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Research Article

HTLS Conductors: A Way to Optimize RES Generation and to Improve the Competitiveness of the Electrical Market—A Case Study in Sicily

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Stringent environmental constraints make more difficult to identify new energy corridors and build new power lines. The increase in the generation of electricity from renewable energy sources (RESs) makes the operation of electrical systems increasingly difficult in some areas. The transmission system operators (TSOs), in Italy Terna, are forced to exploit the existing overhead transmission lines, increasing the possibility of dispatching energy, in particular RES, optimizing the transmission capacity. Therefore, after a brief presentation of the Sicilian electricity system and a brief description of high-temperature low-sag (HTLS) conductors, a case study is presented. It is shown how it is possible to optimize the dispatching from renewable sources and, finally, it is demonstrated how the use of HTLS conductor can contribute, together with other actions taken by the TSO, to the decrease of the zonal price of electricity, to the creation of a market with fewer constraints and to new operating conditions that increase the resilience of the electricity system in case of disturbances.

1. Introduction

The 2007–2013 Energy Saving Interregional Operative Program (POI Energia), with a financial allocation of 1,071 billion euro, financed in Italy 1,887 projects of public administrations and companies of the Convergence Regions (Calabria, Campania, Puglia, and Sicily) (Figure 1). The investments made with the resources of the program have concerned energy efficiency and the production of energy from renewable sources, investment support, upgrading of the network, carrying out studies, and assessing the potential for energy development [1].

Within the overall development policy framework outlined above, the integration between growth and environmental protection is also confirmed by the founding principles of the new European energy policy which aims at the following:

(i) To achieve a true internal energy market
(ii) To accelerate the transition to a low carbon economy, by acting on the development of renewable sources, on the diversification of the mix of sources, and on research in the field of energy technologies able to reduce emissions from energy production
(iii) To adopt a multisector impact energy efficiency plan, with the proposal of a new international agreement for the achievement of common quantitative targets by 2020

The energy-climate strategy at the European level is based on a package of measures aimed, on the one hand, at combating climate change through the reduction of greenhouse gas emissions and, on the other, at reducing the dependence on energy imports and the increase of prices; in this context, the production of energy from renewable sources plays a fundamental role in achieving these objectives. The European Union has recently launched a series of measures that clearly outline the path to be followed from now to 2020 to drastically reduce the effects of energy consumption on the climate; energy and environmental

Figure 1: POI Energia 2007–2013—convergence regions in Italy.

policy at the community level has been strengthened by the decision of the European Council of 9 March 2007, which pursues the integration of energy and environmental policies, setting different targets for 2020, among which they appear relevant, for the purposes of this program:

(i) A 20% penetration of renewable energy sources on primary energy consumption (including 10% of biofuels)

(ii) A 20% reduction in primary energy consumption compared with the current trend

(iii) A 20% reduction in greenhouse gas emissions compared with 1990

So far, the interventions on the electricity grid, which by their nature require long implementation times, have mostly been planned by the operators as a consequence of the evolution of electricity demand and supply and have often followed the same administrative procedures for plant authorization. Instead, conditions must be created for the intrinsic development of the electricity infrastructure, which ensures the conditions for a rational use of the territory and for a reliable operation of the electricity grid. With this in mind, measure 2.4 of the POI Energia aims to introduce an incentive effect towards network operators to allow for the anticipation of direct investments in the evolution of the transmission network, not depending on the individual connection requests, but on the basis of a territorial planning by the regions. The investments for this project, perfectly in line with the purposes of this Public Notice, are not envisaged in Terna's 2014–2018 business plan and therefore would not be realized in the times and in the manner indicated in the absence of the public financial intervention. The allocation for the Sicily region for interventions on power lines amounts to a total of about €23,000,000.

The growing installation of generation from renewable energy sources (RES) and the strict environmental restrictions for the construction of new power lines cause difficulties in the operation of the electricity system. As described in [2–6], the Italian Transmission System Operator (TSO), Terna S.p.A., is optimizing the use of existing transmission lines. Starting from the studies carried out in [7], this document demonstrates how the use of high-temperature low-sag (HTLS) conductors is a possibility to allow the optimization of the use of current energy corridors and also a greater integration of these sources (RES) on the electrical system. After a brief description of some of the technologies of high-temperature low-sag conductors existing in the market today, the authors will evaluate the new range at the thermal limit through the use of the mathematical model proposed by Schurig and Frick. Afterwards, thanks to POI Energia investments, a real case study of reconductoring is analysed checking the benefits in terms of transport capacity, increasing the N-1 security criterion, electricity market benefits, etc. Since reconductoring has affected many 150 kV lines on which wind farms are connected, an analysis of the zonal price of electricity in Sicily in last years will be carried out to demonstrate how this structural intervention, together with others [8], has allowed better integration of RES and therefore a decrease in zonal prices and in HHI index (Herfindahl–Hirschman index).

2. The Power Grid in Sicily

The Sicilian high-voltage electrical system has three voltage levels: 400 kV, 220 kV, and 150 kV. It is connected to the European mainland by a double circuit of 400 kV submarine AC cables. The 400 kV (overhead) electric system consists of a few lines, the 220 kV lines form a ring along the Sicilian coast, and the 150 kV subtransmission system is discreetly meshed. The existing production units in Sicily are large power units (CCGT) and renewable energy sources (RES), such as hydroelectric, PV, and wind farms [6]. In recent years, thanks to the incentive policies developed by the Italian government, numerous wind and photovoltaic plants have been built; today, the installed power in wind farms in Sicily is more than 2 GW, whereas the photovoltaic power is more than 1.5 GW. The average electricity demand, in Sicily, is estimated at 2.1 GW. A model of the Sicilian electrical system was created by authors in a previous paper [7] in order to carry out studies and simulations. The main objective of these simulations was to determine the values of the power flows of each power line. The model of the Sicilian high-voltage network consists of 336 nodes, 346 lines, 90 transformers, 66 synchronous machines, and numerous RES production units. The simulations carried out in [7] have concerned standard operating configurations, relating to winter and summer conditions. Both of these simulated conditions showed the violations of transport capacity limits in some 150 kV overhead lines. The electric system at 220 kV and 400 kV instead has never shown problems of overload (good margins of loadability) and therefore the study will focus on the 150 kV power grid.

3. HTLS Conductors

Usually, the electric transmission lines use bimetallic conductors (ACSR-aluminum conductor steel reinforced). This type of conductor consists of a steel core characterized by a high mechanical strength and external layers of different aluminum wires wound spirally on the core. Today, the market offers different reconductoring solutions with heat-resistant conductors and low linear thermal elongation (called high-temperature low-sag conductor). These features offer, besides the possibility of being able to operate the line up to temperatures even over 180°C, even to be able to use the same existing energy corridors without substantial changes to the structure of the power line. The main HTLS conductors are as follows: TACSR, GTASCR, ZTACIR, and ACSS [9]. These conductors can operate at temperatures between 150°C and 250°C without changing the mechanical and chemical properties. The TACSR conductor (conductor made of heat-resistant aluminum alloy in reinforced steel) has steel wires in the core and TAL wires (aluminum-zirconium alloy which has stable mechanical properties up to 150°C) around it (Figure 2).

GTACSR (gap-type thermal aluminum conductor steel reinforced) conductor presents a small gap between steel core and aluminum outer layers in order to apply strain only on the steel. The gap is filled with heat-resistant grease (filler) to decrease friction between core and outer layers and to prevent water penetration (Figure 3).

ZTACIR (super thermal aluminum conductor invar reinforced) conductor consists of steel-invar galvanized alloy core (ACI core) and ZTAL wires in the outer layers. It does not present annealing phenomena up to 210°C (Figure 4).

ACSS (aluminum conductor steel supported) conductor presents steel wires on the core and aluminum wires in the outer layers subjected to an annealing process. There are two different types: "atandard round strand ACSS" (aluminum rope with circular cross-sectional wires) or "trapezoidal aluminum wire ACSS" (aluminum rope with trapezoidal cross section's wires) as shown in Figure 5.

The conductor most used in electric lines in Italy at 150 kV is the ACSR (aluminum conductor steel reinforced) with a diameter of 22.8 mm. For the purposes of this paper, among the high-temperature and low-sag (HTLS) conductors, the following types of conductors have been considered with the same (or similar) diameter:

(i) G(Z)TACSR (gap-type thermal resistance aluminum alloy conductor), diameter 22.6 mm

(ii) ZTACIR (invar reinforced thermal-resistant aluminum alloy conductor), diameter 22.75 mm

(iii) ACSS (aluminum conductor steel supported), diameter 20.9 mm

The HTLS conductors used, described in [9, 10], are both electrically and geometrically very similar to the conventional ACSR conductor. The main differences are the resistance to high temperatures of the aluminum alloy which constitutes the outer layer and the low value of linear thermal elongation. The advantage deriving from the use of HTLS conductors is that therefore they can withstand a higher temperature (up to 150°C or 210°C) and present lower sag (Figure 6), guaranteeing at the time a certainly higher transport capacity [11–19].

Table 1 compares the electrical and mechanical characteristics of the conductors under study. For the three HTLS conductors, the coefficient of linear expansion is referred to the core.

The authors highlight that other types of HTLS conductors have been developed in recent years. Particularly, conductors with composite core have experienced a high expansion in certain countries and are commercially available. The authors are studying these last types of conductors for future investigation, but they will not be included in the comparison of this paper.

4. Ampacity Calculation

The study, as mentioned, concerned the electrical lines of the Sicilian territory at 150 kV which were overloaded in some operating conditions according to [7] and therefore do not allow a correct dispatching of renewable sources (in particular wind farms).

More precisely, in [7] the following were carried out:

(i) Simulations of the electrical system through the help of Neplan® software and identification of network elements (in particular power lines) in overload that limit the possibility of freely dispatching renewable sources

(ii) Calculation of the maximum conductor temperature

(iii) Comparison between the maximum temperature of different HTLS conductors and the relative sag

The simulation results in standard winter and summer conditions showed that the 400 kV and 220 kV systems do not have overload problems; the only power lines that present these problems were some of those at 150 kV. These lines create problems of local congestion and therefore difficulties in dispatching the RES. In the following, a hypothesis of reconductoring of overloaded lines will be carried out by replacing the traditional ACSR conductor with the HTLS conductors previously described, showing a possibility of operating the electrical system with greater flexibility.

For the calculation of the maximum transport capacity at the thermal limit of the lines, the mathematical model Schurig and Frick was used [20]:

$$P_j = P_r + P_c - P_s, \tag{1}$$

where P_j = Joule losses; P_r = radiative losses; P_c = power dissipated by convection; and P_s = power absorbed by solar radiation.

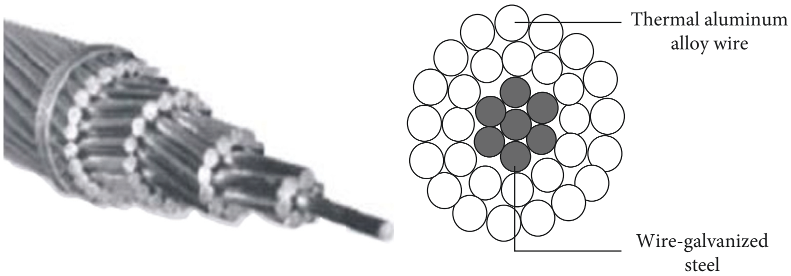


Figure 2: TACSR conductor.

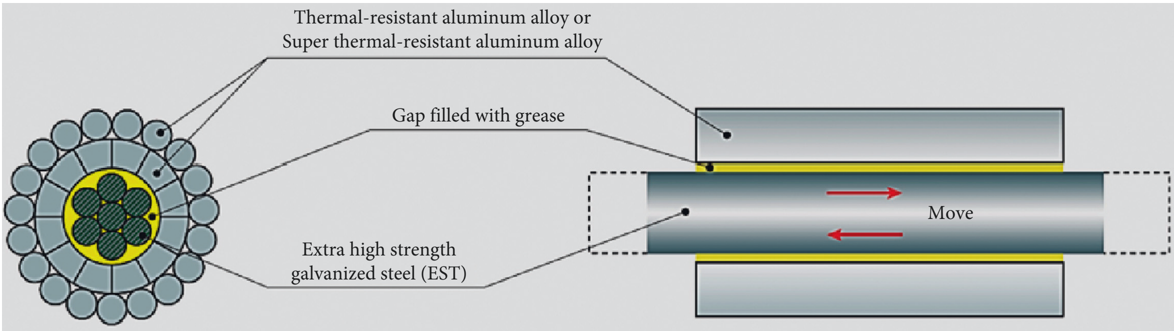


Figure 3: Gap-type conductor.

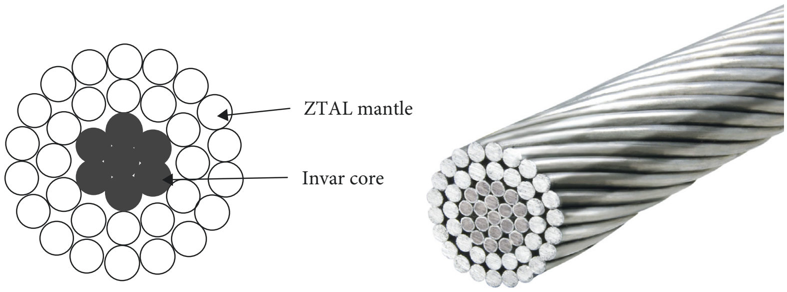


Figure 4: ZTACIR conductor.

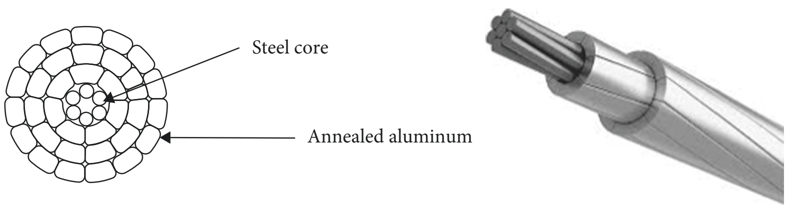


Figure 5: ACSS/TW conductor.

Current is estimated using the following equation [21]:

$$I = 5,6 \cdot \frac{\sqrt{(P_r + P_c - P_s) \cdot 10^4 \cdot D}}{R_T}, \quad (2)$$

where D = diameter of conductor (cm) and R_T = resistance of the conductor (Ohm/km).

The authors remark that the resistance varies a lot with the temperature (particularly important for temperatures above 75°C), and skin and magnetic effects may be considerable at high current densities.

The electrical connections that presented overloads are located in different areas of Sicily. In this paper, authors consider a case study located in the east part of the island; in order

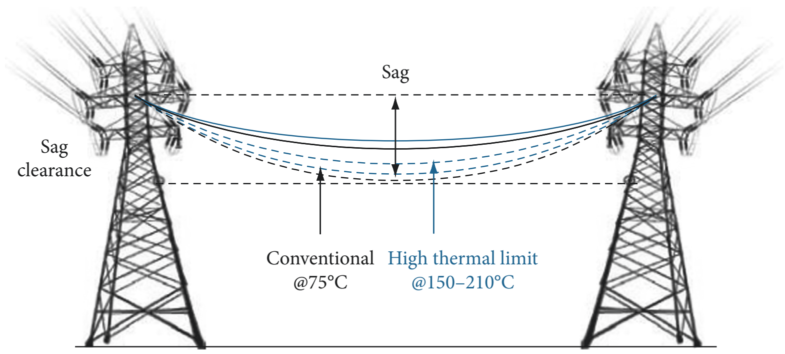


Figure 6: Comparison of sag for ACSR and HTLS temperature limit.

Table 1: Electrical and mechanical characteristics of HTLS conductor.

	Conductor			
	ACSR	G(Z)TACSR	ZTACIR	ACSS
Area (mm^2)	307.7	308.4	306.94	307.7
Rated Tensile strength (kgf)	9944	10962	10066	9901
Rdc at 20°C (ohm/km)	0.109	0.111	0.11068	0.1077
Weight (kg/km)	1068	1098	1083	1068
Coeff. of linear expansion (10^{-6}/°C)	18.9	11.5	4.7	11.5

Table 2: East Sicily ambient conditions.

	Winter	Summer
Ambient temperature (°C)	20	33
Wind speed (km/h)	2	2
Coefficient of solar radiation (W/m^2)	1029.49	1029.49
Coefficient ε emissivity of the conductor	0.7	0.7
Sky conditions	Clean	Clean
Irradiation	Yes	Yes

Table 3: East Sicily HTLS conductors ampacity.

Zone: East Sicily		Maximum allowable conductor temperature (°C)	Maximum allowable current (A)	
Type of Conductor	Diameter (mm)		Winter	Summer
ACSR	22.8	55	390	250
ZTACIR	22.75	180	630	580
ACSS	20.9	250	910	820
G(Z)TACSR	22.6	210	1080	1040

to study the heat exchange between the environment and the conductor more precisely, the meteorological conditions have been identified considering 10-year historical series extracted from meteorological stations close to the considered lines.

The following Table 2 shows the ambient conditions taken into consideration for the line under investigation. The data that were used in Equation (2) are, in a precautionary way, the worst of the series, that is, those that return the lowest current values.

The maximum current value that can cross the electrical conductors has been evaluated both in winter and in summer. The calculation of the maximum transport capacity was carried out for the traditional ACSR conductor and subsequently for the HTLS conductors with which the reconductoring of the lines was hypothesized. The Table 3 shows the maximum permissible current values for ACSR and HTLS conductors according to the area of the Sicilian territory where the overloaded electric line is located.

These values have been compared with those of power lines with overload problems, and the results of the simulation (after reconductoring) show a considerable improvement in the dispatching of RES in the 150 kV electricity grid.

The authors remark that the overhead lines are often limited by sag, and, therefore, the sag-temperature performance of each conductor has to be considered to determine their maximum temperature. In the following case study, the TSO consider lines with sufficient "buffer" and so not limited by sag.

5. Case Study

As said, the allocation for the Sicily region for interventions (POI Energia) on power lines amounts to a total of about €23,000,000.00, and National High Voltage Transmission Network (in Sicily) has been subject of numerous interventions aimed at optimizing the transport capacity on some important 150 kV lines (Figure 7).

The Sicilian electrical system, as well as 400 kV and 220 kV interconnections, is equipped with a 150 kV network which also performs a transport function rather than subtransmission.

In particular, with high demand and the absence of distributed generation (PV on the MV and LV network) or in conditions of high wind power generation in the HV lines, the 150 kV network must be able to carry the power flows to the substation in the first case and to transmit the wind generation (which almost insists on the 150 kV network) in the second case. In addition, the 150 kV network must have characteristics such as to exceed the security operational criterion N-1 in the event of tripping of a section of the 220 kV ring in double circuit.

In addition to these operating conditions, a new N-1 security criterion condition was added in June 2016, linked to the high import power flows (maximum 1200 MW) that

Figure 7: 150 kV lines object of reconductoring.

the Sicilian electrical system normally receives from the continental network in case of tripping of one of the 400 kV mainland interconnections.

In all the scenarios described above, the 150 kV network of the Sicilian electrical system has to be able to continue operating without overload.

In this context, Terna replaced, for some lines which go under overload and here presented as a case study, ACSR conductor with a diameter of 22.8 mm (aluminum conductor steel reinforced) with high-temperature low-sag conductors ZTACIR with a diameter of 22.75 mm.

The following figure (Figure 8) reports a schematization of the section conductor, the geometrical data, and the main mechanical characteristics.

The outer layer is made of an aluminum-zirconium alloy with a thermal limit higher than that of traditional aluminum (ZTAL: super thermal-resistant aluminum alloy) and this means the possibility of optimizing the transport of current. A core consisting of an aluminum-coated Fe-Ni alloy (ACI: alluminum clad invar) characterized by a reduced coefficient of thermal expansion that allows to keep sags similar to those of traditional conductors, even if they operate at higher temperatures. The ZTACIR (diameter mm 22.75) conductor is designed for the replacement of the ACSR analogue diameter mm 22.8 but has a similar current range to that of diameter mm 31.5 ACSR conductor used for 220 kV lines.

Other positive consequences in the reconductoring of some 150 kV links of the Sicilian electric system are as follows:

(i) Reduction of the limitations of wind generation due to local overload on 150 kV

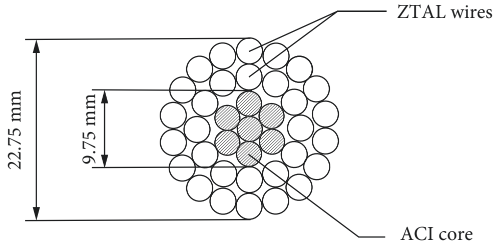
(ii) Possibility to connect new production plants on the reconductored 150 kV lines

(iii) More flexibility for the programmable internal production resources

(iv) Reduction/elimination of some operating restrictions with more flexibility in operation and increase in quality in supplying power

In order to provide an example for the case under investigation, in Figure 9, it is compared the trend of the current recorded for the line under study in a period of a month characterized by the presence of strong wind and therefore a high value of energy production from wind farms. The current flow in the windy period with ACSR is, on average (147 A), lower since the TSO, for operational security, was forced to redispatch production from RES, sometimes not accepting it on the system. The presence of the ZTACIR conductor, on the other hand, allows a greater transits (average value of 242 A), thanks to the possibility of accepting all the wind generation available at the moment with clear environmental and economic benefits for the community (e.g., decrease in the zonal price of electricity and CO_2 emissions). The comparison in terms of average values highlights that, thanks to HTLS conductors, the line can transport (on average) an higher value of current and then of energy (the increase is estimated more than 50%).

In order to verify the positive effects of the substitution activities of the conductors on the Sicilian electrical system, the present paper also considers an analysis of the statistics of GME (Italian energy market operator) on the zonal prices of the electricity market in Sicily from 2014 to 2016 (the 2017 report is not yet available) [22] and on the HHI index (Herfindahl–Hirschman index), also related to the region under study. This is an aggregate market index that measures the degree of concentration and dispersion of the volumes offered and/or sold by market participants. The HHI is calculated, for each hour and for each macro zone, as the



Technical data		
Conductor code	-	249-AT3/58-ACI20SA
Standard	-	UX LC3914
Stranding	-	7x3,25+30x3,25
Diameter of Alu.Clad Fe-Ni wire	mm	3,25 +/- 1,5%
Diameter of ACI core	mm	9,75 +/- 1,5 %
Diameter of ZTAL aluminium wire (AT3)	mm	3,25 +/- 1,0 %
Diameter of complete conductor	mm	22,75 +/- 1,0 %
Outer layer clockwise	-	RIGHT
ACI core cross-sectional area	mm^2	58,07
Total ZTAL aluminium cross-sectional area	mm^2	248,87
Total cross-sectional area of compl. conductor	mm^2	306,94
Unit weight of ACI	kg/km	355
Unit weight of ZTAL aluminium	kg/km	688
Unit weight of complete conductor	kg/km	1083 +/-2 %
Calculated breaking force	daN	9782
Nominal transition temperature	°C	119±5
Modulus of elasticity for ACI	kN/mm^2	138,50
Modulus of elasticity for conductor	kN/mm^2	72
Coefficient of linear expansion for ACI	1/°Cx10-6	4,7
Coefficient of linear expansion for conductor	1/°Cx10-6	16,4
DC resistance at 20°C (max.)	ohm/km	0,11068
Allowable continuous operating temperature	°C	180
Allowable operating temperature temporarily	°C	210

MATERIALS:
- Thermal resistant aluminium alloy: AT3 (ZTAL: Super Thermal Resistant Aluminum Alloy) according to EN 62004
- High temperature Fe-Ni alloy: ACI (Aluminum Clad Invar) EN61232 20SA + customer specification

Figure 8: Geometrical data and the main mechanical characteristics of ZTACIR.

sum of the shares of the volumes sold (or offered) on the market by the market operators is multiplied by 100 and squared. The value of the HHI can vary from 0 (perfect competition) to 10,000 points (monopoly). The HHI is calculated on an hourly basis and then aggregated in monthly simple averages. Figure 10 shows the trend of the zonal price of electricity in Sicily, whereas Figure 11 shows the trend of the HHI index. It is possible to see how after

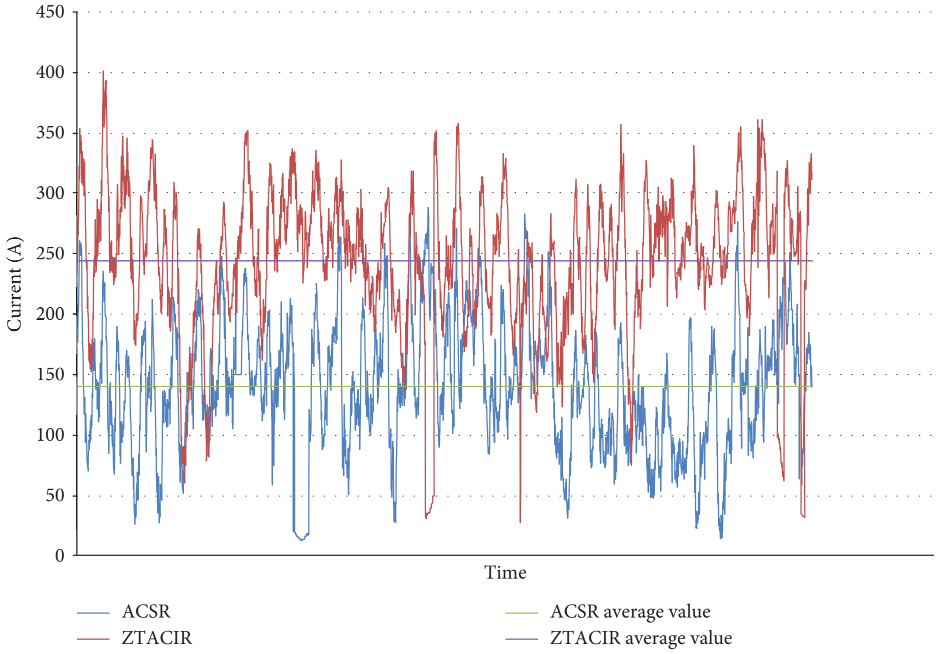


Figure 9: Comparison between ACSR and ZTACIR current flow and relative average values.

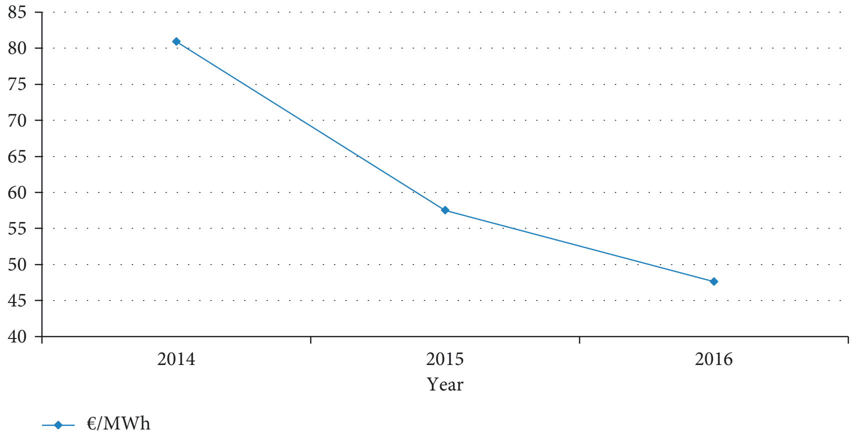


Figure 10: Sicilian electricity (zonal) price (period 2014–2016).

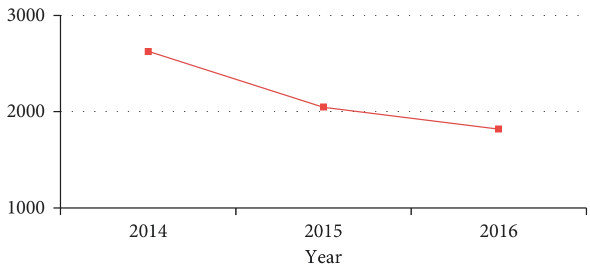


Figure 11: Sicilian HHI value (period 2014–2016).

2014, the year in which reconductoring operations were carried out on the 150 kV network, the zonal price of Sicily decreased significantly from €82/MWh at a price of around €47/MWh recorded in 2016. The Herfindahl–Hirschman index (HHI), which characterizes the competitiveness of a market, also recorded a significant decrease, thus demonstrating greater flexibility of the system. It should be noted that the reconductoring cited is one of the actions implemented by TERNA in Sicily, including the doubling of the connection to the mainland, the connection with the island of Malta [7] and the use of DTR (dynamic thermal rating systems) [23].

The authors highlight that the PUN has decreased throughout Italy, but in percentage terms, Sicily and other regions of southern Italy have had a more marked decrease. This is due to a greater penetration of the RESs on the electricity system that has allowed the energy price to be mitigated.

6. Conclusions

In order to obtain a flexible operation of the electricity system, with particular reference to the possibility of dispatching the power generated by renewable sources without constraints and to mitigate the effects of the unpredictability of the determination of the price in the Sicilian market, it is advisable to use HTLS conductors. Terna, thanks to POI Energia 2007–2013, invested ingent capitals on four regions of the south (including Sicily) for the reinforcement of electricity grids with the aim of making smart grid (HTLS and DTR-dynamic thermal systems) and encouraging the integration of RES for decreasing the zonal price of electricity and limiting the emissions of CO_2. This paper, after a brief presentation of the Sicilian electricity system and a brief description of high-temperature low-sag conductors (HTLS), presents a case study of reconductoring. The analysis demonstrates how the current flow in the windy period with ACSR is, on average (147 A), lower since the TSO, for operational security, was forced to redispatch production from RES, sometimes not accepting it on the system. The presence of the ZTACIR conductor, on the other hand, allows a greater transits (average value of 242 A), thanks to the possibility of accepting all the wind generation available at the moment with clear environmental and economic benefits for the community (e.g., decrease in the zonal price of electricity and CO_2 emissions). The comparison, in terms of average values, highlights that HTLS conductors can transport a higher value of current and then of energy (the increase is estimated more than 50%).

In order to verify also the positive effects of the substitution activities of the conductors on the Sicilian electrical system (the reconductoring was completed at the end of 2014), the present paper also considers an analysis of the statistics of GME (Italian energy market operator) on the zonal prices of the electricity market in Sicily from 2014 to 2016 (the 2017 report is not yet available) and on the HHI index (Herfindahl–Hirschman index), also related to the region under study. The authors highlight that the PUN has decreased throughout Italy, but in percentage terms Sicily and other regions of southern Italy have had a more marked decrease. This is due to a greater penetration of the RESs on the electricity system that has allowed the energy price to be mitigated. It is shown how it is possible to optimize the dispatching from renewable sources and, finally, it is demonstrated how, the use of HTLS conductor, can contribute, together with other actions taken by the TSO, to the decrease of the zonal price of electricity, to the creation of a market with fewer constraints.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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