

## Article

# Dynamic Thermal Rating and Development of Renewable Energy Zones in Sicily

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**Abstract:** Sicily, an Italian region in the south of Italy, is a candidate for becoming an energy “hub” in the Mediterranean in the coming years. Its geographical location, between the African continent and Europe, makes it a key hub for the distribution of electricity flows. The region has great potential for the development of renewable energy sources. Inspired by the Australian “Renewable Energy Zones” model, the identification of existing Renewable Energy Zones (REZs) and the proper design of future REZs on the territory will simplify and improve the operation of the network. A very effective tool in managing REZs is Dynamic Thermal Rating (DTR) technology. This technology allows for dynamic rating of the high voltage transmission system, ensuring that the maximum allowable current is transported while preventing the annealing of the electrical conductor and complying with all necessary safety parameters. The objective of the work carried out in collaboration with Terna S.p.A. (Italian Transmission System Operator) was to evaluate the application of this technology on the Sicilian electricity network in order to reduce potential network congestion and system inefficiencies. The results obtained demonstrate the significant potential of Dynamic Thermal Rating in Sicily. These devices would allow a significant increase in the current flow of electrical lines without violating safety limits.

**Keywords:** dynamic thermal rating; Sicily; electrical transmission system; wind power curtailment; critical span; grid congestion



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## 1. Introduction

As the analyses in this study show, the Sicilian electricity network is characterized by an uneven distribution of electrical loads and energy production. This imbalance results in a significant flow of electricity from the western to the eastern part of the region. This is the main challenge that is addressed in this paper. The current transmission network often struggles to cope with these power flows, resulting in frequent congestion.

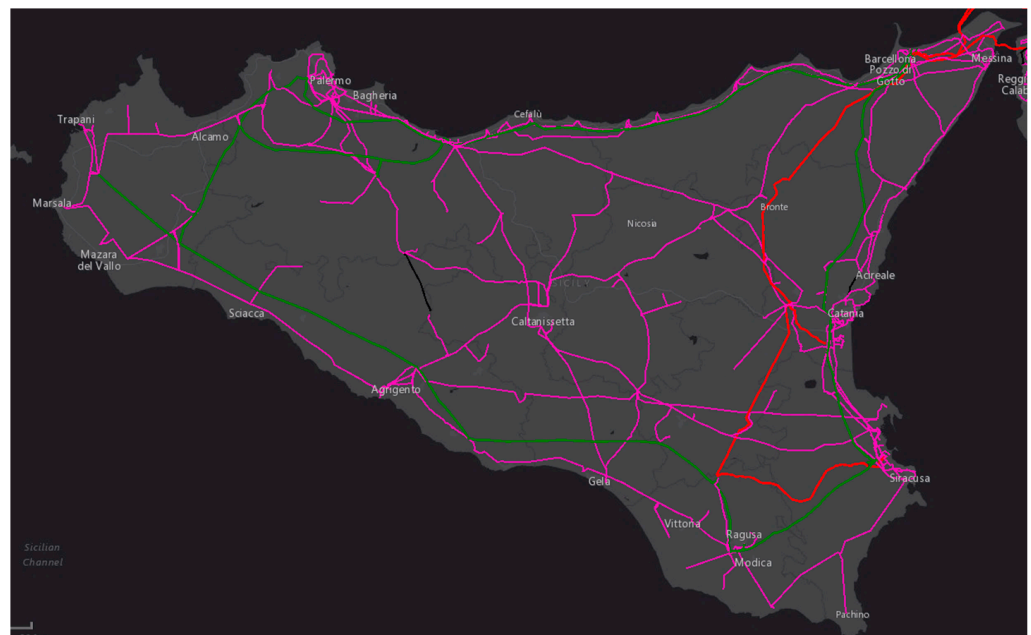
In this study, areas with a high concentration of renewable energy installations have been identified and designated as “Renewable Energy Zones (REZs)”. The main contribution of this paper is the first identification of REZs using a simple and direct method.

The application of Dynamic Thermal Rating (DTR) technology was then evaluated for the transmission lines within each REZ in order to solve the main challenge for the Sicilian electrical network, which is grid congestion. The use of Dynamic Thermal Rating in the analysis of Renewable Energy Zones is also an innovative technical contribution.

The results are significant; the proper implementation of DTR technology would reduce grid congestion by increasing the capacity (ampacity) of critical transmission lines. Furthermore, the required interventions were found to be economically viable.

In summary, there are several general aspects of this paper that are in line with the objectives of the special issue entitled “Design, Optimization and Control Strategy of Smart Grids”. The following topics are covered in detail: power quality and grid reliability with high penetration of renewable energy sources, grid flexibility optimization, and energy curtailment management.

In order to facilitate the understanding of the work carried out, it is necessary to present the current state of the Sicilian electricity grid, integrated into a broader context such as the Italian and international ones. The Sicilian transmission system is currently characterized by three voltage levels: 380 kV (Figure 1, red lines), 220 kV (green lines), and 150 kV (pink lines). The first two voltage levels are designated for transmission, while the 150 kV grid is used for the sub-transmission of electrical energy. The 150 kV voltage grid is the largest in the area and constitutes an energy connection between eastern and western Sicily [1].



**Figure 1.** Electrical transmission system of Sicily, Italy (Sisnet (version 4.01), software owned by Terna).

The traditional paradigm, in which power flows were predominantly stable and unidirectional—originating from conventional power plants to consumers—has been largely disrupted. The electricity transmission network now operates under the need to manage bidirectional power flows, characterized by significant temporal variability [1].

The exponential increase in energy production from photovoltaic and wind power plants, together with the natural aging of some transmission lines, has necessitated a rethink of the management strategies for the Sicilian electricity system. Six of the nine provinces of the Sicily region are prone to high congestion or overload in the presence of high renewable energy generation [1]. In this context, some areas have been identified and classified as critical, two others as medium critical (Catania and Palermo), and only one province (Messina) as low critical [1].

It is useful to analyze the distribution of energy production from renewable and traditional sources throughout the territory, as well as the electricity loads that characterize the region. Electricity is mainly produced by traditional thermoelectric power plants concentrated in the south-eastern area and by numerous RES plants, mainly wind farms, located in the western area [1].

It should be noted that the distribution of installed wind power over the territory is not homogeneous, as 50% is located only in the provinces of Trapani and Palermo, in the western part of Sicily. This heterogeneity is mainly due to the different wind conditions on the western and eastern slopes of the region [2].

If we also consider the production of electricity from traditional sources, about 60% of the total energy is produced in eastern Sicily, and this is due to the greater presence of industrial poles in the eastern provinces compared to the western ones [2].

Energy demand also differs significantly between the western and eastern regions of the island. In the western region, the residential and service are the main energy consumers, while in the east, the industrial sector is the main energy consumer. This difference is mainly due to the higher level of industrialization in the Catania area and the larger population in Palermo [1].

So, the most energy-intensive provinces are Catania, Syracuse, and Palermo [3].

These considerations show that Sicily's electricity load is unevenly distributed, reflecting the imbalance in energy production; this is, therefore, the main peculiarity of the current Sicilian transmission network.

In the light of the above, there are several challenges that will have to be met in the coming years [4,5]:

- Increasing congestion of the network due to uneven distribution of RES installations in relation to consumption;
- The progressive reduction of voltage regulation sources, which leads to significant variations in the voltage waveform after a disturbance in the network, thus reducing the degree of robustness of the network;
- The progressive reduction in regulation energy is driven by the replacement of traditional rotating mass generators with inverter-based systems. The increase in 'inverter-based' generation results in a reduced inertial response of the electrical system, thereby reducing frequency stability during abrupt load changes. In the past, this response was provided by synchronous generators and their mechanically coupled turbines using stored kinetic energy; moreover, the electronics of inverters provide a short-circuit current much lower than that of large thermoelectric power plants, which affects the correct intervention of protections and automatisms, both in terms of timeliness and selectivity;
- The management of extreme weather events, which are responsible for interruptions and reductions in the electricity transmission service.

In order to solve these critical problems in the grid, numerous interventions have already been launched and approved in the Development Plan [1,6]. For example, the Tyrrhenian Link will improve electricity connections between Sicily, Sardinia, and the rest of the peninsula. The TUN-ITA link will create a very important electricity connection between Africa and Europe. These interventions will not only solve the current critical problems of the electricity system but will also be essential to prepare the region for the development scenarios expected in the coming years. This development path is in line with the Fit-For-55 (FF55) scenario, a single policy scenario to 2030, which aims to achieve the European targets of a 55% reduction in emissions thanks to a push towards electrification and a significant increase in renewable energy sources [7].

The significant development of the energy infrastructure and electricity transmission infrastructure will allow the integration of the planned new RES plants. From 2018 to 2022, the requests for the connection of RES plants to the grid in Sicily have increased exponentially, and the expected future scenarios indicate a further increase in requests for the connection of RES plants [4].

In the case of Sicily, a study carried out by the University of Palermo, in collaboration with Terna S.p.A. (Rome, Italy), indicates that by 2030, the power lines and transformers currently installed will be overloaded by more than 70% of their capacity on average, given the rapid increase in new connection requests. The upgrading of the network to 400 kV must also be accompanied by targeted local interventions that would have a major impact on relieving congestion [5]. The connection between Sicily and the other regions of Italy plays a fundamental role during the hours when energy production is at its highest and storage systems are saturated. For this reason, interventions such as that of the Tyrrhenian Link will be extremely important.

## 2. State of the Art: Renewable Energy Zones (REZs)

In order for the grid to be capable of supporting the planned development scenarios [4], it is necessary to create and optimize so-called “Renewable Energy Zones” in the area. A Renewable Energy Zone is a geographical area connected to the local electricity grid that allows for the profitable and cost-effective production of renewable energy [8].

The United States Agency for International Development (USAID) proposes a comprehensive methodology for developing a REZ in six operational phases: process design and vision statement, renewable energy resource assessment, candidate zones selection, transmission options development, final transmission plan design, transmission system upgrade [8].

One of the first countries to make explicit use of the REZ approach is Australia. Australia has some of the world’s most abundant renewable energy resources, but the current grid capacity to connect these high-potential areas is limited. As highlighted in the Australian Energy Market Operator’s (AEMO) Integrated System Plan, the establishment of Renewable Energy Zones (REZs) will be essential to harness these robust resources and enable new generation and storage capacity in the National Electricity Market (NEM) at the lowest cost to consumers [9].

To address this, the Australian Renewable Energy Agency (ARENA) commissioned Baringa Partners, in collaboration with DIgSILENT Pacific, to undertake a study of the technical, commercial, and regulatory challenges of developing REZs in the NEM. The study also aimed to identify practical commercial and regulatory solutions to support the efficient and sustainable implementation of REZs [9]. DIgSILENT is an independent consulting company providing highly specialized services in the field of electrical power systems. DIgSILENT’s software called “PowerFactory (version 3.0)” is used for the analysis and simulation of electrical systems. It allows you to model transmission and distribution networks and perform power flow calculations, fault analysis, dynamic simulations, and harmonic studies.

## 3. Dynamic Thermal Rating

The use of tools such as DTR (Dynamic Thermal Rating) devices, which are able to calculate the maximum current that the electrical conductor can withstand while complying with the current and minimum ground clearance limits imposed by regulations, is very important in the management of the electrical transmission network. To perform this function, these devices must be able to detect all the electrical and mechanical variables that affect the heat exchange between the conductor and the environment in which it is located. This information is processed by models based on meteorological measurements, on the detection of the mechanical sag/voltage of the conductor, or on electrical quantities [10,11].

These devices are based on the following energy balance equation:

$$q_c(T_c, T_a, V_m, \varphi) + q_r(T_c, T_a) = q_s + I^2 \times R(T_c)[W] \quad (1)$$

where

- $q_c$  (function of  $T_c, T_a, V_m, \varphi$ ) represent the heat exchange by convection from the conductor to the surrounding environment [W];
- $q_r$  (function of  $T_c, T_a$ ) represent the heat exchange by radiation from the conductor to the surrounding environment [W];
- $q_s$  represent the heat gain due to solar radiation [W];
- $I^2 \times R(T_c)$  the heat generated by the Joule effect through the conductor crossed by the current  $I$  [A];
- $R(T_c)$  [ $\Omega$ ] is the resistance of the conductor at temperature  $T_c$  [K];
- $T_c$  is the average temperature of the conductor [K].
- $T_a$  is the average temperature of the environment [K];
- $V_m$  represent the speed of the wind striking the conductor [m/s];
- $\varphi$  represent the direction of the wind striking the conductor [rad];

There are several studies in the literature that show how DTR systems can allow the ampacity of the power lines to be increased compared to the conventional static limits imposed before the advent of this technology. The Dynamic Thermal Rating suggests ampacities that are 15–30% higher than the conventional Static Thermal Rating, on average, for 80–90% of the operating period [12].

To take advantage of this significant increase in range, DTR devices must be positioned correctly along the transmission line. The power grid normally crosses large areas that are subject to different weather conditions, which affect the heat exchange of the conductor in different ways. For example, a conductor exposed to strong gusts of wind tends to cool down more than a conductor exposed to low winds. As a result, the ampacity and elongation of the conductor will not be uniform throughout the line. The safest and most conservative practice is to identify the so-called “hot spots” of the line, i.e., the hottest points, where the clearance from the ground is lower, and the phenomena of annealing of the line are more likely. The span corresponding to the above characteristics is called the “critical span”, and its identification ensures that all sections of the line can be traversed with a sustainable current capacity [12].

To identify the hot spots of the line, sample measurements can be made, both homogeneously distributed over the area and according to specific criteria. The article “Identification of Critical Spans for Monitoring Systems in Dynamic Thermal Rating” [13] proposes the comparison between a heuristic method of evaluating critical spans and a homogeneous sampling method on the territory.

An important aspect of Dynamic Thermal Rating is the correct prediction of the operating conditions of the line. An accurate prediction allows the operator to perform the following:

- Optimize the operation of the network;
- Manage the uncertainty of loads and the intermittency of renewable generation;
- Improve grid reliability and economic stability of power flows;
- Minimize any interruption in renewable energy production [12].

Each DTR device consists of three main components [10]:

- Detectors that monitor variable operating conditions;
- Communication devices that receive and transmit the measured data;
- Software that interprets the data and quantifies the ampacity that the line can support.

DTR systems can use both indirect and direct measurement methods. Indirect methods measure meteorological data, while direct methods can measure the sag, the ground clearance of the conductor, the line voltage, or the temperature of the conductor [14].

Some studies have focused on the effect of each of these variables on the heat exchange between the conductor and the environment. In transmission lines characterized by a low current carrying capacity, the heat exchanged by convection  $q_c$  plays a predominant role, whereas in lines where the required current carrying capacity is higher, the heat produced by the Joule effect  $I^2 \times R$  becomes more important. In general, the contribution of solar radiation  $q_s$  is not very significant. When the wind speed  $V_m$  is low (less than 8–10 m/s), the heat exchanged for radiation  $q_r$  can take on values equal to about 40% of  $q_c$ , while at high wind speeds (greater than 10 m/s),  $q_r$  has a smaller contribution [10].

## 4. Methodology

At present, there are no studies describing the presence, configuration, and types of REZs [8] in the Sicilian territory; therefore, the first objective of this study was to develop a methodology capable of identifying the REZs in the region. The specific technical contribution of this study lies precisely in the fact that, for the first time in the world, the identification of REZs is carried out according to a simple and direct procedure. The main reason for the need to identify REZs in Sicily is to reduce grid congestion, particularly the problem of Wind Power Curtailment (WPC). To achieve this, the basic characteristics of a REZ were defined. The different REZs were then identified using software developed by Terna that allows for detailed power flow analysis. Once the REZs in Sicily were identified, the application of the Dynamic Thermal Rating in each of them was simulated; an algorithm proposed by the IEEE was used [14]. Subsequently, based on the data collected in the early stages, the most critical power lines were identified. The use of Dynamic Thermal Rating in the study of Renewable Energy Zones also represents an innovative technical contribution. Finally, economic analyses were carried out, and a verification comparison was made with the devices currently installed in Sicily.

### 4.1. Identification of Renewable Energy Zones

In this context, some typical requirements have been identified for a portion of land to qualify as a Renewable Energy Zone:

- A high concentration of renewable energy systems (RES) connected to the transmission grid within the same geographical area;
- Distribution of electricity flows generated by these RES through common transmission channels for all installations in the REZ. This condition allows the REZ to be treated as a kind of single equivalent grid node, which simplifies the management of the network outside the REZ;
- Analysis of the relationships between all the network elements that make up the REZ.

If a REZ is properly identified and managed, it should be possible to minimize the need for flow management interventions within it.

The evaluation starts with a real scenario identified in 2024, characterized by high renewable energy production using the TDV software (version 3.7.5). This is the software used by Terna to constantly monitor the electricity system. From TDV, it is possible to extrapolate the measurements of the current capacity over a given period. In the case study, it refers to the situation on 19 April at 16:00–17:00.

It is noted that under these conditions, the RES plants connected to the transmission grid in Sicily produced about 2000 MW, and the region's high-voltage energy requirements were about 1350 MW.

Another software (WinCreso, also owned by Terna) was used. This program allows the carrying out of "Load Flow" analyses taking into account different network assets, boundary conditions, and fault simulations. The WinCreso software (version 7.69.01) was used to simulate n-1 operating scenarios under the network conditions of 19 April at 16:00.

Therefore, the loss of an additional element during maintenance conditions could lead to greater overloads.

The software makes it possible to simulate the intervention of the protective system following a fault on all transmission lines.

Due to the high production of energy from renewable sources, several lines were overloaded, and the protection system intervened by disconnecting some of the lines from the grid. The disconnection of each line leads to the distribution of energy flows to other lines in the transmission system, causing further grid overloads.

The lines that overload frequently and with greater intensity were therefore identified. In Table 1, the overloaded lines are indicated with numbering to avoid showing sensitive data. Each overload was detected following the simulation of the opening of the corresponding power line. The disconnection of the line caused an increase in the required flow rate on the numbered line. As can be seen, the nominal current limit is exceeded by a large margin.

**Table 1.** Most overloaded power lines.

Overloaded Power Line	Simulation of a Contingency	Nominal Current [A]	Current Capacity after the Contingency [A]	Increase Compared to the Nominal Current
Line 1	Contingency 1	740	1469	+99%
Line 2	Contingency 2	536	725	+35%
Line 3	Contingency 1	740	896	+21%
Line 4	Contingency 2	480	750	+56%
Line 5	Contingency 2	740	1216	+54%
Line 6	Contingency 3	740	1138	+54%
Line 7	Contingency 3	740	1143	+64%
Line 8	Contingency 1	758	1217	+61%
Line 9	Contingency 4	758	1220	+47%
Line 10	Contingency 4	758	1116	+41%
Line 11	Contingency 5	758	1065	+61%
Line 12	Contingency 6	480	1219	+35%
Line 13	Contingency 7	758	650	+54%

Observing the location of each of the lines potentially subject to frequent and high overloads, one characteristic common to all the lines becomes evident: they are located in the north-western part of Sicily. The distribution of the overloaded lines is, in fact, closely linked to the uneven presence of RES plants in the territory. Network congestions, which are local phenomena, almost always occur in the vicinity of such areas characterized by numerous RES plants.

Based on these analyses, it was possible to identify the lines that are typically overloaded under  $n - 1$  network conditions. Based on the geographical distribution of the overloaded lines, four REZs were determined: A, B, C, and D. As observed, the current Sicilian REZs are located exclusively in the western part of the region, mainly due to the higher concentration of RES plants in this area. However, by consulting development scenarios for the coming years [2], potential REZs have also been identified on the eastern side of Sicily: REZs E and F (Figure 2). To identify them, the same methodology was applied; first, the expected renewable power in the coming years was implemented on WinCreso, then the most overloaded lines were identified, and finally, the expected new REZs were circumscribed.

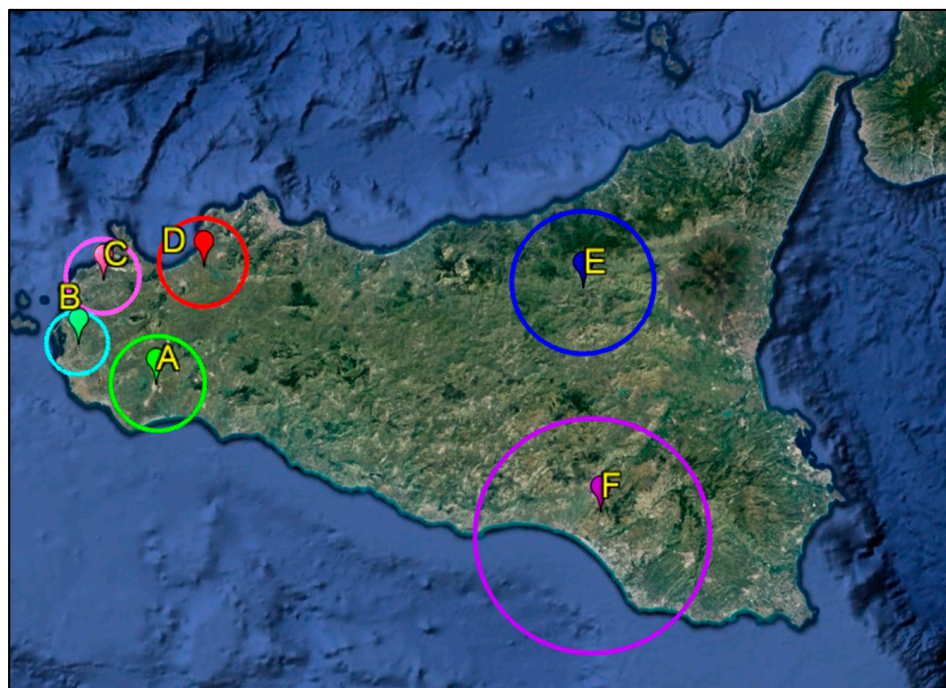


Figure 2. Renewable Energy Zones in Sicily, Italy [15].

Subsequently, the close correlation between overloads occurring within each REZ was highlighted. Almost always, the lines of a REZ suffer equally from the occurrence of a contingency on the transmission network. See Tables 2 and 3 as examples.

Table 2. Effect of contingency 2 on REZ A.

Effect of Contingency 2 on REZ A			
Overloaded Power Line	Nominal Current [A]	Current Capacity Required After the Contingency [A]	Increase Compared to the Nominal Current
Line 1-A	480	750	+56.25%
Line 2-A	536	725	+35.26%
Line 3-A	740	1216	+64.32%
Line 4-A	740	942	+27.30%
Line 5-A	740	1458	+97.03%

Table 3. Effect of contingency 2 on REZ B.

Effect of Contingency 2 on REZ B			
Overloaded Power Line	Nominal Current [A]	Current Capacity Required After the Contingency [A]	Increase Compared to the Nominal Current
Line 1-B	740	1183	+59.86%
Line 2-B	740	1189	+60.68%
Line 3-B	740	1206	+62.97%
Line 4-B	740	1216	+64.32%

This condition suggests that the effective placement of a few DTR devices in the same REZ could allow the reduction of overloads in all neighboring power lines. This is possible because if DTRs are installed on the critical spans of the most vulnerable lines, the increase in current capacity on these lines should ensure, in cascade, an increase in current capacity

on neighboring lines as well. The reason for this is that these lines certainly experience a lower overload and are in a better heat exchange condition than the critical spans of the most overloaded lines. In this step, the most overloaded lines were identified. The next step was to identify the lines that represent hot spots from the point of view of heat exchange. The lines on which the DTRs are to be installed must therefore be among the most vulnerable from both the electrical and thermal points of view.

#### 4.2. Application of Dynamic Thermal Rating to Sicilian Transmission Grid

The aim of the study was to evaluate the potential of DTR in the Sicilian territory. Both current and future scenarios are characterized by high electric power flows produced by renewable sources. The network congestion caused by these flows represents one of the main challenges for the Sicilian electricity system, and the Dynamic Thermal Rating technology can contribute to facing this challenge [1]. A key aspect in the correct application of Dynamic Thermal Rating is the positioning of the devices, and the important innovation of this study was choosing the location of DTR devices based on the specific characteristics of each REZ. Specifically, the work carried out to assess the potential of Dynamic Thermal Rating in Sicily was divided into several phases as follows:

- Climatic study of Sicilian municipalities for Dynamic Thermal Rating. The location of these devices on the territory depends on the identification of hot spots. A study of the climatic conditions typical of the Sicilian territory was carried out. This made it possible to identify the differences in terms of thermal exchange propensity in the macro-areas of the region;
- Implementation of the Dynamic Thermal Rating calculation algorithm proposed by IEEE [14] on Python software (version 3.13.1). Based on the previous climatic study, DTR simulations were carried out for the Sicilian territory using this tool;
- Identification of critical lines based on the simulations carried out. Considering both the current configuration and the 2027 forecasts for Renewable Energy Zones in the area, several hot spots were identified on the Sicilian transmission lines. The installation of DTR devices in these areas would significantly improve the management of the transmission system;
- Brief economic considerations demonstrating the economic sustainability of DTR devices;
- Comparison with current applications of Dynamic Thermal Rating in Sicily.

##### 4.2.1. Climatic Study of Sicilian Municipalities for Dynamic Thermal Rating

The aim of this part of the study was to classify Sicilian municipalities according to their potential for thermal exchange between the conductors and the surrounding environment, typical of the area in which the municipalities are located. The main variables influencing the thermal exchange between the overhead conductor and the surrounding environment are as follows [12]:

- Wind speed;
- Average outdoor temperature.

Therefore, through the online platform “Servizio Informativo Agrometeorologico Siciliano” (SIAS) [16], data were collected from about 40 SIAS meteorological stations evenly distributed over the Sicilian territory. The data collected from the SIAS meteorological stations consist of the following:

- Daily average temperatures from 2018 to 2023;
- Daily average wind speeds from 2018 to 2023;
- Altitude above sea level for each station.

These data were then summarized by calculation (using Excel) for each site:

- Average monthly temperatures and wind speeds from 2018 to 2023;
- The average of the monthly average temperatures and wind speeds from 2018 to 2023.

Since the meteorological stations are sufficiently evenly distributed over the territory, Sicily was divided into 36 micro-zones. The size of these micro-zones was based on the actual concentration of available meteorological stations. Therefore, some micro-zones have a larger area than others due to the lower availability of meteorological data to reference. Conversely, where the concentration of stations is higher, smaller micro-zones were identified.

The places where the stations are located are hereafter referred to as “source municipalities”. The monthly average outdoor temperature and the monthly average wind speed for all other municipalities are calculated based on the values from the source municipality of the same micro-zone. The following formula was used to calculate the monthly average outdoor temperature for each municipality  $T_m$  [°C]:

$$T_m = T_{sm} - (Z_m - Z_{sm}) \times \delta [^{\circ}\text{C}] \tag{2}$$

where

- $T_{sm}$  is the monthly average temperature of the source municipality [°C];
- $Z_m$  is the altitude of the municipality [m];
- $Z_{sm}$  is the altitude of the source municipality [m];
- $\delta$  is the vertical temperature gradient [°C/m].

The determination of this formula and the vertical temperature gradient were taken from the current UNI10349 standard [17]. The altitudes of the stations were taken from the SIAS website [16], while the altitudes of all Sicilian municipalities were taken from [18].

To calculate the monthly average wind speed for each municipality  $V_m$  [m/s], the following formula was used:

$$V_m = V_{sm} \times C \left[ \frac{\text{m}}{\text{s}} \right] \tag{3}$$

where

- $V_{sm}$  is the monthly average wind speed for the source municipality [m/s]
- $C$  is a dimensionless multiplicative coefficient.

The multiplicative coefficient  $C$  has been used to account for variations in wind speed within the same micro-zone. In cases where a small part of the territory is characterized by high average slopes, the wind speed is usually less homogeneous. In order to improve the calculation of  $V_{sm}$ , a multiplicative coefficient was proposed, which can take the following values:

$$\text{if } |Z_m - Z_{sm}| \leq 250 \text{ [m] then } C = 1 \tag{4}$$

$$\text{if } Z_m - Z_{sm} \geq 250 \text{ [m] then } C = 0.9 \tag{5}$$

$$\text{if } Z_{ms} - Z_m \geq 250 \text{ [m] then } C = 1.1 \tag{6}$$

These values effectively simulate the real conditions, as they have been obtained after sample checks of the actual wind speed distribution in high-slope areas in Sicily.

After obtaining the  $T_m$  and  $V_m$  values for all the municipalities in each month of the year, a classification was made for all the municipalities on the basis of their heat exchange potential. The classification was performed as follows:

The temperature range was calculated as

$$T_{m,max} - T_{m,min} = \Delta T_{max} [^{\circ}\text{C}] \tag{7}$$

where

- $T_{m,max}$  [°C] is the highest monthly average outdoor temperature recorded in Sicily for the corresponding month;
- $T_{m,min}$  [°C] is the lowest monthly average outdoor temperature recorded in Sicily for the corresponding month.

The interval  $\Delta T_{max}$  was then divided into three smaller intervals. The range of the intervals was selected to make the classification as effective as possible. Each interval is referred to as a “temperature range (Range  $T_i$ )”.

The wind speed range was calculated as

$$V_{m,max} - V_{m,min} = \Delta V_{max} \left[ \frac{m}{s} \right] \tag{8}$$

where

- $V_{m,max}$  [m/s] is the highest monthly average wind speed recorded in Sicily for the corresponding month;
- $V_{m,min}$  [m/s] is the lowest monthly average wind speed recorded in Sicily for the corresponding month.

The  $\Delta V_{max}$  interval was then divided into three smaller intervals. The range of the intervals was chosen to make the classification as effective as possible. Each interval is referred to as a “wind speed range (Range  $V_i$ )”.

All municipalities were classified into the corresponding temperature and wind speed ranges for each month of the year.

Specifically, the temperature for a given municipality is indicated as follows:

- “Low T” if it falls within Range  $T_1$ ;
- “Medium T” if it falls within Range  $T_2$ ;
- “High T” if it falls within Range  $T_3$ .

Using the same criterion, the wind speed for the given municipality is indicated as follows:

- “Low Wind Speed” (Low W.S.) if it falls within Range  $V_1$ ;
- “Medium Wind Speed” (Medium W.S.) if it falls within Range  $V_2$ ;
- “High Wind Speed” (High W.S.) if it falls within Range  $V_3$ .

Some results are presented as an example (Table 4).

**Table 4.** Classification of municipalities.

Data Referring to January				
Municipality	$T_m$ [°C]	$V_m$ [Km/h]	Temperature	Wind Speed
Acate	9.67	21.63	High T	High W.S.
Adrano	6.94	8.27	Low T	Low W.S.
Aci Castello	10.64	9.58	High T	Medium W.S.
Aci Catena	9.75	9.58	High T	Medium W.S.

In the phenomenon of the heat exchange between the conductor and the external environment, the wind speed impacting the overhead power line usually plays a more significant role than the average outdoor temperature [12]. For this reason, the nine possible combinations of temperature and wind speed have been classified, as reported in Table 5.

**Table 5.** Determination of climatic classes.

Determination of Climatic Classes		
Class	Temperature	Wind Speed
1	Low T	High W.S.
2	Medium T	High W.S.
3	High T	High W.S.
4	Low T	Medium W.S.
5	Medium T	Medium W.S.
6	High T	Medium W.S.
7	Low T	Low W.S.
8	Medium T	Low W.S.
9	High T	Low W.S.

Nine climatic classes were determined. Specifically, moving from one climatic class to the next reduces the conductor’s propensity for heat exchange, as the average monthly wind speed gradually decreases and the average outdoor temperature increases.

Once the methodology for classifying climatic classes had been established, several types of climatic analyses were conducted as follows:

- For each month of the year, the classification of Sicilian municipalities was assessed;
- Potential differences and similarities between Sicilian municipalities were observed.

Looking at the overall classification made during the study, differences and similarities can be seen between all the regions of the island; during the winter months, most municipalities fall into the higher classes, while during the summer months, most municipalities fall into the lower classes. This is due to the fact that some areas of Sicily are characterized by more consistent wind patterns throughout the year, while other areas experience significant variations in wind speed, especially during the transition from winter to summer.

It can be observed that the areas of Trapani, Ragusa, and Syracuse are usually characterized by high wind speeds throughout the year. In contrast, Enna and Messina are characterized by low wind speeds throughout the year. Palermo, on the other hand, has variable wind conditions throughout the year. Low wind speeds are observed in winter, gradually increasing to moderate wind speeds in summer. The Agrigento area also shows an increase in wind speeds from winter to summer, with moderate wind speeds in winter and high wind speeds in summer. The Catania area experiences medium to low wind speeds throughout the year, as does the Caltanissetta area (Table 6).

**Table 6.** Windiness of the provinces.

Windiness of the Provinces		
Province	January–June	July–December
Agrigento	Low T	High W.S.
Caltanissetta	Medium T	High W.S.
Catania	High T	High W.S.
Enna	Low T	Medium W.S.
Messina	Medium T	Medium W.S.
Palermo	High T	Medium W.S.
Ragusa	Low T	Low W.S.
Syracuse	Medium T	Low W.S.
Trapani	High T	Low W.S.

From the above considerations, the potential of Dynamic Thermal Rating (DTR) is not the same in all areas of Sicily. The effectiveness of these devices increases with the wind speed hitting the electric conductor. It is, therefore, more advantageous to install a DTR on power lines in windier provinces such as Trapani, Syracuse, and Ragusa. It is also observed

that the effectiveness of the device depends on the identification of the hot spots of the power line. Identifying hot spots is a complex and challenging task [12]; it is safer to use DTR technology in areas where even at the hot spots, the wind speed is not too low. This reduces the likelihood of overheating in unidentified hot spots.

In areas characterized by consistently low wind speeds (such as the provinces of Enna and Messina), the installation of DTR devices may not be advantageous from a purely climatic standpoint. This is for the following reasons:

- The proposed increase in current capacity from DTR may be too small and not beneficial enough;
- The hot spots in these areas may be critical enough to make the use of DTR unsafe. In this case, the suggested solution is the re-conductoring of the electrical line.

If Dynamic Thermal Rating is insufficient, another solution to address the increase in power flows is to increase the ampacity of electrical transmission lines through “re-conductoring” [19]. This involves replacing old, worn-out lines with new conductors that can operate at higher temperatures while still maintaining the required minimum ground clearance, thus reducing the space occupied by infrastructure. The new-generation conductors are HTLS (High-Temperature Low-Sag) conductors, which have almost identical cross-sections to conventional conductors but improve the transport capacity, efficiency, and reliability of the electrical grid.

While conventional Aluminium Conductor Steel Reinforced (ACSR) conductors typically operate below 75 °C, all HTLS conductors can continuously operate at least at 150 °C, with some capable of operating at 250 °C without significant changes in electrical and mechanical properties. The main advantage of replacing existing conductors with HTLS conductors is that they allow the thermal rating of the line to be increased without structural changes. Therefore, HTLS conductors have significant potential to replace conventional ACSR conductors.

#### 4.2.2. Implementation of the Dynamic Thermal Rating Calculation Algorithm Proposed by IEEE on Python Software

Once the climatic analysis of the Sicilian territory had been completed, a thermal analysis of the transmission lines was carried out. The purpose of the analysis is to calculate the current carrying capacity that the conductor can withstand without exceeding the permissible limits, in particular, those related to the phenomenon of annealing. The algorithm used is the one proposed by the IEEE Power and Energy Society in the document “IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors” [14]. This article presents a numerical methodology in which the temperature of the conductor is related to both the conductor’s ampacity and the ambient weather conditions.

In the study, the algorithm was used to calculate the Dynamic Thermal Rating of an overhead conductor. The output of the numerical method is the maximum current that can flow through the conductor without exceeding the maximum temperature limit. The analyses were carried out under steady-state conditions, considering constant external weather conditions within a one-hour interval. It is assumed that the variables proposed in the methodology evolve slowly compared to the electrical phenomena analyzed. Therefore, results obtained by considering short time intervals (one hour) are valid. For this reason, hourly meteorological data corresponding to the hourly averages recorded in the databases during 2024 in each of the Sicilian locations studied were implemented. These data were available through public Python libraries.

Following the simulations and considering both the current configuration and the forecasts for the Renewable Energy Zones (REZs) in 2027, some hot spots in the Sicilian

transmission lines were identified. The installation of DTR devices in these hot spots could bring significant improvements in the management of the transmission system.

#### 4.2.3. Identification of Critical Lines

After implementing the algorithm proposed by IEEE, a methodology was developed to identify the set of locations where the Dynamic Thermal Rating simulations should be performed. Specifically, the following steps were taken:

- Identification of all municipalities crossed by each REZ;
- Classification of the municipalities in each REZ based on their potential for thermal exchange to identify the hot spot municipalities;
- Once the hot spot municipalities had been identified, Dynamic Thermal Rating simulations were carried out for the municipalities crossed by each REZ in these locations.

To classify the municipalities of each REZ, software owned by Terna called Sisnet was used, which shows the layout of the entire Italian transmission network. In each Renewable Energy Zone, the following municipalities are present:

- REZ A: Mazara del Vallo, Campobello di Mazara, Castelvetrano, Partanna;
- REZ B: Marsala, Misiliscemi;
- REZ C: Trapani, Paceco, Misiliscemi, Erice, Buseto Palizzolo, Custonaci, Castellammare del Golfo;
- REZ D: Castellammare del Golfo, Alcamo, Partinico;
- REZ E: Troina, Cerami, Capizzi, Mistretta, Castel di Lucio, Regalbuto;
- REZ F: Gela, Butera, Licata, Acate, Vittoria.

To determine the hot spot municipalities in each REZ, the following methodology was used based on the climate analyses mentioned in the previous paragraphs:

- For each municipality in the REZ, the climatic class for each month of the year was calculated;
- Each municipality was assigned a score, called the “hot spot score” ( $X$ ), which is calculated as follows:

$$X_m = \sum_1^{12} X_{m,\text{month}} \quad (9)$$

where  $X_{m,\text{month}}$  is a number corresponding to the value of the climatic class of the municipality for the month in question.

It is important to clarify that the meteorological stations used for these climatic analyses may be different from those used for the analysis of the region as a whole. This choice was made to ensure the most accurate results possible. For the analysis of each REZ, only the meteorological stations available in the vicinity of the REZ were used, while for the global and regional analysis, the stations that ensured equal availability of meteorological data over the whole region were used.

The DTR simulations performed consider the meteorological conditions observed on 19 April 2024. This choice is consistent with the fact that the network overloads from which the REZ were identified were simulated under the meteorological conditions of 19 April 2024. Another important point to highlight is that the proposed results consider not only the thermal limit of conductor annealing but also the thermal limit due to the presence of other network elements, such as current and voltage transformers.

Figure 3 illustrates the results of the simulations and compares them with the corresponding current capacity currently in use. It can be observed that the results obtained refer to the hypothetical network scenario of 19 April 2024, characterized by high energy production from renewable sources. In all the sites studied, it was possible to simulate a significant increase in the current carrying capacity of the lines without reaching conductor

annealing conditions and while respecting the current limits imposed by network elements (such as current and voltage transformers). In addition, since the analyses were carried out in the hot spots of the various Renewable Energy Zones, the installation of a few DTR devices in these municipalities should ensure an overall increase in the permissible power flows across all the lines of each REZ.

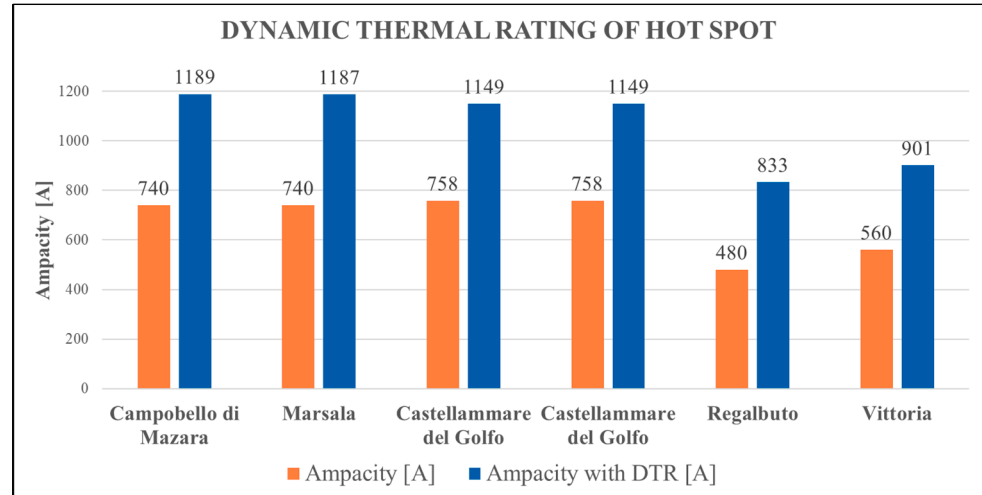


Figure 3. Dynamic Thermal Rating of hot spots.

This section presents the results of the comparison between the following:

- Overloads simulated on WinCreso, under n-1 network conditions on 19 April 2024;
- Overloads following the implementation of Dynamic Thermal Rating on the same lines, under the same network conditions.

An important clarification is made: the overloads have been expressed in terms of active power [MW], assuming, for simplicity, a power factor of 1. This hypothesis, although far from reality, allows us to arrive at equally valid conclusions. Figure 4 shows the results for the municipality of Vittoria.

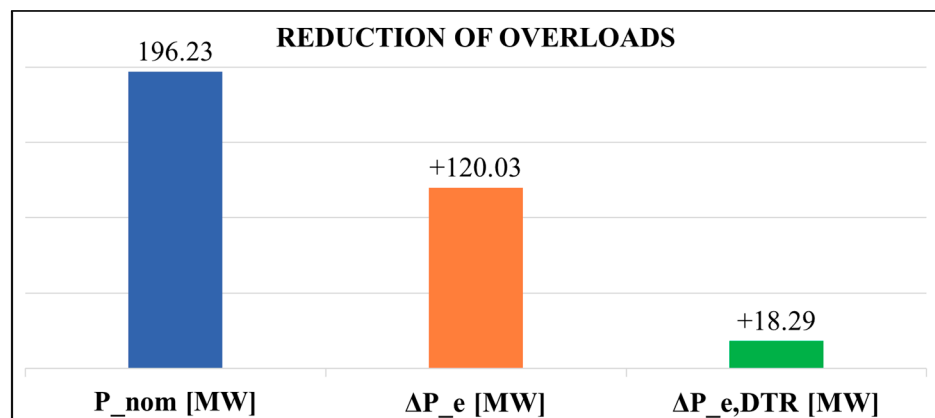


Figure 4. Reduction of overloads in the municipality of Vittoria.

For each line studied, several quantities were calculated, and their meaning is provided below.

The nominal electrical power P<sub>nom</sub> that the line can carry was calculated as follows:

$$P_{nom} = I_{nom} \times V \times \sqrt{3} \times \frac{\cos\phi}{1000} [MW] \tag{10}$$

where

- $I_{\text{nom}}$  is the maximum current that the line can carry under normal conditions [A];
- $V$  is the nominal voltage of the line [kV];
- $\cos\phi$  is the power factor.

The excess power  $\Delta P_e$ , which the line would theoretically have to carry if  $I_{\text{nom}}$  were equal to the current overload  $I_s$ , has been calculated as follows:

$$\Delta P_e = (I_s - I_{\text{nom}}) \times V \times \sqrt{3} \times \frac{\cos\phi}{1000} [\text{MW}] \quad (11)$$

where

- $I_s$  is the overload current simulated on WinCreso following an electrical system contingency [A].

The excess power  $\Delta P_{e,\text{DTR}}$  due to overload, which the line would theoretically have to carry if the nominal current  $I_{\text{nom}}$  were equal to  $I_{\text{DTR}}$ , was calculated as follows:

$$\Delta P_{e,\text{DTR}} = (I_s - I_{\text{DTR}}) \times V \times \sqrt{3} \times \frac{\cos\phi}{1000} [\text{MW}] \quad (12)$$

The power increase  $\Delta P_{+\text{DTR}}$  that can be carried by the line if the circulating current  $I_{\text{nom}}$  were the one proposed by the DTR  $I_{\text{DTR}}$  simulation was calculated as follows:

$$\Delta P_{+\text{DTR}} = (I_{\text{DTR}} - I_{\text{nom}}) \times V \times \sqrt{3} \times \frac{\cos\phi}{1000} [\text{MW}] \quad (13)$$

As shown in Figure 4, the overload that would have occurred with the use of DTR devices would have been approximately 18 MW (9% more than the nominal power of the line). Without DTR devices, the simulated overload was equal to 120 MW (61% more than the nominal power of the line). After analyzing the results of the Dynamic Thermal Rating simulation in each of the Renewable Energy Zones, it can be stated that the use of DTR technology would undoubtedly be beneficial and effective. In fact, in all the studied hot spots, the congestion that could occur following the installation of DTRs would always be less severe than the contingencies that would currently occur without the DTR devices.

## 5. Brief Economic Considerations

The transmission of high-voltage electricity is managed by the National Transmission System Operator (TSO), which is the joint stock company TERNA. It is the TSO's task to adapt production to the needs of the network, and the correct management of power flows makes it possible to improve both the overall efficiency of the electrical system and its economic performance. Among the measures implemented for the management of the electrical system, Terna reduces wind power production through dispatch orders, resulting in Wind Power Curtailment (WPC) [20]. In 2022, the WPC in Sicily was 30 GWh, mainly due to grid congestion [7,19].

An important Italian body involved in the management of renewable sources is the "Energy Services Manager" (GSE S.p.A). It is an Italian joint stock company wholly owned by the Ministry of Economy and Finance, which is entrusted with the task of promoting and developing renewable energy sources and energy efficiency.

Users of one or more wind power generation units whose energy production has been reduced due to dispatch orders issued by Terna may submit a request to GSE and, for informational purposes, to Terna for compensation for the wind power curtailment. Therefore, avoiding such WPC would result in significant economic savings for GSE and TSO. Assuming that the network congestions simulated on WinCreso (on 19 April 2024, in an  $n - 1$  grid condition) were entirely caused by excessive wind generation, the economic

return from the installation of DTR devices was calculated in each of the REZs. The reduction in economic costs ROE consists of the avoided payment that the TSO would have made to producers due to the circulation of the power proposed by the DTR ( $\Delta P_{+DTR}$ ) for one hour in each of the analyzed hot spots.

In detail, for each DTR simulation, the reduction in economic costs (REC) was calculated using the following operation:

$$REC = P \times \Delta P_{+DTR} \left[ \frac{\text{€}}{\text{h}} \right] \tag{14}$$

where

- $\Delta P_{+DTR}$  is the increase in power that can be carried by the line if the current flow corresponds to that proposed by the DTR simulation;
- P is the average electricity price set at 90 EUR/MWh.

Table 7 and Figure 5 show the REC of the hot spot of each REZ.

Table 7. Brief economic considerations.

REZ'S HOT SPOT	$\Delta P_{DTR}$ [MW]	REC [EUR/h]
A	116.80	10,511.69
B	116.28	10,464.97
C	101.74	9156.26
D	101.74	9156.26
E	91.77	8259.51
F	88.69	8259.51

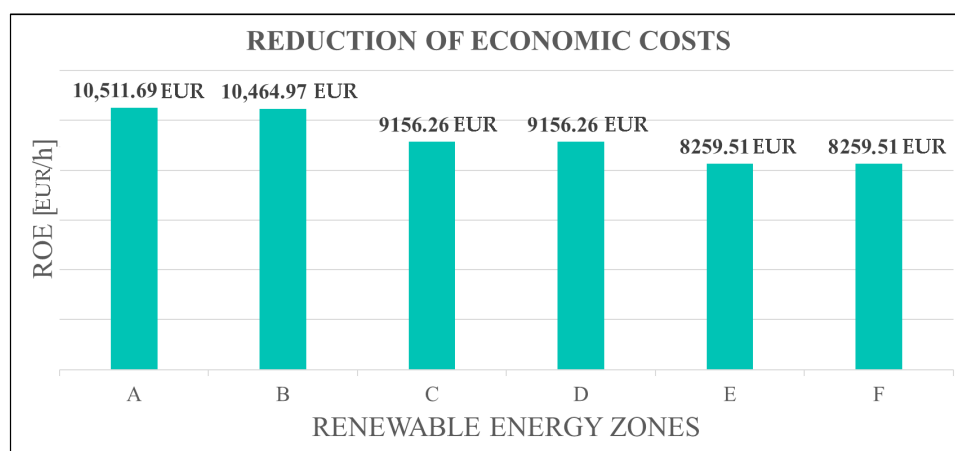


Figure 5. Reduction of economic costs.

Considering that the current cost of DTR technology is EUR several tens of thousands per device and taking into account the cost of resolving congestion in the Ancillary Services Market, the results obtained also confirm the economic sustainability of this technology.

## 6. Comparison with Current Dynamic Thermal Rating Applications in Sicily

This section presents a comparison between the Dynamic Thermal Rating simulations carried out and the current supplied by some DTR devices already installed in Sicily.

Specifically, the operational DTR devices have been installed on the following lines:

- 220 kV electrical transmission line;
- 150 kV electrical transmission line.

The validation of our algorithm aligns with the results obtained by Terna under certain considerations:

- The implemented IEEE algorithm extracts data from a database with a resolution of 1 km<sup>2</sup>;
- Terna's DTR devices, on the other hand, perform point measurements at the installation sites and compare them with data provided by Aeronautica Militare [21].

Considering these premises, the daily average current provided by our algorithm was compared with the daily average current provided by the DTR devices on 19 April 2024 (Table 8).

**Table 8.** Comparison of Dynamic Thermal Rating results.

Transmission Line	Average Ampacity DTR Terna [A]	Proposed Average Ampacity [A]
220 kV line	1370	1371
150 kV line	785	886

Table 8 shows that the values are very similar to those provided by Terna's DTR devices. This allows us to conclude that the methodology used for the simulations provides reliable results.

## 7. Discussion and Conclusions

Following the research carried out for this study, it is evident that the development prospects of the Sicilian transmission grid are both challenging and critical for the national and international electricity system. Structural interventions such as the Tyrrhenian Link, connecting Sicily, Sardinia, and Campania, and the TUN-ITA electrical channel, connecting Europe and Africa, are expected [1,4]. The integration of renewable energy sources is a fundamental aspect of the growth and development of the transmission network. In line with the Fit-for-55 development plan, the number of renewable energy plants connected to the grid is expected to increase significantly in the coming years. For this reason, the proper management of the identified Renewable Energy Zones (REZs) and the potential development of new ones will optimize energy dispatch and transmission [1,4].

This study identified six Renewable Energy Zones, some of which are already operational (A, B, C, D) while others are planned for the coming years (E, F). The application of "Dynamic Thermal Rating" (DTR) technology will improve the operation of the transmission system and the management of energy flows from renewable energy sources within the REZs. Current DTR technologies are effective, but they still have potential for enhancement.

The results demonstrate that the potential of DTR is not uniform across the various zones of Sicily. The effectiveness of these devices increases with higher wind speeds hitting the conductor. It is, therefore, more cost-effective to install DTRs on lines in windier provinces such as Trapani, Syracuse, and Ragusa. Conversely, in less windy areas (e.g., Enna and Messina), the installation of DTRs may not be economically advantageous due to a marginal increase in the line's capacity, making the investment less worthwhile. Critical hot spots in these areas could make the use of DTR less safe. In such cases, reconductoring the line is recommended.

In all the locations studied, it was possible to simulate a significant increase in current carrying capacity without reaching the annealing conditions of the conductor and while respecting the current limits imposed by network elements (such as current and voltage transformers). Furthermore, as the analyses have been carried out in the hot spots of each Renewable Energy Zone (REZ), installing a few DTR devices in these municipalities should ensure an overall increase in the allowable power flows on all lines within each REZ.

In particular, if each REZ is properly identified and managed, it should be possible to minimize dispatching actions within the zone. Currently, network congestion caused by a high level of renewable energy production is resolved by uniformly distributing wind production cuts evenly across Sicily. This approach reduces renewable energy production in areas not affected by congestion, resulting in untargeted interventions that do not minimize the overall production reduction. As observed, the targeted use of DTR within each REZ effectively reduces network congestion.

An economic assessment was also carried out, confirming the financial viability of DTR devices. In conclusion, a comparison between the DTR simulations and the results of devices currently installed at the same sites demonstrated the validity of the analyses performed.

It is important to emphasize one key point: the sensitivity analyses carried out in this study refer to a scenario of high renewable energy production (April 19, 2024). While this scenario is significant, it is not representative of all possible operating conditions. Comprehensive sensitivity analyses covering the full range of possible grid scenarios would be required and are beyond the scope of this study.

A potential future development of this work could include a detailed study of the electricity flows characterizing the micro-zones that make up each REZ. This approach could help to identify criticalities, quality issues, and key aspects of internal management within each REZ.

The results of this work, therefore, demonstrate that optimizing the number and placement of DTR devices can enable the grid to support a significant average increase in power flows. Dynamic Thermal Rating proves to be a highly effective tool for managing Renewable Energy Zones and, more generally, the Sicilian transmission system.

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