating the possibilities of providing a specified region with high renewable energy sources participation and discovering correlations between integrating an RSE-powered supply system with community heating and transport. Spatial scope relates to the empirical aspect of the research and focuses on Poland, including data from around Europe. The research focuses on economic analysis from the standpoint of electrical end-users and excludes legal and political issues. This includes statistics from national energy operators, statistical offices, and the International Renewable Energy Agency.

2. Methodological approach

This research was quantitative and qualitative. Agent-based modelling, supplemented by qualitative research, was used in the quantitative study. Idat-Matlab functions based on ARIMA models were used to anticipate model inputs such as demand or environmental characteristics based on historical data.

Model simulations were carried out with the application of the multilayered Danish algorithm, used by the state Danish operator and research institutes for modelling 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 literature on the subject (Mathiesen et al. 2015), (Lund et al. 2012), (Lund 2010), (Bunn 2004), (Weron 2014), 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.

$$dE' = De - dEH \tag{1}$$

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

$$DE' = \sum dE'$$

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.

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

where: qM-Oil – conventional heat energy, hM-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

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

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:

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

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

$$SElcM(X) = SElcM(X\text{-}1) + f \; M\text{-}H2CHP\text{-}Average - fM\text{-}H2CHP\ (X) \quad (12)$$

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

$$\text{If } SElcM > SElcM \text{ then } f \; ElcM = f \; ElcM - (SElcM - SElcM) \quad (6)$$

$$CElc\text{-}MIN = Hour \; max(f \; ElcM) / \alpha ElcM \quad (7)$$

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

$$eGeothennal = FACGeothennal * CGeothermal * dGeothennal / Max(dGeothermal) \quad (8)$$

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

where: eGeothennal - energy production from geothermal sources, Cgeothennal - installed capacity of geothermal power plant MW μGeothermal – sprawność, dGeothermal - distribution of production in hourly intervals / year, FACGeothennal - production-to-installed capacity coefficient f, FGeothermal - fuel demand for a geothermal power plant, eGeothennal - production of geothermal energy

Water energy, Electricity production through hydropower plants

$$eHydro\text{-}ave = \mu Hydro * WHydro / 8784 \quad (9)$$

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

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The hydrogen production per hour is defined as follows:

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

SElcM(X) = SElcM(X-1) + f M-H2CHP-Average - fM-H2CHP (X) (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) (7)

CElc-MIN = Hour max(f ElcM) / αElcM (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

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Electricity production by geothermal power plants

eGeothennal = FACGeothennal* CGeothermal* dGeothennal / Max(dGeothermal)(8)

f Geothermal = eGeothermal / μGeothermal

where: eGeothennal - energy production from geothermal sources, Cgeothennal - installed capacity of geothermal power plant MW μGeothermal – sprawność, dGeothermal - distribution of production in hourly intervals / year, FACGeothennal - production-to-installed capacity coefficient f, FGeothermal - fuel demand for a geothermal power plant, eGeothennal - production of geothermal energy

Water energy, Electricity production through hydropower plants

eHydro-ave = μHydro * WHydro / 8784 (9)

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), 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)

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 (Mathiesen et al. 2015).

3. The system with high V2G energy storage capacity, wind energy, PV and non-renewable energy sources

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 (Tesla 2021), 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 in 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 euro (Red Eléctrica 2021). 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.

It is solar power (red colour) 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 import. 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.

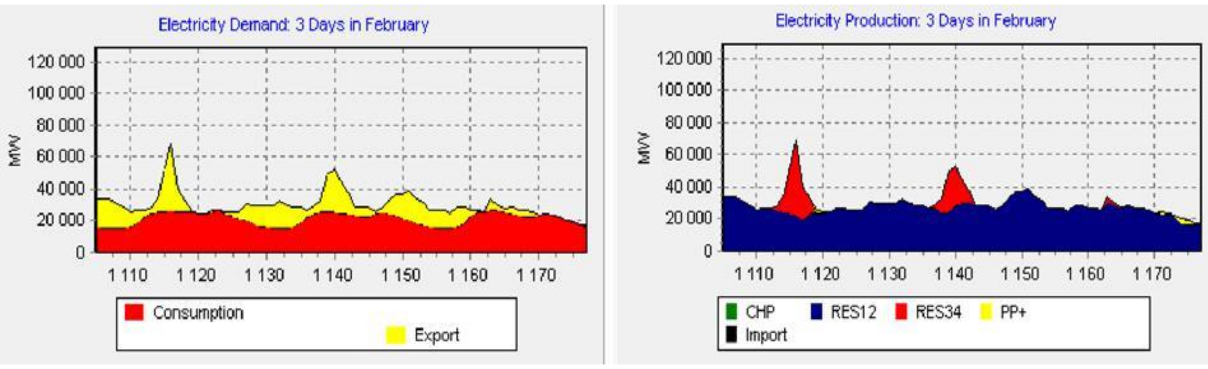

Figure 1. Three-day electricity production in February, with a breakdown by the production technology (the chart on the right), the three-day demand for electricity with the export of production surpluses in February (the chart on the left). Source: Authors' own work. The high installed capacity of wind power plants and a few-day long continuous winds in February allowed powering the energy system with RES in 100%, with the significant advantage of wind turbines (blue colour). In real conditions, electricity prices could stay on level zero or have negative values (Eurostat 2017a). On Figure 1 (from the right), we can notice a small area in yellow colour, which reflects conventional energy sources.

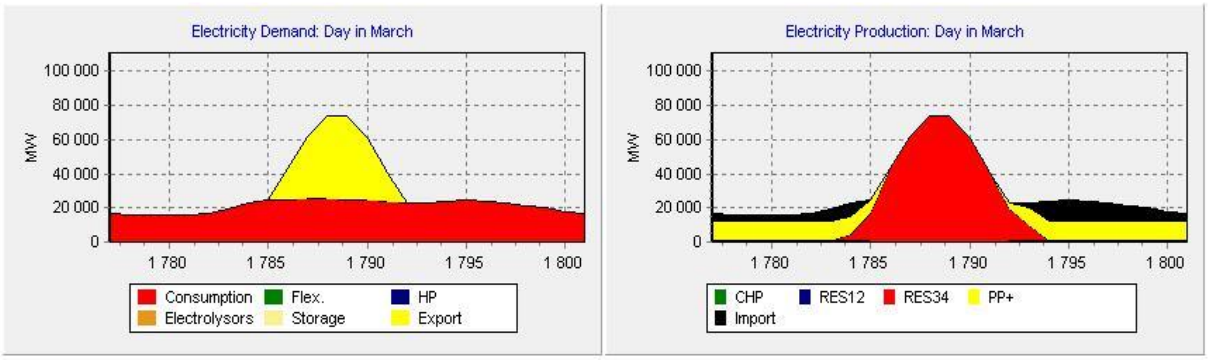

Figure 2. One-day electricity production in March with a breakdown by the production technology (the chart on the right), the one-day demand for electricity with the export of production surpluses in March (the chart on the left). Source: Authors' own work.

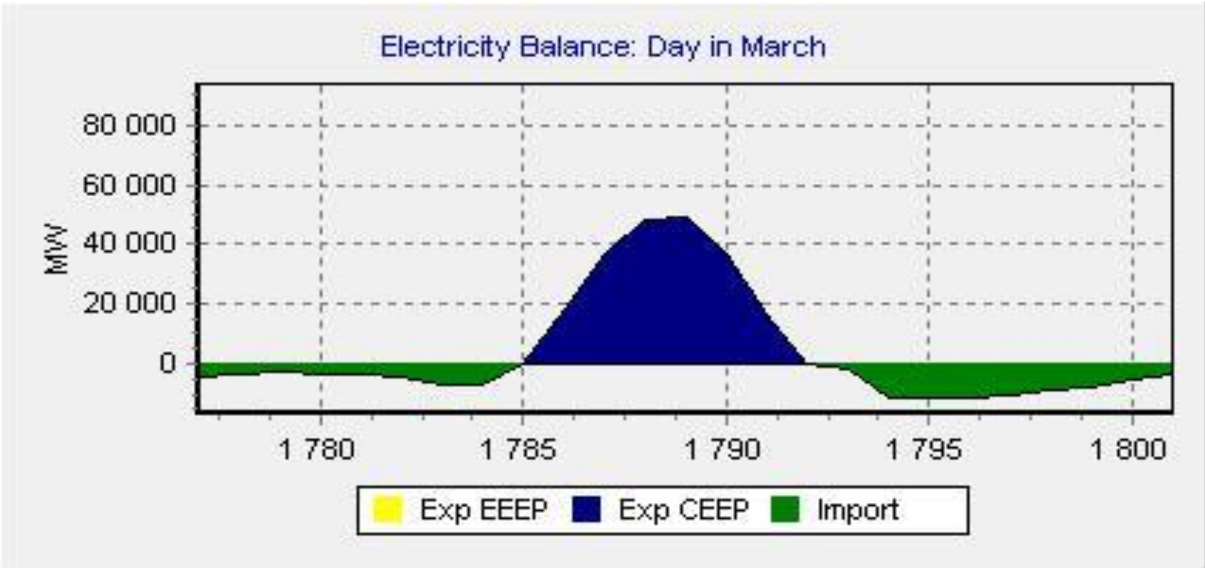

Figure 3. Import and export on the selected day in March. Source: Authors' own work.

The excess of export over import of energy may play a key role from the economic point of view. In Figure 3, navy blue colour 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.

4. The increasing share of electric vehicles in the integrated energy system

The increased share of electric vehicles in transport entails a rise of 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 economy thanks to the excess production of energy and partly compensate for energy shortages, which are usually filled with import 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 assumes an increase in the share of electric vehicles in satisfying the demand for electricity in the integrated energy system. In 2015, were 20 723000 passenger cars registered in Poland (PZPM 2021). For the sake of the simulation, we assumed the share of electric passenger vehicles from 0 to 100%, the average annual mileage 20,000 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 (Eurostat 2017b).

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 colour represents the relationship between the number of vehicles and EV's demand for energy, while yellow colour shows the same relationship for petrol-powered cars.

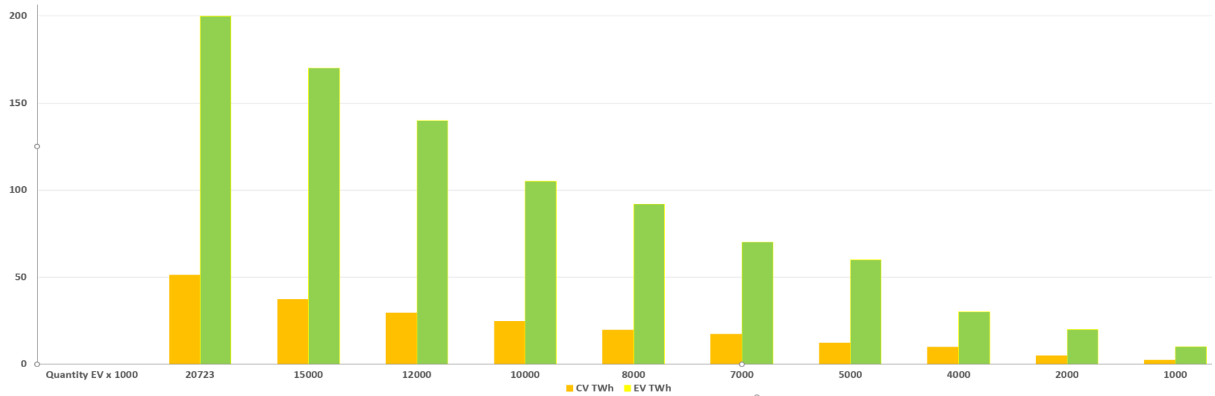

Figure 4. The relationship between the number of electric and combustion vehicles and the demand for energy, Source: Authors' own work.

The analysis of the chart shows that electric vehicles have 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 (Lund 2009). 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.

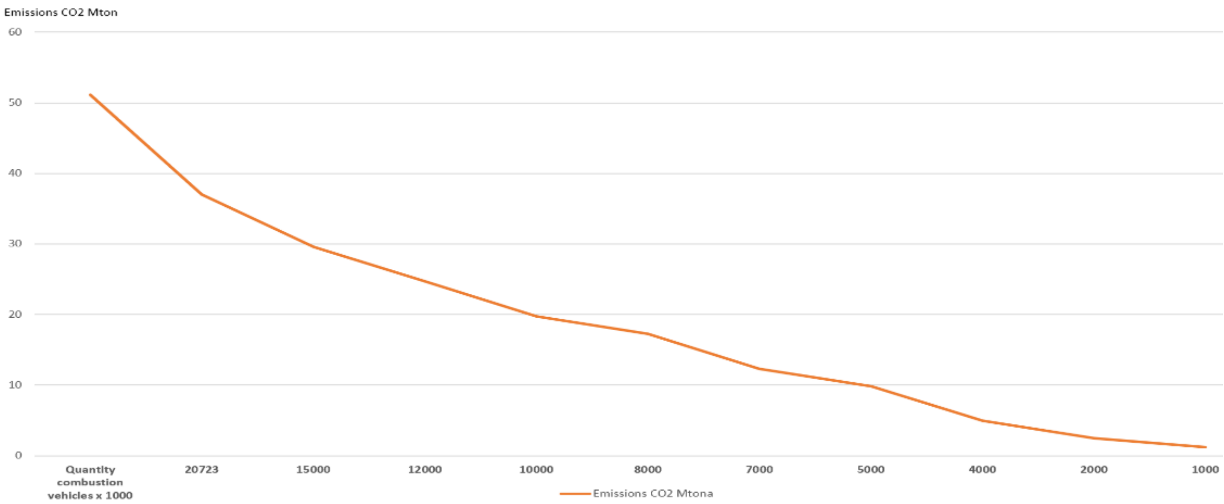

Figure 5. The relationship between the number of internal combustion cars and carbon dioxide emisión. Source: Authors' own work.

The reduction of carbon dioxide emission and of other substances produced by burning fossil fuels is an increasingly important issue in Europe (Willenbacher 2013). 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. In comparison, a modern RES system suitable for Poland, which is examined in simulation 8, emits only 37 million tons. At the same time, it must be emphasized that emission standards for electric vehicles are the same as for new cars from 2015 (Eurostat 2017b). 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 emission.

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 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 (URE 2021), 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 licenced thermal energy producers at the level of 56,048 MW and the demand for system heat of 94,937 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.

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

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 in 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 CO2 emission for these systems is 98.853Mt. 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.

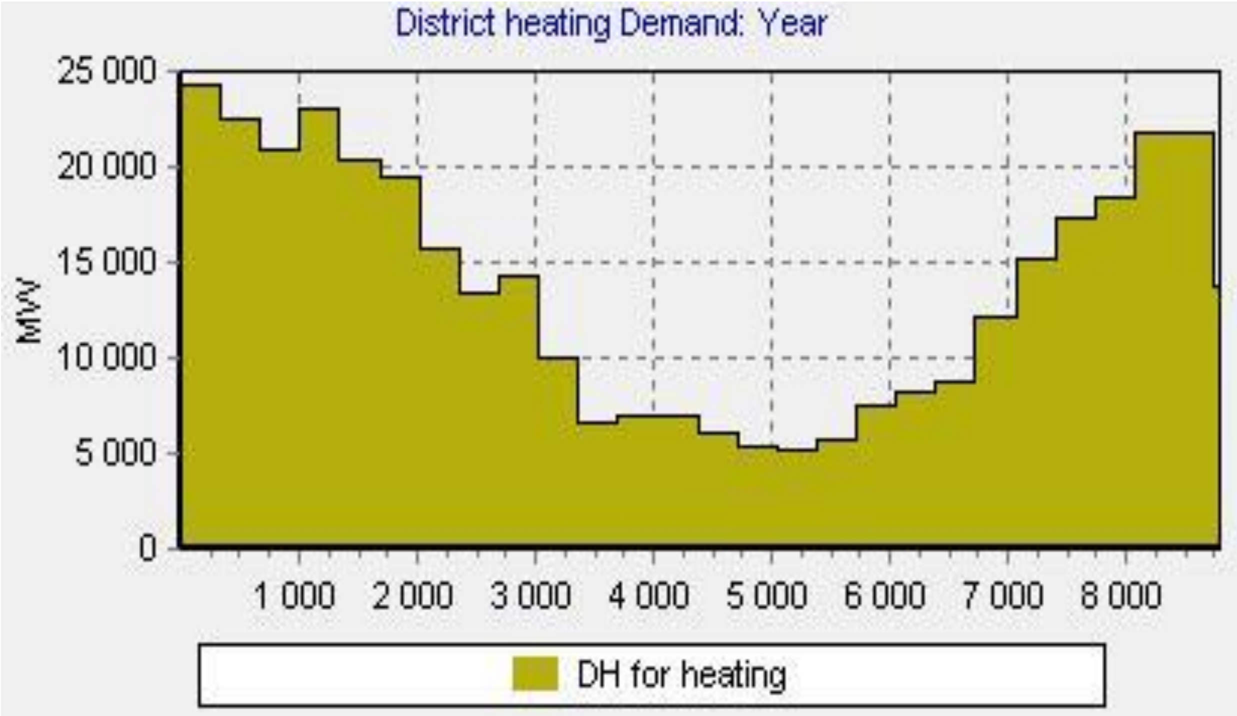

Figure 6. Distrcit heating demand in 2015 Source:(GUS 2021), (URE 2021). Source: Authors' own work.

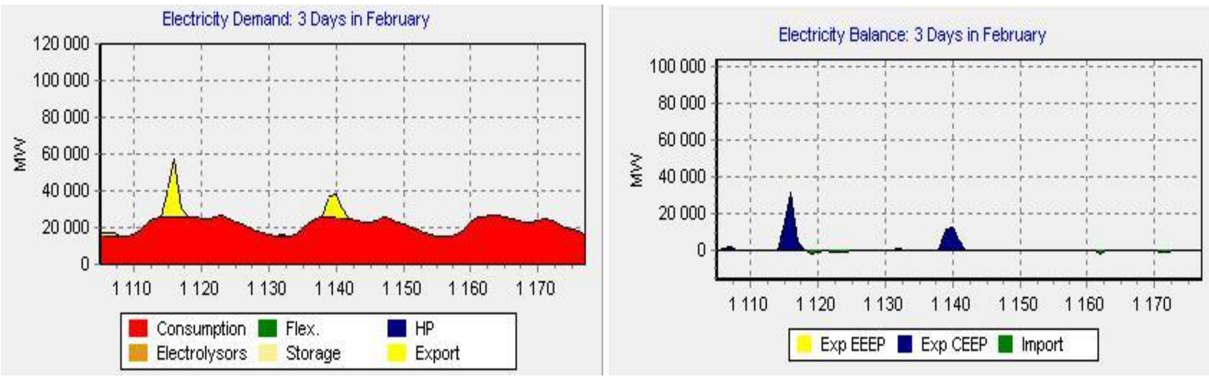

Figure 7. Three-day demand for electricity along with the export of production surpluses in February (the chart on the left), three-day export/import of electricity in February (the chart on the right), in the integrated system of electricity and heating generation without the share of heat pumps. Source: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

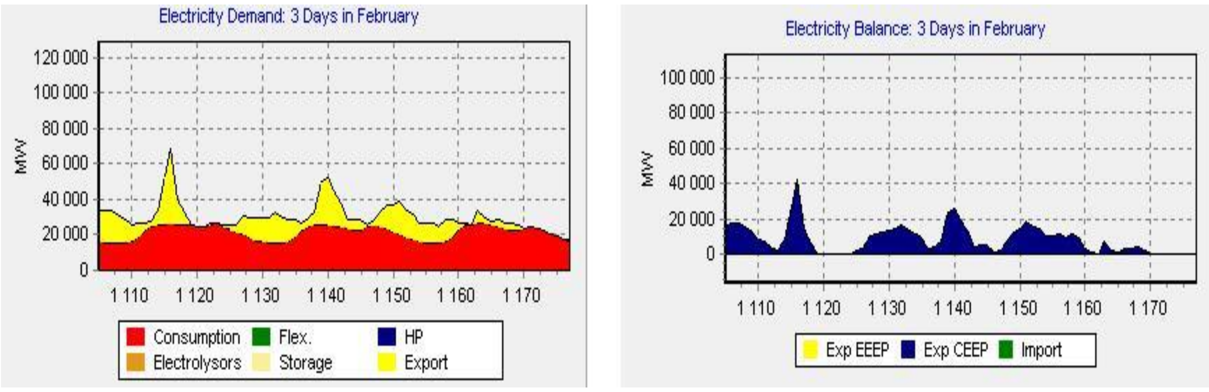

Figure 8. Three-day demand for electricity along with the export of production surpluses in February (the chart on the left), three-day export/import of electricity in February (the chart on

the right), in the integrated system of electricity and heating generation with the share of heat pumps. Source: Authors' own work.

When comparing Figures 7 and 8, one might notice that by replacing a part of coal-fired power plants of the installed capacity of 10,000MW 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 import 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 (Mathiesen et al. 2015). 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.

The production of biofuels and synthetic fuels on the basis of the excess production of electricity from RES - Simulation 4

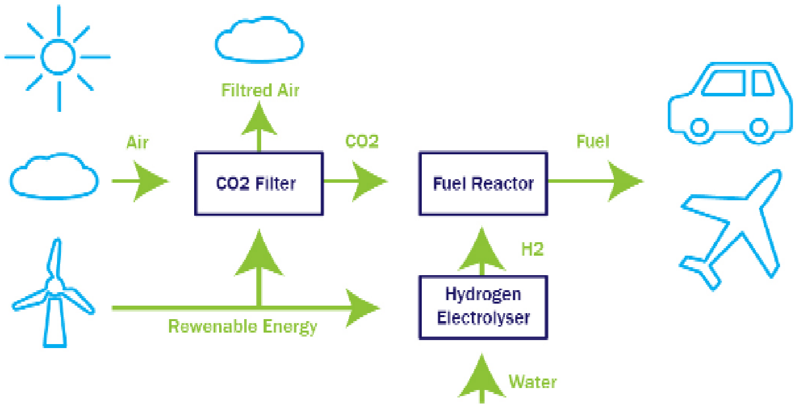

Figure 9: Schem1. The simplified scheme of the production of synthetic fuel based on RES. Source: Authors' own work.

The production of synthetic fuels and biofuels based on electrical energy from RES is a lot more complex process than the use of heat pump 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. Synthetic fuels or biofuels may be used in industry or transport, which, due to its 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.

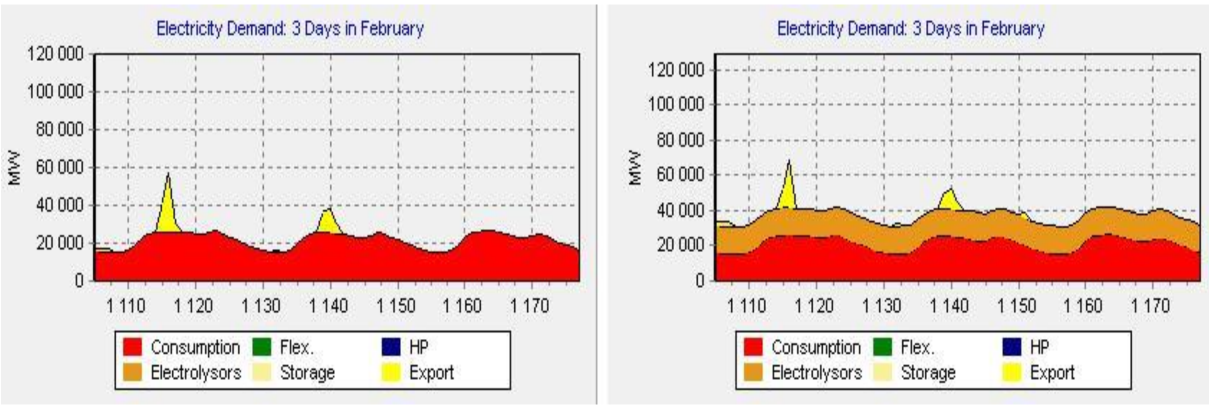

Figure 9. Three-day demand for electricity along with the export of production surpluses in February in the integrated system of the production of electricity and heating power and electricity with the share of heat pumps (the chart on the left). The chart on the right presents the system enriched with 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 on the level of 150 TWh annually.

6. Conclusions

This research paper presents the diverse aspects of the energy system transformation in the context of the increasing share of renewable energy sources, 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 emission. 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 economy.

To conclude, thanks 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 of a country the size of Poland.

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

Acknowledgement

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