

Progress and Challenges Connected with the Integration of Renewable Energy Sources with Railway Distribution Networks

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Abstract: Rail is the most efficient and low carbon means of transport, but efforts are still being made to improve the energy efficiency of this sector. In Poland, one of the elements of the implementation of the energy transformation in rail is the “Green Railway” program, which assumes an increase in the share of renewable energy sources (RES) in the power supply structure of the sector to 50% in 2025 and 85% in 2030, and ultimately, to 100%. An increase in energy efficiency leads to a reduction in financial costs, and also contributes to improving the environment and, consequently, to enhancing the economic and social benefit through a cost–benefit analysis. Energy consumption in railway operations is characterized (unlike in construction) by being repetitive. This energy consumption is produced in four areas: in the movement of trains; in auxiliary systems in the trains; in auxiliary systems in the infrastructure (lighting consumption of tunnels or sections of track, point heating systems, the signaling and communication systems, etc.); and in stations, workshops and by other consumers. The aim of this article was to review modern technologies using renewable energy sources in rail transport for traction and non-traction customers.

Keywords: renewable energy sources; energy efficiency; PV energy sources; power supply



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1. Introduction

The world’s energy consumption is increasing fast, which is why the concept of energy efficiency (or energy optimization) has now become one of the main concerns of humanity around the world. The majority of the Earth’s population uses fossil fuels to meet energy needs, which causes a high degree of environmental pollution; therefore, it is absolutely necessary to search for sustainable and environmentally friendly energy systems. While all traditional energy sources pollute the environment, renewable energy is virtually free of this negative effect of polluting the environment. Diversification of energy sources is becoming an economic and environmental imperative. Alternative energy sources are called renewable energy sources (RES), and the best known of RES are solar energy (direct, photovoltaic and thermal), wind energy (as a derivative of solar energy), hydraulic energy (using the potential and kinetic energy of water), geothermal energy, bioenergy, etc. [1–3].

A reduction in greenhouse gas emissions is one of the main challenges that the European Union will face in the coming years and decades. In response to the Paris Agreement, the European Green Deal sets the overarching goal of making Europe the first climate-neutral continent by 2050 and includes a number of policy initiatives from the European Commission. The European Green Deal was published at the end of 2019, but in December 2020, the European Council voted to increase the greenhouse gas reduction target for 2030 from the current 40% to at least 50% and to 55% in comparison to 1990 levels [4–7]. In turn, on 24 June 2021, the European Parliament adopted the EU climate law, which legally binds the goal of this emission reduction by 2030 and climate neutrality by 2050. For this purpose, the European Commission recommends increasing the share of renewable

sources in the EU energy mix to 40%. Reducing energy consumption is essential to lowering both emissions and energy costs for consumers and industry. The Commission proposes to achieve an overall reduction of 36–39% in final and primary energy consumption by 2030 [8]. Achieving the intended emission reductions requires a thorough transformation of the energy sector. EU energy legislation and the EU Strategy on Energy Technology and Innovation aim to create framework conditions that will facilitate the development of existing and the creation of new low-carbon technologies that will be able to meet the needs identified for sustainable, cost-effective energy. The European Strategic Energy Technology Plan (SET Plan) is a key step in accelerating the transition to a climate-neutral energy system by developing low-carbon technologies in a fast and cost-competitive way [9]. In particular, the above legislative initiatives promote the deployment of renewable energy sources (RES), the electrification of demand-side sectors and better energy efficiency in the electricity, heating and transport sectors.

Poland is heavily dependent on oil, gas and coal imports. The prices of these raw materials in world markets are high, which has a devastating impact on the economy and investments. Accelerating the development of renewable energy sources is one of the main strategies in reducing the import of expensive energy resources, lowering energy prices and creating an emissivity economy. The key will be the development of wind and solar energy, which are technologies which have been proven to be successful in Polish conditions (the cost of generating energy is competitive in relation to conventional generation technologies from coal and gas). Their development potential is significant: by 2050 they can cover about half of the energy demand in Poland [10].

This article contains an analysis of modern technologies using renewable energy sources in rail transport for traction and non-traction customers. This article also aims to provide an up-to-date and comprehensive overview of improvements in the energy efficiency of railway systems. Section 2 outlines global trends in the use of renewable energy sources in rail. Section 3 presents the use of RES for traction and non-traction customers (focusing in particular on solar energy) along the railway track. Section 4 outlines the criteria for connecting generation sources to the distribution network (especially the operators of the non-traction railway network and the distribution system network). Section 5 contains a description of the problems arising in the distribution network caused by the presence of renewable energy storages. This section also includes possible solutions to these problems. Finally, in Section 6, the trends and technical solutions are summarized and concluding remarks are made.

2. Use of Renewable Energy Sources

2.1. Traction Consumers

There are several renewable energy sources that can be used on-board trains to reduce their reliance on fossil fuels and decrease their carbon emissions. Some of the most common renewable energy sources that can be used on-board trains are:

- Solar power: Solar panels can be installed on the roof of trains to harness the power of the sun and convert it into electricity. This electricity can then be used to power the train's lighting and air conditioning and other systems [11–14].
- Wind power (not widely used in trains yet): Wind turbines can be installed on the roof or sides of trains to harness the power of the wind and generate electricity [15–20]; however, detailed analyses are needed since the wind turbine could slow down the train.
- Hydrogen fuel cells: Hydrogen fuel cells can be used to generate electricity on-board trains by combining hydrogen and oxygen to produce electricity and water [21–25]. This can be a particularly effective way to power trains that operate in areas where electricity is not readily available.
- Kinetic energy recovery systems (KERS): KERS can be used to capture the kinetic energy generated by a train when it brakes and use this to power the train's systems [26–29].

This can be a particularly effective way to reduce the amount of energy needed to operate a train.

Overall, the use of renewable energy sources on board trains can help to reduce their carbon emissions and make them more sustainable. However, the effectiveness of these solutions will depend on a range of factors, including the specific train design, the operating environment and the availability of renewable energy sources in the area. Although using solar panels and other renewable energy sources on board trains is a more complex option, it is also possible to feed some of the train auxiliary systems using such technology.

There are many examples of the use of renewable energy in trains operating all over the world. Indian Railways has developed and tested a solar-powered Diesel Electric Multiple Unit (DEMU) train. Indian Railways launched its first solar-powered DEMU (Diesel Electric Multiple Unit) train from Safdarjung railway station in 2017. The train runs from Sarai Rohilla in Delhi to Farukh Nagar in Haryana [30]. The solar-powered DEMU train has a total of 16 solar panels fitted on its roof, with each panel generating a capacity of 300 watts. The train also has a battery bank that stores the excess energy generated by the solar panels, and this stored energy can be used when the amount of power generated by the PV panels is not large enough. The train can run for up to 72 h on a single charge, which means that it can run even during periods of low or no sunlight. The solar-powered DEMU train was tested successfully in Jodhpur, Rajasthan, in 2017, and it was found to be capable of saving up to 21,000 L of diesel per year, resulting in a reduction of around 54 tons of carbon dioxide emissions per year. Moreover, one should notice that PV panels and batteries reduce the power consumed from the power network which has a positive effect on the distribution system since voltage fluctuations are reduced. The successful testing of the solar-powered DEMU train shows that solar power has great potential to be a viable and sustainable alternative to traditional sources of energy for powering trains. Figure 1 shows the solar-powered DEMU train in India.



Figure 1. Solar powered DEMU train at Safdarjung Railway station (press materials) [30].

The second example of solar-powered train is the Byron Bay Train in Australia [31,32]. At the end of 2017 in South Wales, Australia, a train powered entirely by solar energy was launched. The Byron Bay Train is a heritage rail service that runs on a short stretch of track between the town of Byron Bay and the nearby resort town of Sunrise Beach. The train walked along a small route between the city and the Byron Bay resort area—only 3 km. The train is designed to have 100 seats. The train's roof was fitted with 6.5 kilowatts of solar panels, which generate electricity to power the train's batteries. The batteries can store enough energy to run the train for up to three days. The train operates purely on energy from the sun. In total, 23% of the energy generated from the solar panels on the train shed's roof feed the onboard batteries which power the train, along with the power generated by panels on the roof of the train itself. The remaining 77% of energy is fed into the grid to power the local community via the green energy provider Enova. The train is also fitted

with regenerative braking, which uses braking energy to also recharge the batteries as the train slows down. Figure 2 shows the main view of the Byron Bay Train [31].



Figure 2. The Byron Bay Train in Australia (press materials) [31].

In Germany, Alstom have developed and tested the world's first passenger train powered by a hydrogen fuel cell called Coradia iLint (Figure 3), which produces electrical power from traction [29,33]. The train is quiet, moves much more smoothly than combustion units, and most importantly, it is fully emission-free—it only emits steam and water. Coradia iLint was designed in Salzgitter in 2016, first presented at InnoTrans from 20 to 23 September 2016 in Berlin. The trains have a range of up to 1000 km, which allows them to work all day without refueling. The propulsion system combines a hydrogen fuel cell with two batteries with a total capacity of 220 kWh. The maximum speed of the train is 140 km/h, but the EVB units are able to run at a speed of 80 to 120 km/h. Coradia iLint is designed specifically for use on non-electrified routes, and in the European Union, this is 40% of railway lines [34] (and in Poland about 37% [35]).



Figure 3. The train Coradia iLint by Alstom (press materials) [33].

Another example of a hydrogen train is the Chinese CRRC locomotive [36]. This machine is designed primarily for maneuvering work. The power of the drive system is 700 kW, and the locomotive's towing capacity is 5000 tons. The train was the fastest of its kind in the world, with a speed of 160 km/h. The machine works completely emission-free, and does not require access to the catenary, which significantly increases its usability. CRRC

estimates that hydrogen trains could replace up to 90% of the 7800 diesel locomotives operating in China. In Poland, Pesa is working on the SM42-6Dn range machine (Figure 4), in which two hydrogen cells with a total power of 170 kW are responsible for energy generation [37]. The locomotive was also equipped with an autonomous driving system. It is expected that the first trains towed by a hydrogen locomotive will be launched on Polish tracks between 2025 and 2026.



Figure 4. The locomotive SM42-6Dn by Pesa (press materials) [37].

Another way of using wind energy is to power electric trains with energy from wind farms. This solution has been used by the national railway carrier in the Netherlands since the beginning of 2017, where 100% of Nederlandse Spoorwegen's (NS) trains are powered by wind energy [38]. According to NS, approximately 600,000 passengers use their trains daily, and each trip powered by wind energy helps cut down their carbon footprint. Annually, trains consume around 1.2 billion kWh of electricity, which is equivalent to powering all households in a large city such as Amsterdam (about 1% of energy consumption in The Netherlands). An example of another country using 100% renewable energy to drive trains is Austria, where the electricity supplied to the traction is mostly generated from hydropower plants, but also from solar power plants. The generated energy is supplied directly to the railway overhead line, which largely eliminates the need for new electrical lines. Moreover, the trains are powered by wind energy directly, so the energy losses are much lower [39].

In its FLIRT trains, Stadler uses ABB Bordlin traction converters, which recover the energy from braking and feed the energy to on-board devices, e.g., air conditioners and heating. This allows energy consumption to be reduced and reduces the cost of operating trains [40]. The first trains of this type appeared in the rolling stock of the largest Polish railway operator PKP Intercity in the last quarter of 2022 [41]. Such systems are used also in the German trains of Deutsche Bahn (DB). The company declares that all modern electric trains at Deutsche Bahn are equipped with a braking energy recuperation function. When they brake, their motors act as generators, converting kinetic energy into electrical energy, which then flows back to the traction network and is then reused by other trains. In 2022, the recovery systems generated around 1500 gigawatt hours of electricity savings [42]. The German operator DB intend, by 2038 at the latest, to source 100% of its traction current from renewable energy sources in order to meet our target of climate neutrality by 2040. The solar power park at Gaarz near Plau am See went into operation in May 2021. DB Netze Energy now receives about 80 GWh of eco-energy annually, thereby saving up to 40,000 t of CO₂ per year in comparison to gray energy from the 50 Hz markets, and up to 60,000 tons of CO₂ when compared to sourcing power from a coal-fired power plant. DB

plans to increase the share of renewable energies in the DB traction current mix in Germany to 80% by 2030. In 2021 the part of the renewable energy in DB traction current mix reached 62.4% [43].

2.2. Non-Traction Consumers

Installing equipment that provides energy from renewable sources (e.g., solar panels, wind generators) to feed non-traction loads in both facilities and on board trains may have a significant impact on the energy costs in a railway system. Moreover, such equipment may noticeably reduce CO₂ emissions, hence making railways more environmentally friendly. Installing photovoltaic panels, wind generators and other systems that harvest energy from renewable sources requires an important investment, particularly if a large area (such as the roof of a train depot) is to be covered with PV panels. However, the cost of the energy that is no longer provided by the external grid may cover this investment in a matter of 9–10 years in medium and large facilities. There are different renewable energy sources that may be used to supply part of the energy needs of a railway system, such as geothermal energy or mechanical energy harvested with piezoelectric elements. However, the most common and efficient devices are solar panels and wind generators [44].

Local renewable sources such as photovoltaic panels and wind generators may be installed to feed railway facilities such as stations and depots. Likewise, trains may be equipped with renewable energy systems to power some auxiliary needs like lighting or heating ventilation and air conditioning (HVAC). The aim of both measures is to partially power non-traction loads with clean energy and thus reduce CO₂ emissions. Railway facilities such as depots and stations tend to occupy large areas and have large roof zones where photovoltaic panels may be installed to cover some of their energy needs. This approach has been studied carefully in [45].

Choosing the network configurations for each different installation solution depends on the technical analysis related to the general characteristics of the railway station. First of all, it is important to underline that it is almost impossible to abandon the public distribution system because the 3000 Vdc power line does not have the necessary reliability to supply the station loads (it is often interrupted for scheduled maintenance activities). The public supply system is also preferred compared to batteries and other back-up systems. Because of concerns about the conversion from 3000 Vdc to 400 Vac, the solution using single mono-directional converter is preferred because it has a lower cost.

The different network configurations that allow the loads to be supplied to the station integrate the PV panels placed in the shelters and, just in case, can also be powered by the railway 3000 Vdc power line. It is made up of the following different modules [46]:

- Conversion system between 3000 Vdc and 400 Vac. The conversion system can be realized with two different modules: the first one is made up of a step-down chopper that converts and stabilizes the 3000 Vdc voltage to $650 \div 800$ Vdc and the second one is made up of an inverter that converts the dc voltage from the output of the chopper to 400 Vac voltage to supply the station loads.
- Station electrical load. Evaluation of network configuration, contracted capacity, generation profile and capacity.
- PV shelters. Optimal inclination and exposition of PV modules.
- Distribution company. A connection to the distribution network can be present in order to allow the bi-directional energy exchange with the railway station power plant; this can be present and used only in emergency conditions to supply the railway station loads or absent.

It is important to underline that, in those configurations without power supply from the public network, the PV cannot supply the load. In order to supply the load in case of a black-out it is necessary to take into account an additional Storage System, as shown in Figure 5.

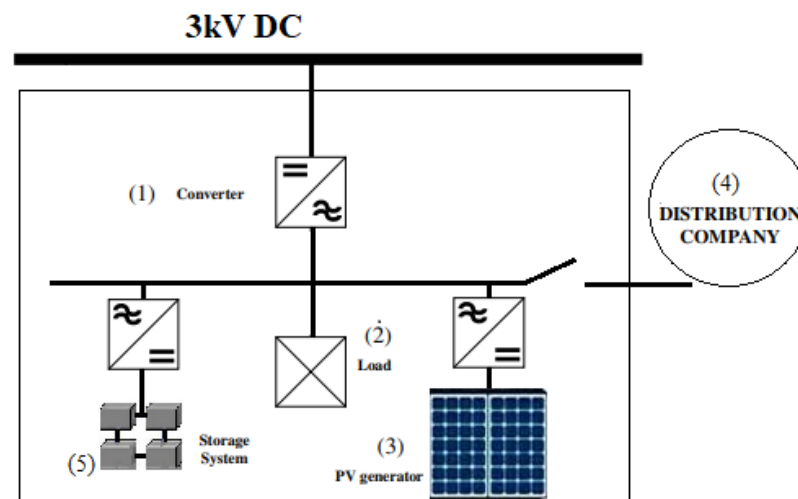


Figure 5. Modular network configuration with a Storage System (own study based on [47]).

There are some good examples of using RES in railway companies for railway station consumers, such as installing renewables on traction substations and using it for control devices. In the examples cited, the authors focus on the use of solar energy, because it is the most common source of energy used for non-traction purposes.

The Valencian public railway company Ferrocarrils de la Generalitat Valenciana (FGV) is keeping the commitments established in their sustainability declaration. FGV installed 10,400 photovoltaic cells on the rooftops of the Metrovalencia and the TRAM d'Alacant workshops in 2008. This action generates 3114 million kWh annually. The energy produced, which is equivalent to the average consumption of about 1000 Valencian homes, reduces CO₂ emissions into the environment by 3500 tons. The 10,400 solar panels cover approximately 18,000 m². This makes it the largest photovoltaic cell installation on industrial rooftops in the Valencian Community and one of the largest for a public company in Spain [48]. The company also installed solar collectors for the production of domestic hot water in fixed installations and changing rooms for rolling stock work-shop personnel [49].

Indian Railways, the fourth largest railways in the world by network, has envisioned to become a Green Transporter by reducing its carbon footprint. The energy consumption of Indian Railways in FY 2020 was around 18,410 Million Units for traction and 2338 Million Units for non-traction load. Indian Railways has taken significant strides to reduce its carbon footprint and fuel cost and is committed to becoming a “net-zero” carbon emissions organization by 2030. Some of its key initiatives towards decarbonization are 100% electrification of the railway's broad gauge network, a reduction in energy consumption and meeting energy demand through the use of RES. Indian Railways already has 220 MW capacity of RE power, with a nearly 3450 MW capacity in the pipeline. The company has the potential to generate 20 GW of solar energy and plans to use its vacant plots to build onshore solar power plants for traction power [50]. Figure 6 shows rooftop solar power plant installed on one of the Indian railway stations.

Solar panels can be combined with other renewable energy sources to increase the amount of renewable energy available, a country like India is a prime example of this. About 50 stations in the country are completely dependent on solar power, and 300 have solar or wind power systems. Jaipur, the newest solar railway station, saves 7.2 lakh rupees a year on electricity bills. As of April 2015, the water supply to Perugamani Station and the adjacent railway districts is powered by solar-powered water pumps. At Thiruvananthapuram, railway gate signaling is powered by solar energy. At Ratnagiri, Maharashtra, a solar power plant was built to power the station. In Birur, Karnataka, a 15 kW wind and solar power plant was built in 2015, generating approximately 20,000 units of electricity. Similarly, a 26 MW windmill in Jaisalmer was commissioned in December 2015 [51].



Figure 6. A 3 MW rooftop solar plant at Howrah Railway Station [50].

Since 2021, the energy portfolio of Deutsche Bahn contains solar-generated electricity from the new Gaarz solar farm near Plau am See in Mecklenburg-Vorpommern. The 90-hectare solar park has supplied green electricity for trains for 30 years. In the future, Deutsche Bahn will also feed renewable power from a solar farm directly into Germany's rail traction power network [52]. Solar panels on German railways are installed on station roofs and noise barriers along the tracks. The German Deutsche Bahn and the British energy company Bankset are testing the use of photovoltaic systems on railway tracks [53]. During the tests, solar batteries were installed on the sleepers. This design, according to Bankset's calculations, can produce up to 0.1 MW of electricity per kilometer. If we consider the entire length of the German railway network of 33,000 km (about 60,000 km of tracks), then the potential volumes of electricity generated in this way could be compared with the capacities of several nuclear power plants. Figure 7 shows a view of the solar panels installed on the sleepers in Germany.



Figure 7. General view of the solar panels on the sleepers [53].

At the Italian company Greenrail, a start-up from Milan is integrating solar panels that turn railway infrastructure into a photovoltaic field, and Greenrail Piezo uses a piezoelectric system to generate electricity as the train passes. Each kilometer of Greenrail solar sleepers can produce 35 MWh, enough energy to meet the annual electricity needs of 10 households over year. Considering that there are around 380 million concrete sleepers in Europe alone, the potential is huge. In September 2018, the company launched the first pilot section of smart sleepers on the Reggio Emilia—Sassuolo line in Italy [54].

Renewable energy sources are also used at traction substations. Their role is to transfer energy supplied from the electrical grid and distribute it to all subsystems within the railway network. Substations have their own auxiliary systems that may consume as much as 60 MWh per year and substation. Auxiliary consumptions at the traction substations are connected to the secondary of the power transformer or directly to the catenary [49]. In order to supply part of this energy, Société Nationale des Chemins de fer Français (SNCF) has developed a program called ZAC (Zero Auxiliary Consumption) which aims to equip all substations with a combination of solar and wind generation devices.

The authors of reference [55] analyzed the use of the photovoltaic stations for auxiliary loads in traction substations in Ukrainian conditions. It was considered that the amount of auxiliary electricity consumed in a DC traction substation reaches 41,440 kWh in the period April–September. The average value of consumption for the station's own needs per day for this period would be 226.45 kWh, i.e., 9.435 kW. Considering a DGE-SP120-W photoelectric converter, and that the total roof area of a typical DC Ukrainian traction substation is 918 m², the authors came to the conclusion that photovoltaic modules will occupy only 12% of the total roof area. This will be enough for the needs of the traction substations.

Other actions are taken by PGE Energetyka Kolejowa through the Green Substations program. Its aim is the installation of PV modules at traction substation sites. The electricity generated by the installations is used to fulfil the traction substations' own needs. The Green Substations program [56] which was implemented by PGE EK has resulted in the company's network of photovoltaic installations being the most numerous in the railway industry today and one of the most numerous in Poland. As part of the program, PV installations have been installed on 360 traction substations, with a total of 11,000 m² of panels in operation [57]. This number of PV modules makes it possible to generate almost 2 GWh of clean energy per year. With this amount of electricity generated from PV installations, the company is able to reduce its carbon footprint by more than 1500 tons of CO₂ per year. The installation of photovoltaic installations on 360 traction substations represents the placement of installations on more than 70% of all such railway power supply facilities in Poland. The project thus covered the majority of locations where there were technical possibilities for installation. The location of each installation was selected individually, so that the greatest efficiency and effectiveness could be achieved.

Renewable energy sources could also be used to power traffic control devices [58]. The possibilities of applying solar batteries to supply power to railway automatics and telemechanic device in Uzbekistan is presented in reference [59]. The research is focused on the questions of energy/effective control of turnout electric drives from solar batteries on intermediate stations. Using the example of "Sabir Rakhimov" station, an assessment of the average daily quantity of turnout switches has been made, the calculation of the quantity of electric energy used by turnout electric drives has been pursued, and the possibilities of replenishing this energy from solar batteries have been defined.

In Polish conditions [60], in order to power the traffic control devices, the PV panels should be oriented to the south. The angle of inclination to the horizontal plane should be approx. 50–55° in winter and 34–37° in summer. In some designs, solar batteries can be placed on special bases that position them perpendicularly to the sun's rays. The capacity of the installed solar batteries, incorrectly marked in the catalogs as Wp (watt peak), corresponds to the solar radiation 1000 W/m² and the temperature in the semiconductor junction being 20 °C. Such conditions occur sporadically in Poland. For this reason, the installed capacity of the solar battery is only used for about 1000 h per year. On average, in Poland, it is possible to acquire approx. 100 W from one square meter of battery surface. Table 1 shows the average annual energy consumption for selected rail traffic control devices.

Table 1. Average annual energy consumption of selected traffic control devices.

Devices	Annual Energy Consumption (kWh)	Average Monthly Consumption [kWh]	Average Daily Consumption [kWh]	Average Hourly Consumption [kW]
Automatic block section	5101	425.08	14.17	0.59
Level crossing	5425	452.08	15.07	0.63
DSAT devices	7789	649.08	21.64	0.90

2.3. Railway along the Railway Track

One of the key methods for increasing the usage of RES in railways is to build and connect them to a distribution system, which powers the railway with new, local, energy sources like PVs or wind farms.

This method requires grid conditions which allows new energy sources to be connected; approval for connection is based on grid analysis by the Distribution System Operator (DSO), especially by short circuit power and energy flow calculations. Depending on these conditions, the connection of new energy sources may hardly be available for some parts of grids, especially with small numbers of connected customers or very low short circuit power. Grids which power railways very often have trains such as these, as they may be a subgrid of another distribution system operator—DSO. Nevertheless, in Poland, PGE Energetyka Kolejowa (PGE EK), as the DSO, connected 24.62 MW to its grid, which allows it to generate approximately 28.68 GWh of energy annually. Most sources installed are photovoltaics (PVs).

Information on RES generation installations connected to the PGE EK network are presented in Tables 2 and 3; data are for 2022 [61].

Table 2. Data on micro-installations in the PGE EK network.

Number of Micro-Installations Connected to the Grid [-]	Installed Capacity of RES Micro-Installations [MW]
650	11.83327

Table 3. Data of other RES installations in the PGE EK network.

Number of Small-Scale and Other RES Installations Connected to the Grid [-]	Installed Capacity of Small-Scale and Other RES Installations [MW]
17	12.792

Public awareness of environmental issues is growing, and 73% of Poles intend to use ecological public transport [62]. Taking that into consideration, CEEK (Polish Railway Energy Efficiency Centre)—a joint initiative in the railway sector—was created in response to the challenges facing the rail sector in the area of energy consumption. To date, CEEK has defined initiatives that contribute to reducing energy consumption by 1.2 TWh by 2030. CEEK cooperates with 70 bodies. Companies representing the railway industry are responsible for 95% of energy consumption in the sector. The initiative develops and implements energy-efficient and, at the same time, environmentally friendly solutions that serve all participants of the railway market. At the same time, in line with CEEK's position, increasing the competitiveness of the industry requires the energy used in rail transport to come from renewable energy sources. It will be possible thanks to the implementation of the Green Railway Program [63]. The Zero Emission Rail Programme is an example of a possible energy transition in the rail sector, which could be a milestone towards zero emission transport in Poland. The uniqueness of the concept is due to the consolidation of the entire industry around this goal from carriers, energy supplier and rail infrastructure managers. One of the objectives of the programme is to strengthen the individual components of railways as zero-emission transport:

- Existing and newly electrified railway lines will be powered with RES energy;
- Creation of a zero-emission access infrastructure to the CPK airport, as part of the CPK Rail Programme being implemented;
- Implementation of investments in line with the Rail Plus Act, mainly the restoration of disused lines and the prevention of rail infrastructure decommissioning, in a way that does not increase CO₂ emissions;
- Making rail passenger transport more attractive by introducing the “green ticket” concept for passengers.

The Green Railway will generate 1.8 GW of new green power in the country's energy system as part of a ‘green smart power plant’ dedicated to the railways through distributed RES generation sources. The expected outcome of the Programme is the creation of several hundred small and dozens of large PV farms and wind sources.

The volume of energy sold by PGE EK to rail operators in 2022 as part of the Green Rail programme was 143,308 GWh [63]. The use of energy from renewable sources to supply special purpose applications is also promising. The study in [64] describes the application of a PV station together with energy storage to supply anti-theft system for the overhead contact line.

3. Criteria for the Connection of Generation Sources to the Distribution Network

In the of connecting RES generation sources to the low voltage grid in Poland, one needs to follow the rules outlined in the “Connection criteria and technical requirements for micro and small installations connected to the low voltage distribution grid” [65]. This document is applicable during the planning, construction and commissioning phases of connecting an RES generator to the low-voltage grid. The document takes into account applicable national legal regulations, standards and provisions and similar experiences from other European countries. The verification of the possibility to connect generation sources to the low-voltage grid consists of checking the voltage level behavior is within $\pm 10\%$ of the grid voltage and voltage variations (deviations and voltage level changes), checking the limits of rapid voltage changes caused by switching off a single source, checking the long-term current carrying capacity, checking the short-circuit strength of power equipment, checking the power rating of the transformer installed in the MV/LV substation.

In a medium-voltage network, one need to follow the rules contained in the “Technical criteria for assessing the possibility of connecting generation units to the medium-voltage distribution network” [66]. With regard to ensuring the criterion of power reserve in the HV/MV node are met, we compare the power of the transformer unit feeding the MV distribution network plus the minimum total load of active power of the transformer, as determined by the DSO, with the sum of the active powers of the generation sources operating and planned to be connected to the MV network. The calculations are performed for the operating state of the HV/MV transformer station “ $n - 1$ ”, i.e., with the operation of a single transformer of the smallest capacity, assuming that the long-term load degree of the HV/MV transformer cannot exceed 100%. Then, the maximum active power in the generation sources which are connected and planned for connection to the MV network should not exceed the sum of the transformer's rated apparent power (minus the assumed $\cos\varphi$ offtake, where $\tan\varphi$ offtake is equal to 0.4) and the minimum active power load of the transformer as defined by the DSO. In a situation where it is necessary to carry out investment works consisting of the replacement of the existing HV/MV transformer unit with a unit with greater capacity or with a unit with different technical parameters, which will go beyond the scope provided for in the Development Plan, or if it is necessity to change the operating layout of the HV/MV node, the application is qualified for the rejection of the connection conditions. According to the above, the maximum allowable power of the generation sources for the traction substation cannot exceed the value, calculated according to the following formula [66]:

$$P_{RES} \leq S_{T15} \cdot \cos \varphi + P_{load} \quad (1)$$

where:

P_{RES} —permissible power of planned sources;

S_{T15} —apparent nominal power of the 15 kV winding of transformer;

$\cos\varphi$ —value of $\cos\varphi$ of load;

P_{load} —minimum active power load.

4. Grid Problems Caused by RES and Possible Solutions

In order to maximize the connection capacity, one should adapt the generation profile to the load profile. Adaptation can be achieved by adapting the power of PV panels as well as the orientation of PV panels or by careful analysis of the wind profile [67]. Despite the energy balance, one needs to consider dynamic issues, among which the most basic issue is a high variability in the load, which results in rapid voltage drops and flicker factor degradation. The example of traction station load is presented in Figure 8. One can imagine that the combination of voltage drops resulting from traction load connected with voltage drops and rises coming from renewables will further degrade the voltage stability and could lead to violation of power quality indexes therefore one needs to consider regulation of active and reactive power carefully.

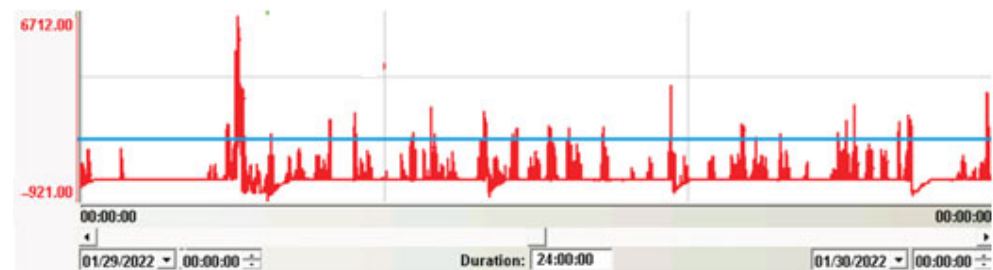


Figure 8. Exemplary traction station power [68].

Unfortunately, the renewables themselves have limited capabilities to solve the above mentioned issues [69]. In order to develop renewable sources and increase the installed capacity of RES, it is necessary to simultaneously develop energy storage technologies that to some extent balance the irregularity in generation, high voltage in the network or overloading of the lines and transformers [70–72]. Furthermore, the operation of high-power traction rectifiers and inverters is connected with significant harmonic emission, as well as other PQ issues [73]. The renewables and energy storages need to be able to operate properly under degraded PQ indexes and repeating transient disturbances, e.g., arcing in the pantographs. An extensive PQ review may be found in [74].

The rapid increase in the installed capacity of renewable sources in Poland observed in recent years has contributed to distribution system operators and transmission system operators facing the challenge of balancing the National Power System. The challenge of balancing the grid is even greater due to the state of the grid infrastructure. This results in an increasing number of refusals to connect RES installations.

These problems can be solved with the help of energy storage. The ability to recharge the storage during periods of excess generation can enable the local distribution network to be balanced. The stored energy can then be used during periods of increased consumption. Another aspect of the cooperation between energy storage and RES sources that supported the construction of the first traction energy storage in Poland was the fact that new energy storage installations can provide an impetus to increase the share of RES by providing connection capacity without the need for extensive and costly grid modernization. RES working with energy storage can play a special role in the Polish railway sector. The electrified railway is the least energy-intensive means of transport in Poland, but despite this, it is largely powered by fossil fuels. The reason for this is the country's power generation structure, which is dominated by conventional power plants. For this reason, it

is necessary to increase RES sources in the electricity system, which may be made possible by new energy storage installations in the system.

One of the examples being prepared for testing is a photovoltaic farm and a prototype hydrogen energy storage facility created by PGE Energetyka Kolejowa in Garbce, Poland [75]. This installation will cooperate with the existing application of electrochemical energy storage (the largest traction storage in Europe [76]). The installed capacity of the photovoltaic farm is approximately 150 kWp. An innovative solution that has been applied to the installation is the connection system. The first connection point is the DC bus in the traction substation, connected via a 3×0.4 kV AC/3 kV DC rectifier system. The second point of connection is the traction substation's own AC switchgear.

The main task of the photovoltaic farm is to supply the traction energy storage and/or to supply the overhead line directly. In this way, the traction energy storage will be able to additionally stabilize energy production, which is the typical purpose of most facilities of this type built in Poland and worldwide. A secondary purpose, carried out when the traction energy storage is fully charged and there is no overhead line demand, is to cover the substation's own needs. The measures described will reduce the amount of energy drawn by the substation from the external DSO network. At the same time, these measures will increase the share of green energy in the supply of the local part of the railway network. Excess energy generated from the photovoltaic farm that is not used for traction needs or the traction substation's own needs will be used to produce hydrogen by electrolysis. The hydrogen produced will be stored in specially adapted pressurized cylinders. It will then be burned in fuel cells. The energy produced this way will be used to supply the substation's own needs in the absence of power from the photovoltaic farm or in the case of limited generation.

5. Discussion

There are different types of traction power supply systems around the world. There are both AC, from 15 to 2×25 kV, and DC systems—typically up to 3 kV—which can be grouped according to voltage level and frequency, e.g., 16 2/3 Hz or 50 Hz [77,78]. There are different supply transformers and arrangements, e.g., Scott transformers or rectifier transformers, for DC networks [79]. The rectifiers transformer can transform energy from MV networks or HV networks. In the case of an MV network and a six-pulse rectifier, two winding transformers are used; in the case of an MV and a twelve-pulse rectifier, three winding transformers are used. Four winding transformers are used in the case of an HV supply and a twelve-pulse rectifier. Fourth winding is used to reduce voltage to MV level to supply non-traction loads. A comparison of potential different connection points of renewables is presented in Table 4. The connection to the rectifier side of transformer is excluded from analysis because of PQ technical limitations.

The comparison is made taking into consideration diode rectifiers, which allows one way power flow; however, two-way electronic converters are currently being researched, which could further change the situation in the future [80]. Furthermore, one needs to remember that it is a generic comparison only and one should carefully analyze each location carefully, e.g., there can be almost no load in non-traction lines, only a very limited load in non-traction lines or a large load resulting from consumers. Each traction substation may also work under different PQ conditions depending on the situation in the distribution system and the construction of the traction substation, e.g., older filters or the newer gamma type [81].

Furthermore, one must meet the needs of differently designed supply systems—with overhead lines and supply lines in rails or the so called third rail [82]. The third rail is utilized in urban areas whereas the overhead lines are used for the rest, e.g., inter-city connections. The construction of rail lines and supply lines have a big impact on the utilization of rail-dedicated PV panels and result in the possibility of assessing the connection based on differences in the electrical parameters.

Table 4. Renewables' connection capacities and functionalities depending on the connection point.

Connection Point/Functionality	110 kV (HV) of DC Traction	MV (15) Supply Side of DC Traction	MV Non-Traction Load of 110/15 Transformer in DC Traction	AC Traction	DC Side (1 Way Power Flow) + Energy Storage	Train + Energy Storage in DC
Typical active power capacity	<100 MW	<10 MW	~1 MW	A few MW	A few MW	A few -tens kW
Compensation of load inductive power	Possibility to reduce losses in 110 kV lines	Possibility to reduce losses in MV lines (losses are higher than in 110 kV)	Limited possibilities to reduce reactive power flowing through 110 kV lines	Large potential	Reduction of reactive power losses by reduction of load active power	No
Reduction of active energy supplied from the network	Yes, effectiveness depend on load and generation profiles					
Recuperation capabilities of energy storage	Only if 2 way inverter is used for traction supply	Only if 2 way inverter is used for traction supply	Only if 2 way inverter is used for traction supply; limited power	Yes	Full capabilities irrespective on inverter	No
Stabilization of voltage in traction network	Limited potential	Big potential	Limited potential	Large potential	The largest potential	Minimal, by reduction of train peak power
Reduction of traction transformer peak power	Minimal by optimization of voltage level and reduction of current for same power; large potential if renewables are connected to secondary windings of AC transformer in case of AC traction				Large potential	
Reduction of losses	Significant	Larger potential than in HV lines, particularly in case of long supply lines				Noticeable
Compensation of capacitive no load power from distribution system	Yes				No	
Grid support	Virtual inertia, synchrocheck support [83,84]				Limited	

One of the basic ideas behind using local energy sources is to connect sources close to the loads. The integration of PV panels into the train, rails or direct neighborhood is, however, connected with additional technical issues. The PV panels on a train's rooftop could be negatively affected by the shadows of the overhead lines, whereas PV panels installed between rails could be almost instantaneously covered by the passing train which would additionally increase the problem of power and voltage fluctuations. Further the integration of PV panels with rooftop may be difficult because conventional train supply system may require serious modification or even almost complete overhaul of the electric installation.

6. Conclusions

Renewable energy sources are increasingly being introduced into rail transport. There are many technical solutions based on renewable energy sources dedicated to improving the energy efficiency and environmental friendliness of railway transport. The energy crisis, caused firstly by the recovery from the COVID-19 pandemic, and then by Russia's attack on Ukraine, showed how important it is to accelerate the development of RES in Poland and the EU, including for railways.

Potential issues in integration of renewables and severe limitations from connection capacity are presented and a general comparison of different connection points is provided.

The analysis of scientific works, technical reports, recommendations of the UIC, open information published on internet portals of railway operators, infrastructure managers and railway undertakings, allowed us to define the main methods which could be used to increase the use of renewable energy sources in railways. In the given reports, the authors discussed the examples of implementing different types of renewable energy sources for traction and non-traction consumers and for special applications.

There is great potential in the implementation of renewable sources by railway companies for their own needs. Local renewable sources such as photovoltaic panels and wind generators may be installed to feed railway facilities such as stations, depots, traction substations.

Further research should be focused on the utilization of energy storages and the development of dynamic control algorithms as well as the size of the energy sources.

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