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Advancements in Insulator Coating Technologies: A Comprehensive Study on Enhancing Power System Reliability

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INTRODUCTION

This thesis is centred on the critical feature of coating high-voltage insulators with Room Temperature Vulcanizing (RTV) Silicone. The study is to critically examine the historical evolution, material attributes, technological developments, and economic impacts of RTV silicone coatings, highlighting their crucial contribution to the sustainability and improvement of performance and reliability of electrical power transmission and distribution systems.

The requirement for efficient insulator maintenance technologies has been conspicuous from the 1970s as power system reliability suffers due to pollution induced flashovers that occur quite often. Initial treatments such as manual cleaning and grease applications were tedious and temporary so, silicone-based coatings were introduced. Of all these, RTV silicone coatings proved to be revolutionary by their superior hydrophobic characteristics and resistance to environmental stresses.

The research will focus on the material properties of RTV silicone coatings that make them capable of repelling moisture and pollutants on insulator surfaces. Such coatings form a durable, hydrophobic layer and prevent leakage currents as well as electronic discharges. The study will explore the chemical composition and curing methods of RTV silicone, demonstrating how such characteristics improve the performance of the insulators in various weather conditions.

Fully investigated in this research will be technological innovations in processes of applying RTV silicone coatings, e. g. spraying, dipping, and brushing. The development of automated systems such as Automated Mobile Coating Systems (AMCS) is an important innovation that has enhanced application efficiency, uniformity, and environmental sustainability.

A large percentage of the thesis will focus on the advantages of using RTV silicone HVIC, in terms of economic and operational aspects. The quantitative data will show the financial effects relative to traditional methods. Issues with barriers to a general adoption will also be tackled, like inequitable start-up costs, peculiar equipment needs, and skilled labor needs. The innovations such as AMCS and Leakage Current Monitoring Systems (LCMS) will be emphasized in improving application as well as monitoring procedures.

The case study of EKD Project – an engineering company that is an expert in RTV silicone coatings – will explain the practical courses of technological progress and operational enhancements in maintaining high-voltage insulators. The switch of the EKD's coatings process from manual to automated shows remarkable advances of quality, consistency, and environmental sustainability. This could be really useful in the learning process, for utility companies and stakeholders that would like to use them as references for the RTV silicone coatings.

In addition, the thesis will delve into the regulatory impact and environmental stewardship linked to RTV silicone coatings, in terms of how regulatory frameworks and policies determine adoption strategies and contribute to sustainability objectives.

The role of partnerships between utility companies and technology providers will be highlighted as one of the factors that can help to overcome adoption hurdles and maximize insulator coating performance.

Utilizing extensive case studies and analysis, the purpose of this study is to achieve a complete picture of the actual use and positive effects of RTV silicone coatings in different geographical and environmental contexts. The research provides the industry practitioners and stakeholders with some valuable insights and specific recommendations by concentrating on the critical role of RTV silicone to coat high-voltage insulators. The results support the strategic use of RTV silicone coatings to improve the reliability, effectiveness, and sustainability of the power transmission infrastructure.

CHAPTER 1

OVERVIEW OF INSULATOR COATING TECHNOLOGIES AND RTV SILICONE

1.1 Definition of Insulator Coatings and Historical Context

The insulator systems are critical in electrical power transmission and distribution in terms of integrity and reliability. Insulators, which are important elements that anchor, and isolate conductors used to carry electricity, are exposed to many types of environmental stresses that can influence their functions. The introduction of insulator coatings, especially Room Temperature Vulcanizing (RTV) Silicone High Voltage Insulator Coatings (HVIC), is a major technological answer to these issues.

The insulator coatings started being developed in the 1970s as there was growing need to overcome flashovers, which were frequent hat and costly due to pollution on the insulator surfaces. These effects were initially tried to be reduced with cleaning and through use of grease that seems to be only temporary solutions and labor intensive, however. A revolution took place with the silicone coatings that provided a durable hydrophobic layer that repelled water and pollutants, improving the performance and life span of the insulator.

1.2 Material Composition, Properties and Technological Advancements

The unique material properties are characteristic of RTV silicone coatings. These coatings are silicone polymers which cure at room temperature to form a durable, hydrophobic barrier on the insulator surface. This barrier blocks the moisture and pollutants from cumulative, thereby reducing the leakage current and the chance of the electrical discharges to take place ending up in power outages. The use of these coatings might be adapted to the on-site needs, using methods like spraying, dipping, or brushing, based on the placement and environmental requirements of the location of application (P. Rogal, I. Peña, 2009).

The success of RTV silicone coatings in varied environmental conditions, starting from saline coastal areas to chemical contaminated industrial sites, have made them to be universally applied across the global utility industry. Advancements of technology in the application process, including generation of automated systems, have strengthened their position as the most suitable method of upgrading insulator reliability and life. These developments have helped to overcome some of the early adoption obstacles by streamlining the coating process and guaranteeing increased uniformity and efficiency.

1.3 Economic and Operational Advantages

The substantial influence of insulator coatings, especially RTV silicone HVIC, is mainly based on their effects in operational efficiency and financial savings. These coatings improve the service life of insulators, minimizing the frequency of pollutants-induced flashover maintenance required. The fact that this quality is sustainable results in a substantial operational saving, the allocation of resources is optimized, and service levels are kept high all the time for the end-users. The fact that these coatings are intrinsically stable in the long-term and require little upkeep brings to the fore their cost-effectiveness as a practical means to address environmental issues which impede insulator function.

1.3.1 Overcoming Adoption Hurdles and Embracing Future Possibilities

Despite the clear benefits that insulator coatings bring us, the path to their popularization is fraught with serious obstacles such as substantial upfront investment for coating application, the need for specialized machinery, and the need for skilled workers to manage the process. To these challenges, the sector is responding with major innovation in the form of Automated Mobile Coating Systems (AMCS) and Leakage Current Monitoring Systems (LCMS), for example. These technological improvements of the coating process make monitoring easier and increase the sector's commitment to improving the reliability and operational efficiency of the power transmission infrastructure, in an environmentally friendly manner.

A critical part of modern approaches to improve the reliability of electrical power infrastructure is insulator coatings, particularly those based on RTV silicone HVCI technology. The constant flow and improvement of these coatings are evidence of the industry's persistence in solving the challenging problems posed by pollution and differing climatic conditions. The increasing dynamism of innovation and wide adoption within the sector elevates the importance of insulator coatings in ensuring that electricity transmission is done smoothly and effectively.

1.4 Industry Overview and Power Demand

The power transmission and distribution sector are a cornerstone of contemporary civilization, promoting the modern way of living, placing the foundation for economic places and societal development, as well as the general lifestyle. This industry at the moment is in the process of serious changes that are caused by a combination of global factors and challenges. Of these, the transition to renewable energy sources, increasing power requirements, and need for sturdy and resilient infrastructure are the most striking.

The worldwide drive towards renewable energy is caused by environmental sustainability targets and the necessity to combat climate change and as such, renewable energy is transforming energy industry. However, this transition is not without complications in the power transfer and delivery system since the renewable sources such as wind and solar are intermittent. At the same time, the global increase in demand for electricity caused by the growth of industry, urbanization and the development of technology, requires the expansion and modernization of the existing electricity infrastructure to provide reliability and efficiency.

1.4.1 Insulators at the Crossroads

The insulators are also an essential part of this infrastructure, with the important role of supporting and isolating electrical conductors. The performance of them is critical for the steadiness and safety of the electricity supply. However, insulators are subjected to a constant attack by a variety of environmental stressors that can destroy their performance. Industrial emissions, salt fog from the coast, and chemicals used in agriculture introduce pollutants that stick to insulator surfaces, potentially causing contamination-induced flashovers. Incidents like this not only constitute safety hazards but also break power supply, which has severe economic and operating consequences.

1.4.2 RTV Silicone Coatings: A Technological Response

To counter these challenges, Room Temperature Vulcanizing (RTV) Silicone High Voltage Insulator Coatings (HVIC) have become a revolutionary technological answer. Such coatings fundamentally change the relation of insulators with their surroundings. Due to hydrophobic nature, RTV silicone coatings make the surfaces of insulators free from moisture and pollutants that minimize the probability of flashovers. This property becomes extremely critical in high pollution regions and harsh climate areas, where routine maintenance strategies bring ineffective results at best and at worst – financial burden.

1.4.3 Adoption Landscape

The adoption of RTV silicone coatings by the industry is a part of a wider trend to increase resiliency in infrastructure and operational efficiency. Nevertheless, the adoption landscape is characterized by variability where different regions and utilities are at varied stages of integration. This variation is driven by a number of factors, such as the local environmental features that stipulate the level of necessity, the regulatory systems that can accelerate or slow down the implementation, and the economic criteria that include upfront investment costs, long-term savings and impacts on operating budgets.

On the other hand, the introduction of RTV silicone coatings into already established power systems involves the solutions of logistical and technical problems. These include the choice of the right coating formulations of insulation to adapting coating application methods to different insulator designs and environmental conditions. Additionally, this process is further complicated by the requirement for equipment and trained personnel; therefore, strategic planning and capacity building are crucial for utilities going this route.

The path of the electricity power transmission and distribution sector in implementing RTV silicone insulator coatings is symbolic of the issues and advantages of modernizing and making critical infrastructure future-proof. In this regard, innovative technologies that are informed by abundant research, industry collaboration, and policy support systems will remain the key in understanding the relationship between the reliability, efficiency and sustainability demands in the sector that is still changing.

1.5 Research Purpose (Managerial Aspects of the Sector)

The primary objective of this study is to explore the managerial implications of Room Temperature Vulcanizing (RTV) Silicone High Voltage Insulator Coatings (HVIC) in the power transmission industry. This research is based on the realization that the incorporation of this progressive technology goes beyond simple technical operation getting into the core of the operational, strategic, and economic elements of utility companies. The focal points of this investigation encompass several critical managerial dimensions. The focal points of this investigation encompass several critical managerial dimensions:

- <u>Strategic Decision-Making Processes</u>: The study will look at the strategic approaches that utility services providers use in deciding whether to adopt the RTV silicone coatings. The central point of this analysis is a cost-benefit evaluation that, besides the immediate expenses related to the implementation of this technology, includes long-term savings on maintenance costs, longer life of the assets and improving system reliability. This dimension will examine the parameters and measures which the decision-makers use to evaluate the economic and operational advantages whereby silicone coatings are being used in conjunction with the organization's strategic objectives and financial constraints.

- <u>Comprehensive Implementation Strategies</u>: The development of RTV silicone coatings as a technology is a multi-dimensional approach rather than a mere deployment of the technology itself and entails its comprehensive integration into the utility's existing set-up. This research will look at the practices utilities use to manage this difficult process, including supply chain management issues, specialist staff training in silicone coating application techniques, and the incorporation of these maintenance routines into the overall operational framework. Particular focus will be placed on the process of utilities moving from old maintenance strategies to those suited for coated insulators and preventing disturbances to existing activities.

- Regulatory Influence and Environmental Stewardship: The regulatory frameworks and environmental policies also determine the approach utility companies take with RTV silicone coatings. This study aims to determine how current regulations and sustainability imperatives impact the choice of insulator coverings which will look into the interaction of necessity to follow regulations, environmental concerns and technology adoption. The next part of the analysis will focus upon how utilities use silicone coatings to achieve sustainability targets and improve their environmental performance, integrating the adoption of technology with the wider environmental goals.

- Innovation Ecosystem and Technological Synergies: The synergy between utility companies and technology providers plays a key role in promoting the use of RTV silicone coatings. This research will focus on the innovation ecosystem that supports this technology, how partnerships between utilities and suppliers drive technological advancements and customize solutions to specific operational requirements. The purpose will be extended to supporting technologies, like Automated Mobile Coating Systems and Leakage Current Monitoring Systems, that enhance the silicone coating value proposition by dealing with application challenges and promoting more efficient asset management.

1.6 Methodology

This document will utilize a refined mixed-methods approach to clarify the managerial complexities of the adoption of RTV silicone insulator coatings in the power transmission sector, combining qualitative perspectives with quantitative methodology. The approach is intended to reveal a comprehensive understanding of the process of adoption, the challenges it poses, and its strategic implications. The approach is detailed as follows:

Comprehensive Literature Review: This research is based on a thorough literature review provided by both academic and industry-oriented sources. This phase aims to:

a) Basis the study on a comprehensive theoretical framework, which builds on extensive research on insulator coatings, their technological advancement, and their performance consequences.
b) Point out the areas of lack of knowledge especially in the managerial and economic parts of RTV silicone coatings adoption which provide the foundation for new research contributions.
c) Examine case studies and reports on utilities' encounters with RTV silicone coatings to deduce initial findings about best practices, challenges, and results.

In-depth Case Studies: Case studies are the foundation of the qualitative analysis providing detailed information on the practical use of RTV silicone coatings. This component will:

a) Choose a variety of utilities with different track records in the application of RTV silicone coatings so that a wide range of geographical, environmental, and operational conditions is covered.
b) Analyse the processes of decision-making that resulted in the adoption of RTV coatings with a focus on considerations of cost-benefit analyses, risk assessments, and strategic alignments with broader organizational outcomes.
c) Analyse the implementation approaches indicating the logistical, technical, and human resource hurdles faced and how they were addressed.
d) Evaluate the results of the adoption of RTV silicone coating, considering benefits obtained in operational efficiencies, changes that occurred in maintenance strategies and the global effect on system reliability and economic performance.

Expert Interviews: Conducting semi-structured interviews with a variety of industry experts would diversify the viewpoints reflected in the research, thereby enriching the depth of qualitative analysis. This stage will:

a) Interact with utility managers who have managed RTV silicone coating projects, technology suppliers who have designed and furnished these coatings and regulatory professionals who can offer some policy insight into the world of insulator coatings.
b) Employ a semi-structured interview design to facilitate detailed conversations and to ensure that all interviews are consistent with one another for the purposes of comparability.
c) Examine the strategic, operational, and regulatory subtleties around the adoption of RTV silicone coating, drawing expert thought on best practices, ongoing challenges, and future prospects.

Rigorous Quantitative Analysis: The quantitative side of the methodology is set to test the impact of RTV silicone coatings in terms of statistics on utility performance. This phase will involve:

a) Obtaining a complete data set from utilities that will participate that includes maintenance records, outage reports, financial documents, and other pertinent operational data.
b) Utilizing statistical analysis methods in order to determine the effect of RTV silicone coatings on overall economic efficiency, longevity of assets, outage frequencies, maintenance costs, and other important performance indicators.
c) Integrating qualitative insights gleaned from case studies and interviews with quantitative data to test hypotheses and arrive at subtle conclusions.

The combination of qualitative and quantitative results will support the comprehensive comprehension of the managerial environment of RTV silicone insulator coatings. The present synthesis will add not only important recommendations to academic literature, but also practical recommendations for industry professionals who either consider or are currently implementing RTV silicone coatings. The study will result in actionable recommendations, based on empirical evidence and expert opinions, to improve the strategic adoption and operational management of RTV silicone insulator coatings in the power transmission industry.

CHAPTER 2

RTV SILICONE: WHAT IT IS AND ITS MARKET

2.1 Impact of RTV Silicone Coatings on China's Power Industry

Within the quick development of China electric power sector, the coming of Room Temperature Vulcanized (RTV) silicone coatings is the example of the strategic innovation and environmental protection. This chapter discusses the ways in which RTV coatings have changed insulator maintenance and reset industry norms and sustainability practices.

The arrival of Room Temperature Vulcanizing silicone coatings in the mid-1980s in the sphere of high voltage power transmission and distribution as the revolutionary measure to the challenge of pollution flashovers of electrical insulators. The innovation and diffusion of RTV coatings over the diverse landscapes of China represent a major milestone in strategic innovation management. The period is characterized by extensive research activities to improve the coatings adhesive properties, improve their ability to regulate leakage current, and understand the mechanism of transfer of hydrophobicity that was complicated. The achievement of annual consumption figures of almost 800,000 kg is conclusive proof of the efficiency of this innovation in meeting the important requirements of the power transmission sector.

RTV silicone coatings market dynamics are determined by a number of factors such as extremely large investments in research and development and stringent requirements for their use. The competitive advantage of RTV coatings is their technological superiority to traditional maintenance methods which creates a unique value proposition that makes them stand out in the market.

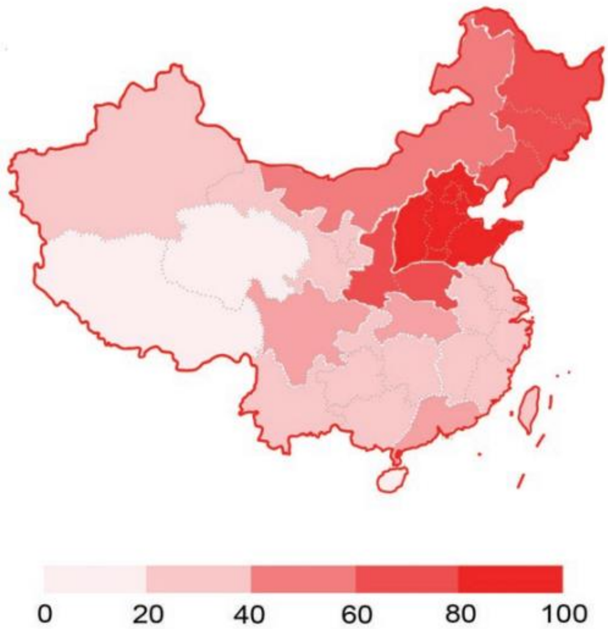
The most important factor of the success of RTV coatings' incorporation into the power industry was the multi-sector cooperation that covered academia, industry stakeholders, and governmental bodies. This collaborative effort facilitated the integrated approach to the research and development and standardization of the coatings, a necessary condition for their successful introduction and spread in the market. Pilot projects and scalability analyses were indispensable in informing the strategic decision-making processes, which were characterized by an assessment of the long-term operational benefits versus the initial costs.

Operationally, the influence of RTV coatings does not only relate to their success in preventing pollution flashovers, but to their positive effect on environmental sustainability. The durable nature of RTV coatings minimizes the necessity of ongoing maintenance actions thus decreasing the ecological footprint of the power transmission systems. However, full knowledge of the environmental implications associated with the manufacturing, use, and disposal of these coatings is fundamental for the understanding of their sustainability effect.

RTV coatings life cycle is associated with its problems in determining its expected life, failure mode, and formulation of effective strategies for re-application. Focused compliance with national standards and strict quality control procedures are a prerequisite for perpetuating performance and reliability of the coatings. As the power sector changes, the future insulator coating technologies landscape will also be advanced due to materials science and application techniques, highlighting the importance of management approaches that can embrace flexibility and sustainable practices.

In conclusion, the coming of RTV silicone coatings into the electrical power industry and its subsequent integration is an interesting example of technological innovation, strategic achievement, and environmental care. This paragraph critically examines the RTV silicone coatings, presenting operational and strategic dilemmas in adopting and managing complex advanced insulator coating technologies in the face of shifting market trends and sustainability challenges to industry practitioners. The experience and lessons gained from the use of RTV coatings in China provide crucial roadmap on how to negotiate the challenges and prospects posed by future technological changes, promoting the dedication to the innovation, collaborative action, and environmental responsibility in the actions aimed at the operational excellence and sustainability.

Figure [1]. Use of RTV coatings in different areas of China. 100 means 100 percent porcelain and glass insulators and bushings were coated with RTV silicone coatings, and 0 means none of them were coated.



Source: "*Development of RTV Silicone Coatings in China: Overview and Bibliography*", IEEE Electrical Insulation Magazine, Vol. 24, No. 2

2.2 Advancement and Impact of RTV Silicone Coatings in High-Voltage Applications

The production landscape of RTV silicone insulator coatings has undergone more extensive changes, which have been associated with the growth of the market for insulators and the rate of consumption of these coatings. Today, the sector is extremely competitive, and there are roughly around a dozen of suppliers globally.

At the beginning of development in the early 1970s, major formulations of RTV coatings were silicone sealants diluted with solvents making use of the hydrophobic properties of silicone. The next thing that was introduced was silica powder which served the purpose of a physical enhancer. The evolution of RTV High Voltage Insulator Coatings (HVIC) resulted in the substitution of silica powder with metal hydrate fillers, e.g. aluminium trihydrate (ATH), to enhance performance in critical operating conditions. Nevertheless, the ATH-filled coatings while popular still have alternatives in the market, which do not use fillers at all or continue to use silica powder. Studies have revealed that these diverse formulations can bring cost-effectiveness savings with little performance loss. In addition, the industry has experienced the development of innovative coatings with super-hydrophobic, self-cleaning, and ice-phobic features, which extends the area of their use to solve the problems of flashover in icy and polluted situation.

2.2.1 Procedures

The way how RTV silicone coatings are applied to ceramic insulators including those made of glass or porcelain is very important to preserve the functionality of the insulators and prevent early peeling problems.

Figure [2]. Example of peeling of RTV coating.

Source: INMR Enriching Technical Knowledge of T&D Professionals, "High Voltage Insulator Coatings: State-of-the-Art & Future Development"

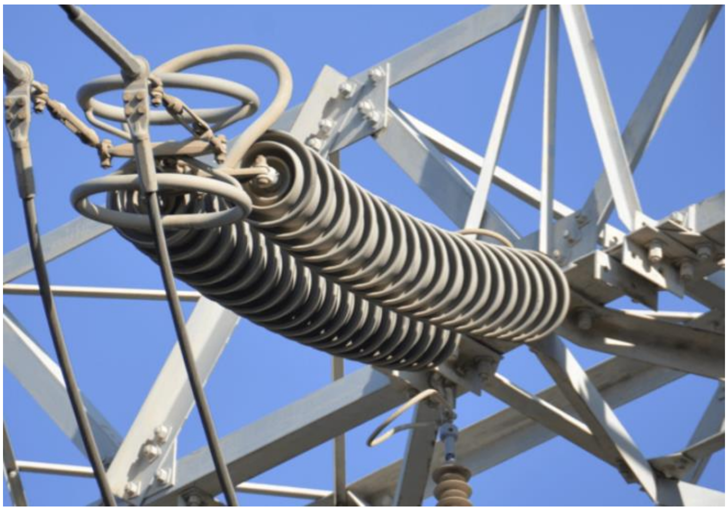
An example is China, where, especially in ultra-high voltage (UHV) applications, a growing number of insulators are being used which are pre-coated with RTV silicone. Such coatings are usually utilized by means of automated dipping or spraying procedures in immaculate controlled formulas which prevent any wind or dust, and also keep a steady temperature, including solvent recovery systems. This approach is in a sharp contrast with the old and traditional systems where the coatings were done on the spot at substation or power line, resulting into considerable savings in volume of coating used and volatile organic compounds emissions.

Figure [3]. In-field application on RTV coatings in Brazil (top) and Greece (bottom).

Source: INMR Enriching Technical Knowledge of T&D Professionals, “High Voltage Insulator Coatings: State-of-the-Art & Future Development”

Automatization of the application process is of great importance to the attainment of the same quality all the time and everywhere in the coating. However, a significant number of the total of about seven million pre-coated insulators that are still in use worldwide have been processed with automated and controlled spraying methods. For instance, in Italy the national TSO, Terna, has more than a million such insulators in operation.

Figure [4]. RTV-coated glass string on transmission line in Italy.



Source: INMR Enriching Technical Knowledge of T&D Professionals, "High Voltage Insulator Coatings: State-of-the-Art & Future Development"

In Italy, the spraying has been favourite method since it provides a more uniform coverage when compared to other methods such as dipping. The launching of the factory-coating process required careful choice of the silicone compound and preparation for clean insulators prior to application. Important issues like a consistent covering thickness, precise processing of curing, and proper handling and packaging were determined to be critical to achieve quality end products.

Traditionally, the application was carried out manually according to the guidelines of the material suppliers, causing quality and efficiency to fluctuate depending on the skill of the operator. The usual challenges were uneven coverage, missing spots, and rework needs, low productivity, and high waste levels, which affected both the costs as well as environmental safety. In the response, automation has dominated, where the modern systems are using programmable logic controllers for the spraying process in specially designed environments that are sealed. These improvements also generate significant environmental and process cost savings and quality benefits with the automated processes producing a uniform coating thickness variance of ±20% across the insulator's surface.

2.2.2 Field Experience

Terna, the Transmission System Operator of Italy, has checked the efficiency of more than one million insulators treated with pre-coated insulation a place severely polluted with marine pollution and remarked that there was no flashover after the insulation. Initial concerns on the longevity of these coatings led to Terna conducting annual inspections and tests on the insulators. With these assessments, it was concluded that the coatings could certainly withstand over 15 years in difficult environments. The amazing performance of coated insulators in alternating current (AC) systems saw Terna extend their use to direct current (DC) lines in 2008 which brought about a spectacular improvement of line reliability and a significant reduction in flashovers. Terna also started to apply pre-coated porcelain for station posts at new high-voltage facilities located in highly polluted areas.

The specialists in the area are of the opinion that certain types of insulators are more appropriate for specific environmental conditions. In areas where sea spray and desert sand mixture or high salt content is prevalent, materials that could transmit hydrophobic, such as composite or RTV-coated insulators, may be necessary. In the opinion of these experts, all insulator designs, if properly engineered (including the correct use of corona rings for composite insulators) and produced with high quality, are probable to work satisfactory. They stress the need for complete investigations of any failures in order to determine whether they are due to the bad quality of insulators or the design defects such as insufficient ultimate specific creepage distance (USCD) or the inappropriate shielding for composite types. They warn of quick conclusions that have not been properly researched and thoroughly investigated.

Moreover, experiments conducted in some of the world’s most severe climates such as Koeberg in South Africa, Martigues in France and Al Fadhil in Saudi Arabia provide useful data for the evaluation of the durability of RTV coatings and the comparison of the effectiveness of different types of coatings. This information helps the engineers to make proper decisions as to long-term application and efficiency of various coatings of insulators.

Figure [5]. GCCIA interconnection system operates in harsh desert environment.

Figure [6]. Station insulators coated with RTV at Al Fadhili back-to-back converter station.

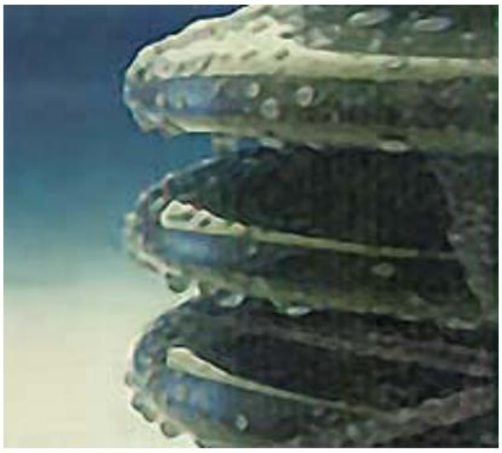
Source: INMR Enriching Technical Knowledge of T&D Professionals, "High Voltage Insulator Coatings: State-of-the-Art & Future Development"

2.3 RTV Silicone Coatings and Power System Reliability in Polluted Environments

The challenges of pollution flashovers are uncovered in this detailed study of how to maintain high-voltage (HV) insulation in polluted environments to support a power system performance. Pollution flashovers, because of environmental pollution on insulators, are greatly intensified in the presence of high humidity or fog, which may result in power outages. The study critically reviews shortcomings of the traditional maintenance strategies—periodic water washing and silicone grease application—in term of economics and recommends RTV silicone rubber coating as a more effective maintenance measure.

In the beginning traditional maintenance methods are effective in pollutant removal, but need frequent reapplication, which makes them labor-intensive and economically inefficient. This activity requires the use of distilled water and particular equipment, which creates more logistic and operational costs. In the like manner, the use of silicone grease that creates a temporary protective layer against pollutants is considered impractical in high Non-Soluble Deposit Density (NSDD) environments. However, its efficiency is reduced by environmental factors, such as wind and rain that can remove the greasing layer, leading to reapplication within a year. The high price and difficulties in uniform coverage over a complicated insulator shape also emphasize the unsustainability of silicone grease as a lasting solution.

Figure [7]. Insulator surface hydrophobicity after greasing



Source: “TECHNICAL & ECONOMICAL EVALUATION OF USING SILICONE RUBBER RTV COATING FOR H.V. SUBSTATION IN POLLUTED AREA”, International Conference on Electricity Distribution

The utilization of RTV silicone rubber coating has been an innovative solution to insulator maintenance in polluted areas. This innovative approach provides a hard, hydrophobic layer, which efficiently repel the adherence and conductivity of contaminants on the insulator surface, substantially reduces the flashover risk. Contrary to traditional practices, RTV coatings functions well in both high and low NSDD conditions and have a significantly longer life span, making them to be a suitable replacement product.

Detailed financial analysis on a case study of a 230kV substation in Queshm, demonstrate the economic benefits of RTV coating when compared to the conventional maintenance methods. The analysis of a 30-year maintenance period shows that RTV coating is cost-effective, and it ensures the operational efficiency, which not only results in reducing the number of maintenance interventions but provides a substantial long- term saving. This is especially applicable to the “heavy” classification of pollution of the Queshm substation following IEC 60815 standards, which represents the challenging conditions in several locations.

Figure [8]. Grease oxidation

Source: “TECHNICAL & ECONOMICAL EVALUATION OF USING SILICONE RUBBER RTV COATING FOR H.V. SUBSTATION IN POLLUTED AREA”, International Conference on Electricity Distribution

The study therefore identified RTV silicone rubber coating as the most efficient and cost-effective technique for HV insulator maintenance in polluted environments, pointing out that it is an ideal best practice within the power industry. RTV coating also provides superior performance, durability and reduced maintenance requirements making in an attractive solution for long term reliability and efficiency of power systems in areas susceptible to pollution flashovers. This extensive investigation not only exposes the limitations of conventional insulator maintenances methods, but it also advocates the substantial advantages offered by the use of RTV silicone rubber coating, thus providing very insightful recommendations for enhancing the operation of the power systems under polluted conditions.

2.4 Market Analysis

In the changing world of electrical insulation technology, the trend is to apply coatings to improve the properties and life of insulators, which has become a critical area of innovations. Notably, Room Temperature Vulcanized silicone coatings have received wide interest because of their desirable properties and efficacy in protecting pollution-induced flashovers, which is a common problem in power transmission and distribution systems. The purpose of this chapter is to investigate the development of insulator coatings market, with a special interest in RTV silicone coatings since direct market information on insulator coatings is quite rare.

Due to the scarce explicit data on the insulator coating market, this study applies an analytical method to indirectly assess the market expansion and trends by analyzing the general RTV silicone market. Silicone based RTV, which is a main ingredient in insulator coatings, is connecting the technology developments in material science with the application in electrical insulation. This study aims to link the growth and developments within the RTV silicone market with the expected trends and expansion in the insulator coating industry.

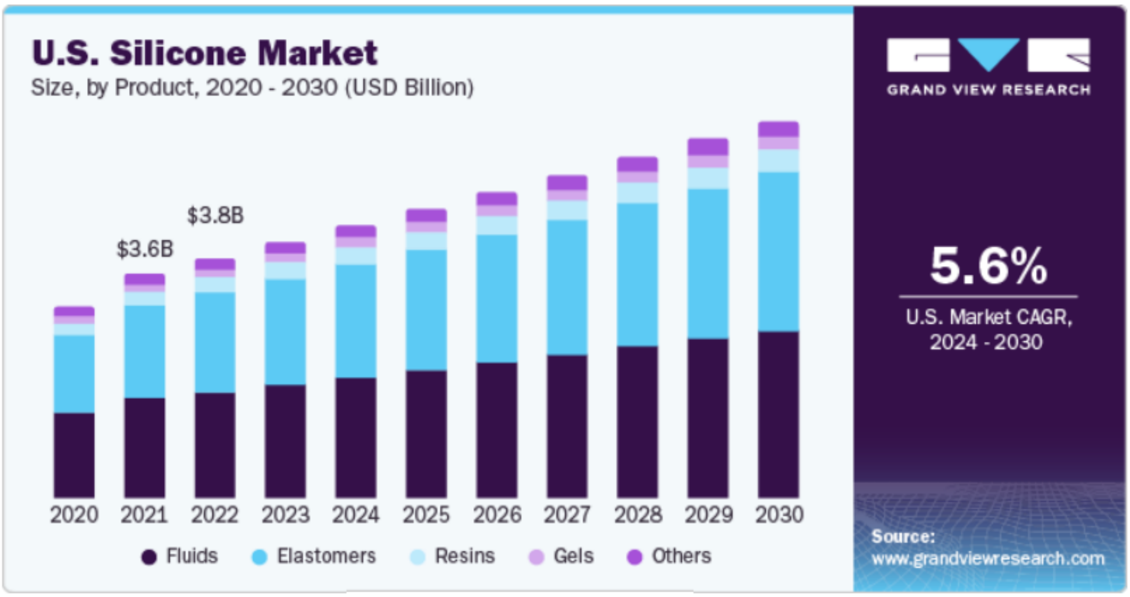
This is based on the assumption that the demand dynamics, innovation trends, and regulatory changes affecting the market of RTV silicone are representative of, and possible predictive of, the trends within the insulator coating market. The research thereby attempts to deduce the growing needs, opportunities, and threats in the insulator coating market by analysing the growth patterns, technological advancements, and application domains of RTV silicone.

The justification for this approach lies in the importance of that RTV silicone plays in insulator coatings and the belief that the market forces affecting the raw materials and technology platforms will always have an impact on the end applications. This analysis targets to offer comprehensive picture of insulator coating market at present and future outlook together with strategic implications for the stakeholders, in the absence of direct market data. This research, therefore, is not only of academic value to material application in electrical insulation but also provide practical implications for the industry practitioners into the complexities of market evolution and technology adoption.

2.4.1 Industry Insights

The valuation of the global silicone market was approximated at USD 21.33 billion in the year 2023, with projections indicating a compound annual growth rate (CAGR) of 5.6% from 2024 to 2030. This anticipated growth is largely attributed to escalating demand for coatings in sectors such as consumer goods and construction, which are expected to catalyse the expansion of the industry.

Figure [9]. U.S. Silicone Market Size, by Product, 2020-2030 (USD Billion)



Source: Grand View Research, "*Silicone Market Size, Share & Trends Analysis Report By Product (Fluids, Gels, Resins, Elastomers), By End-use (Electronics, Transportation, Construction, Healthcare, Industrial Processes, Energy), By Region, And Segment Forecasts, 2024 - 2030*"

The competitive landscape of the silicone coating sector is characterized by the existence of a multitude of participants, each vying for market predominance through the differentiation of their product offerings for a variety of applications. In an effort to achieve this differentiation, corporations are engaging in research and development activities aimed at the creation of novel and innovative products. Efforts of this kind are essential for entities to keep up with market rivalry. Technological advances, as well as innovation and detailed research that will look to expand the area of application of the products, are expected to increase demand throughout the forecast period.

The expanding use of conformal coatings in various industries like defence, automotive, industrial and building & construction will likely push manufacturers to adopt backward integration in the coming years. The improvement of integration within different value chain components is expected to help in shortening the time required for the raw material to shift to the finished goods and to create a cost advantage. The direction of the integration of the processes from inbound logistics to after-sales services is becoming a principle in the silicone market providing better quality of products and lower costs. This alignment is expected to attain the best performance and maximum product lifetime value.

Due to increasing market needs, producers of silicone are extending their production facilities and infrastructures. In addition, the big players in the coating sector are entering into mergers and partnerships to ensure a continuous source of raw materials. The industry is based on such acquisitions and joint ventures, which help companies to strengthen their market positions.

2.4.2 Silicone Coating Market Trends

The use of silicone coatings covers several industries which include the building, consumer goods, automotive and manufacturing sectors, and which help in overall progress of economy. The construction sector, led by infrastructure and capital projects, is expected to drive silicon coatings demand in the years to come. Although the silicon industry has average performance due to the old market situations of manufacturing industries and uses of silicones, the innovations in products and progress in technological advancements will move the use of silicone to the emerging markets.

The silicone coatings market is growing significantly on the global scale due to the growing construction sector. This growth calls for the need for effective coating solutions that will protect building infrastructures from environmental adversities. Silicone coatings are a protective layer enhancing the life of the buildings by providing resistance to harsh weather, including roof waterproofing and UV resistance improvement. By 2019, the global construction sector spending had exceeded over US dollars 11 trillion and the projections were expected to grow to near US dollars 14 trillion by 2025. The upward trend of construction investments is anticipated to significantly increase the requirement of silicone coatings. Therefore, the thriving construction industry teamed with the need for strong and protective coating solutions will drive the market for silicone coatings industry throughout the forecasted period.

2.4.3 Regional Insights

In 2023, the Asia Pacific market remained the leading market, with a revenue share of over 45. This is due to the heterogeneous market players, from small to large companies, which are a characteristic of this region’s market share that is close to one hundred percent. Beneficial factors of lower labor costs, ease of availability of raw materials, and a broader reach of market penetration across many sectors including construction, electronics, transportation, industrial processes, personal care, consumer products, energy, and healthcare are expected to drive the relocation of production facilities from North America and Europe to Asia Pacific. This change is expected to lift the production of silicon in the region during the forecast period.

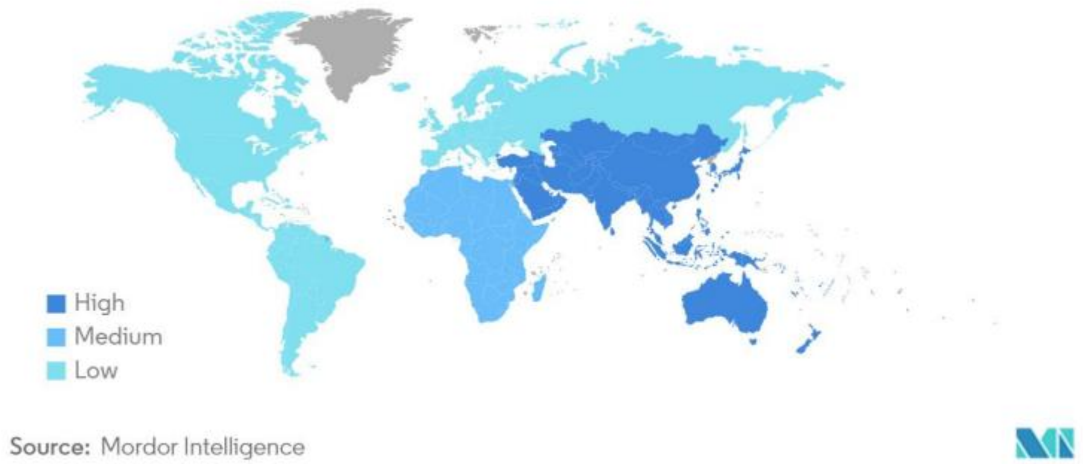
Figure [10]. Silicone Market Trends, by Region, 2024-2030

Source: Grand View Research, "*Silicone Market Size, Share & Trends Analysis Report By Product (Fluids, Gels, Resins, Elastomers), By End-use (Electronics, Transportation, Construction, Healthcare, Industrial Processes, Energy), By Region, And Segment Forecasts, 2024 - 2030*"

The second largest market is Europe, and it is expected to have 5 rate of growth. starting from 2024 to 2030. The growth of construction industry in several European countries including Germany, the United Kingdom, France, Russia, and Spain is expected to lead to an upsurge in demand for the products during the forecast period. The additional funding from the European Union, which is to be supported by a variety of measures such as incentives, subsidies, and tax advantages offered by individual governments, is likely to boost the development of the construction sector in the region. In addition, the rising use of silicone in renewable energy industry, e.g. in wind farms and solar panels, and health care segment for aesthetic implants, is expected to drive silicone market.

North America is one of the important markets for silicone additives, due to the high demand across sectors such as plastics and composites, manufacturing chemicals, paints and coatings, food and beverage. Furthermore, the area has a significant medical-grade silicones growth potential since the segment is well supported by strong demand from the healthcare industry and many large-scale manufacturers in North America.

Figure [11]. Silicone Market – Growth Rate by Region, 2022-2027



Source: Mordor Intelligence, "*Silicone Coating Market Size & Share Analysis - Growth Trends & Forecasts (2024 - 2029)*"

2.5 Considerations

In summary, the linkage of the growing silicone market and the insulator coating industry, especially in relation to Room Temperature Vulcanized (RTV) silicone coatings, reflect one of the major trends in the field of electrical insulation technology. The expected growth of the world silicone market, in which an approximate annual compound growth rate (CAGR) of 5.6% during 2024-2030, indicates a stronger growth led by the construction, consumer goods and other key sectors demands. Such growth trajectory can also be found in the insulator coating market, in which RTV silicone coatings are fast gaining recognition due to their high performance and their ability to mitigating pollution-induced flashovers in power transmission and distribution systems.

The regional dimension emphasizes the Asia Pacific's leadership derived from strategic production re-shuffles and the significant role of Europe in the market, while North

America retains strong demand in certain silicone applications. Such trends demonstrate not only the dynamics of the global market but also its immediate influence on the need for silicone-based insulator coatings. The focus of silicone industry in innovations, technological advances, and value chain integration is anticipated to improve the performance and application of RTV silicone coatings in electrical insulation.

Further, strategic impact on stakeholders in both silicone and insulator coating markets are significant. Continuous innovation and technological advancements in the silicon market are critical for the ability of silicone insulator coatings to evolve. That is, these developments also offer a direct advantage to insulation technology sector as they enhance the performance and life as well as the reliability of the power transmission and distribution systems.

Basically, the relationship between the silicone market and the insulator coating industry demonstrates a symbiotic association, which is important for the evolution of electrical insulation technologies. The impact of silicone market on development and application of RTV silicone coatings in the insulator coating market remains undeniable as the silicone market is ever evolving driven by the demand across various industries. This relationship is not only an enabler of creative advancements in the material science but also a prime mover of the efficiency and sustainability of power systems throughout the world thus having contributed to the progress in the technological development of electrical insulation.

CHAPTER 3

ENVIRONMENTAL IMPACT

3.1 Environmental Impact of Silicone Coating on Insulators

Insulators are an important part of power transmission systems, formulated to sustain electrical stability and mechanical strength in different environmental situations. The performance of insulators is highly dependent on material properties and design that need to be customized for specific voltage and environmental requirements in their applications.

Environmental and operational stresses are major obstructs to the durability and functionality of insulation. Electrical stresses like corona effects, ionize air molecules making the surface of insulation conductive and a continue sequence of electrical discharges. This can result in leakage currents or even electrical hazard of conducting “islands” formation on the surface of the insulation. Physically, insulators are characterized with the stresses of thermal expansion, as well as of degradation by such effect of environment as acid rains, salt spray and ultraviolet radiation which could accelerate aging and reduce their efficiency. Ceramic is a traditional material of insulators that provide very good mechanical strength and high dielectric strength dying in contact with environmental contaminants. Other methods including the utilization of polymer insulators or the coating of ceramic insulators with protective polymer are now being studied. Polymer coatings, particularly the silicone ones, are chosen for their hydrophobic nature and their resistance to a range of environmental stresses, which include UV, temperature variations, and chemical attacks. Coatings improve the insulation durability and resistance to environmental conditions and also prevent adverse effects of contamination and moisture.

The assessment of the environmental consequences of such insulating coatings shall be the focus of the current chapter, with particular emphasis on the silicone-based coatings known for their capacity to cope with the complicated requirements posed to insulators in another contaminated, adverse environment. The focus of this chapter is to enhance the relationship of how these coatings help in promoting the life and productivity of the insulators in sustainable energy transmission and their potential to reduce the operational costs and environmental impacts.

3.2 Advancements in RTV Silicone Coatings for Polluted Environments

Different cleaning methods have been developed for high-voltage insulators working in polluted areas. One of the coatings, room temperature vulcanized (RTV) silicone rubber, has been widely used for many years but, currently it has been gaining in popularity. The original application was only in substations, but now, it is used on overhead wires. Among the key performance characteristics of these coatings are strong dielectric properties, flexibility over a wide temperature range, resistance to UV rays, chemicals, thermal degradation, and corona discharges.

Figure [12]. Coated bushings at coastal test station in Greece.

Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, “Technical Review of RTV Insulator Coatings”

In ideal state, the low surface tension of RTV silicon does not allow insulator surface to become wet and water droplets are formed. Under pollution his silicone fluid emerges from the coating, creating a monolayer that prevents the dissolution of the pollutants, and holds them with a hydrophobic coagulating envelope. This behaviour undermines the creation of conductive layers, making large leakage currents and consequent flashover much less probable.

Figure [13]. Hydrophobicity of coated glass and ceramic insulators.

Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, "Technical Review of RTV Insulator Coatings"

Begun in the late 1960s on the U. S. West Coast, RTV coatings received their first widespread use in 1987. Initial problems have been minimal, but further improvements are targeted at increasing adhesion, prolonging resistance to leakage currents, and reinforcing durability against environmental degradation. Advancements also comprise applications processes simplification even when the insulators are energized.

3.3 Key Aspects

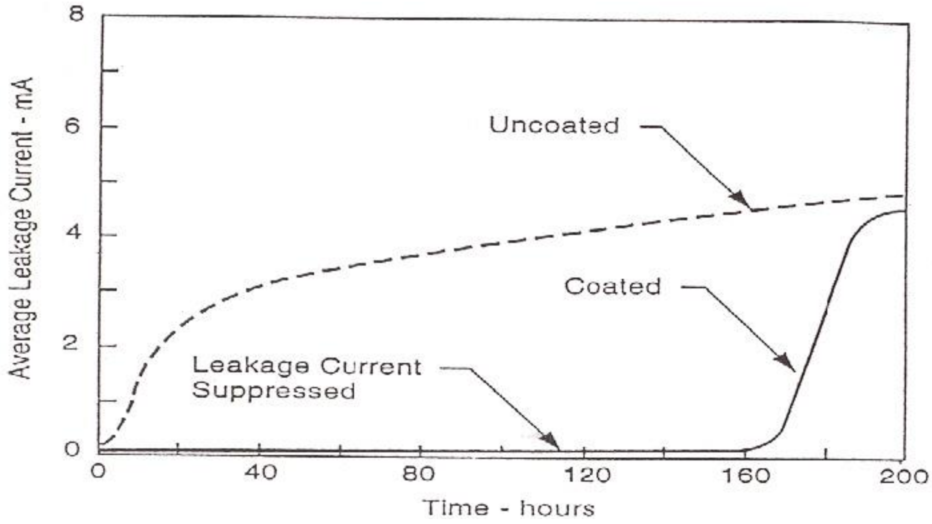
Formulation

Commercial RTV silicone coatings are a complex formulation that involves polydimethylsiloxane (PDMS) as the main polymer, which is reinforced with additives such as fumed silica and alumina trihydrate to provide better erosion resistance. Such systems also involve pigmenting dyes, extra fillers, cross-linking agents as well as condensation catalysts which improve adherence to insulator surfaces. Whole mixture is spread evenly in a carrier that serves as a solvent to transfer the silicone to the surface of the insulator. As the solvent vaporizes, the humidity of the ambient air initiates the vulcanization, leading to a tough rubberized coating. The vulcanization process is affected by such environmental factors as the solvent used, as well as temperature and air humidity. Several parameters of the polymer, type and number of fillers, and crosslink density in the coating significantly affect its electrical and mechanical properties including the adhesion to such materials as porcelain, hydrophobicity, and propensity to the development of leakage currents, which are the key to the performance and reliability of the system.

3.3.1 Suppression of Leakage Current

Several investigations have focused on the containment of the current flow by RTV coatings in salt-fog chambers and rotating wheel apparatuses. The appearance of leakage currents indicates a decline in the hydrophobic properties of the coatings.

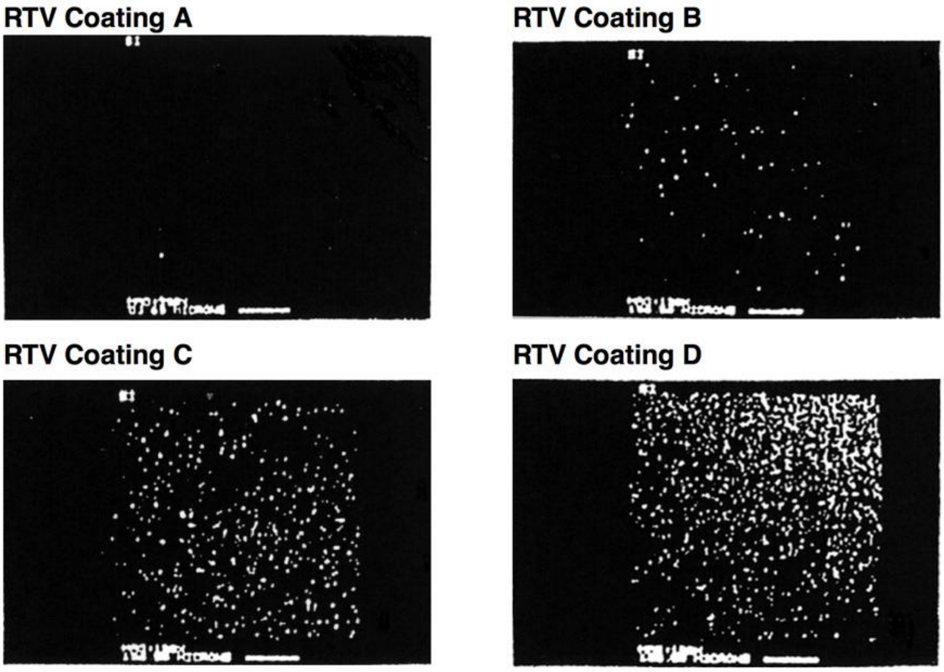
Figure [14]. Leakage current suppression of RTV-coated insulators.



Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, "Technical Review of RTV Insulator Coatings"

X-ray mapping is a method using a scanning electron microscope, which shows how low molecular weight silicone polymers find their way from deep within the coating to the outer surface. This translocation creates protective cover over pollutants, improving the surface ability to repel water. In the long run, moisture makes this protective layer to become reduced, the result that the coverage has many capabilities to suppress leakage currents. The retention period and the time of recovery of the wetting are determined by the particular formulation of RTV coating.

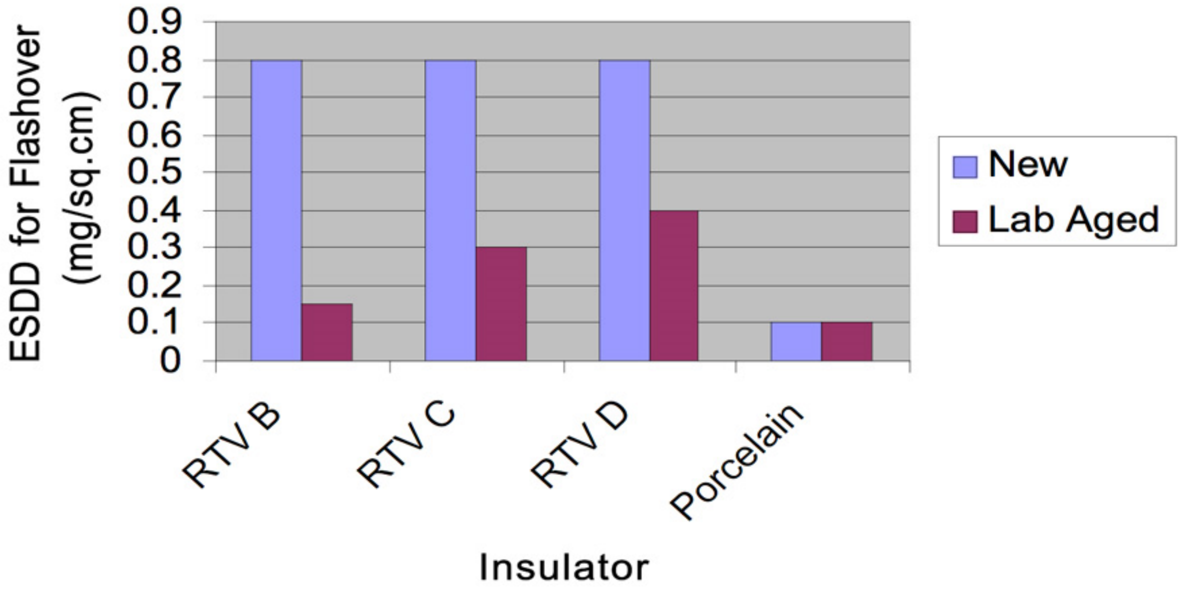
Figure [15]. X-ray mapping depiction of diffusion of LMW polymer chains responsible for hydrophobicity retention and recovery. Ability to maintain hydrophobicity for a longer time and regain it quicker (indicated by dots) after temporary loss is highest for RTV coating D, followed by coatings C, B and A.



Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, "Technical Review of RTV Insulator Coatings"

Figure 15 depicts the diversity in efficiency of various RTV coatings to decrease leakage currents. This influences the coated insulator's ability to withstand contamination under normal operating voltages, more especially after aging. In the new environment, the identification of this variability under polluted conditions is difficult. Coating D withstands higher pollution levels before flashover in comparison to Coatings C and B, as demonstrated by Figure 16, whereas a well-coated insulator, like Coating A, shows hardly any difference in case of aging.

Figure [16]. Illustration of ability of RTV coatings to withstand contamination under nominal operating voltage. Coatings were tested in new condition and after artificial ageing in fog chamber using a cycle shown to be representative of field ageing.



Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, “Technical Review of RTV Insulator Coatings”

The efficiency of silicone fluid to provide hydrophobicity is reduced by denser layers of contamination such as cement. Formulation of RTV silicone coatings involves fillers such as ATH to improve resistance to erosion and prevent tracking which however can reduce the hydrophobic character and hence the possibility of dry band arcing and the ability to control leakage currents.

3.3.2 Adhesion

The first use of RTV coatings for porcelain insulators under marine application highlighted the importance of adhesion. Erosion induced by salinity winds caused the failure of the coating as it peeled off, thus, exposing the underlying surfaces to damaging salt and moisture. The same requirement for robust adhesion is noticed in desert conditions and close to industrial facilities, for instance cement plants, where environmental particulates can speed up degradation.

Under these conditions, ineffective adhesion, or absence of adequate prior cleaning of the insulator surfaces may cause the coating to be removed in the course of routine high-pressure cleaning operations that are meant to wash away the accumulated debris. Therefore, proper adhesion does not only improve the durability of the coating but also its functional efficiency in preventing flashovers caused by environmental pollution.

Figure [17]. Peeling of coating due to poor adhesion.

Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, "Technical Review of RTV Insulator Coatings"

3.3.3 User Concerns

One of the key worries of users of RTV silicone coatings is their durability. Consumers rate long-term effective service life of these coatings that compensates the significant costs of insulator application and subsequent cleaning. However, the matters about the stripping and reapplication of the coatings are usually deemed as less important. The concern with the durability comes from the fact that labor expenses in relation to the system are quite high.

1. Life expectation

The life of an RTV silicone coating can be evaluated by its ability in preventing flashovers. Degradation of performance usually occurs in highly contaminated atmospheres or places where natural cleaning is not sufficient, and the contamination reaches a high level. Clean – as – necessary practice is effective in extending the life of a coating, but once it stops repelling moisture as good as an uncoated insulator, cleaning becomes unnecessary. A definitive end to the service of the coating comes when its hydrophobic properties do not sufficiently prevent the accumulation of pollutants so that maintenance levels are equal to those of the uncoated insulators. Though some coatings have been effective for more than a decade, studies into the longevity of silicone coatings have been inconclusive. But other special conditions such as corona degradation and polymer reversion can fasten coating failure, hence, the requirement for careful monitoring and maintenance strategies.

Figure [18]. Evidence of end-of-life of coating at polluted substation in China.

Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, “Technical Review of RTV Insulator Coatings”

2. Corona degradation

In certain designs of station posts, corona discharges at the energized ends may have an influence on the surface of porcelain insulators. Since the inert properties of porcelain protect it from any serious damage, the RTV silicone coatings on the insulators do not perform the same way. The corona discharges cause the coating to age due to an electrochemical process under exposure, which leads to such phenomena as cracking and hydrophilicity. This is one of the signs that the major surface parts of the coating lost their ability to repel water, and this means that the functional life of the coating is over, and it should be removed. Subsequently, the renewed application of the coating in these cleared areas is feasible. To prevent such type of deteriorations, appropriate voltage grading and hardware adjustments is very important. This prolonged preventive approach ensures the integrity and performance of the coated insulators.

Figure [19]. Degradation of coating at line end of coated string.

Source: INMR Enriching Technical Knowledge of T&D Professionals, 16 December 2022, "Technical Review of RTV Insulator Coatings"

3. Coating reversion

The polydimethylsiloxane (PDMS) degradation is inherent to the environmental exposure since depolymerization is accelerated by presence of moisture. Such hydrolysis results in non-specific cleavage of polymer chains and leads to a remarkable decrease in their molecular weight. These include factors such as temperature and electrical stress that may speed up this deterioration, which in turn may turn the polymer into a sticky substance, a state called reversion. This degradation happens when the coating is specifically porous, potentially from incorrect application or formulation. One method for evaluating reversion is a boil test. During the test, the enamelled porcelain is boiled in water for an extended time, and the softening is checked to see if the substance turns into gel.

3.4 Case Study: Coastal Insulator Maintenance in Peru

In the coastal parts of Peru, the minimal rains and the chronic salty winds have rendered the preservation of the electrical infrastructure a daunting task. Such environmental conditions promote salt deposit on electric system structures, particularly insulation performance and durability decline. Traditionally, the regular maintenance requirement for cleaning porcelain and glass insulators in order to avoid pollution-induced flashovers has been a major operational expense for the local power suppliers.

Approximately thirty years ago, the polymeric insulators were introduced in the hope that it would eliminate the requirements of frequent washing of insulators which were consuming huge expenses. Nevertheless, the desire for economic relief was very short-lived because these insulators started to have an incredible rate of mechanical failure in which most of it was caused by the brittle fractures. To solve this unexpected challenge, Red de Energia del Peru (REP) - Peru's transmission system operator (TSO) had to reconsider its strategy and think of other possible ways.

A major development occurred in 2009 with the advent of room temperature vulcanized coated glass (RTV) insulators. These insulators were particularly installed on lines in coastal problem areas, such as the Chilca region south of Lima. This change signalized an important twist in the attitude to the island maintenance when it comes to the Peruvian coast. However, one of these lines is captured in the International Nonlinear Mapping

Review (INMR) report, which calls attention to the recent installation and operational effects of new RTV-coated glass insulators.

Figure [20]. Region surrounding Chilca, south of Lima, experiences little rainfall and high levels of salt contamination.

INMR Enriching Technical Knowledge of T&D Professionals, 22 March 2024, "Applying RTV Coated Glass & Polymeric Insulators Under High Salt Contamination & Humidity"

This case study also provides an analysis of the environmental and economic effects of switching to RTV coatings in place of traditional polymeric insulators. It looks at the efficiency of this technological shift and evaluates its viability in addressing the stark coastal environment of Peru. The study is aimed at to create a comprehensive description of maintenance strategies evolution, emphasizing decrease in operating costs and increase in system reliability via creative use of RTV coatings.

3.4.1 Cost-Benefit Analysis

It is a typical example of cheap and effective environmental management, and it is RTV silicone coating adoptions in Peru, particularly in Chilca areas. They are coatings that have changed the traditional maintenance approaches due to their ability to withstand severe environmental conditions like high salinity and industrial pollutants.

1. Reducing maintenance costs

In polluted or coastal areas, the maintenance of electrical insulators was historically a problem that demanded expensive and frequent manual cleaning for the prevention of flashovers. Besides being capital-intensive, this traditional method involved the regular use of the chemical cleaners, hence making the operating costs of the approach higher. The use of RTV coatings immensely decreased these costs via elongation of cleaning intervals. RTV coatings properties such as durability and hydrophobic enable insulators to retain their performance and thus should not be washed frequently, consequently saving labor hours and others maintenance resources.

2. Long-term financial benefits

The financial analysis of the RTV coatings implementation shows long-term advantage mainly because of the reduction of direct maintenance costs and the extension of insulator life. While application costs of RTV coatings are higher compared to traditional methods, the investment in this product is cost-effective due to reduced ongoing maintenance. For instance, in areas where salt deposition is high, RTV coatings' function of keeping the salt and moisture from sticking to the insulator surface diminishes the possibility of contamination-induced degradation. It not only minimizes maintenance cycle but also prolongs the life of insulators, consequently, allowing postponing the capital expenditure related to their replacement.

3. Improved material efficiency

The RTV coatings application is also sustainable in the sense that it provides an opportunity for the sustainable use of materials, for the reduction of the amount of detergents and water used in the maintenance processes. This is due to the fact that the coatings are hydrophobic in nature and thus the adhesion of the contaminants is minimized hence lessening the impact of the chemicals and the water that may be required to wash them off. Furthermore, the longer durability of the coatings and their better performance means that they do not need to be reapplied as often, which in turn, means that the application of the material during the service of insulators is improved.

3.4.2 Economic Impact in Chilca

Coastal city Chilca is a fine illustration of economic advantages of RTV cladding. After the replacement of the common polymeric insulators with RTV-coated glass insulators, the local energy company realized a decrease in maintenance costs. The insulators coated with RTV showed better performance in resistance to severe coastal conditions, thereby, fewer service interruptions and the resultant cost cutting. The cost savings from these improvements were illustrated through the tables given below.

Table [1]. Comparative Costs of different Types of Maintenance

Manual Cleaning with a Rag

Materials, personnel, and equipment	Unit Cost (S/.)
Industrial Cloth	2.4
Lineman Staff	45
Vehicle Cmta 4x4 D/C	25.00
Personal nutrition Líniero	10
Supervisor	10
Supervisor Power	8.33
Cost per 220 kV chain	100.73

Hot Wash

Materials, personnel, and equipment	Unit Cost (S/.)
Treated water (demineralized)	1.65
Lineman Staff	4.17
Washing Equipment	23.61
Cart with 3000 l tanker	4.17
Líniero personal nutrition	0.69
Supervisor	5.00
Supervisor Power	0.97
Cost per 220 kV chain	40.26

Source: Chemist Doctor Emiliano Barisano, Technical Report, D. Lgs. n. 152/2006, EKD project s.r.l.

The table [1] compares the costs for two methods of maintenance of electrical insulators: the manual cleaning using industrial rags and pressure washing with hot water. The unit costs of all items needed in the maintenance processes are provided.

The table provides a list of items used in manual cleaning which includes industrial wipers, personnel and vehicles and the cost for each of them, emphasizing the direct cost associated with this conventional approach. Furthermore, it involves the cost of fuelling maintenance personnel and supervisors, adding to the total cost per 220 kV string.

The hot washing method, however, demands, in addition to demineralized water, a washing machine and a vehicle with a 3,000 litres tank. This approach is also accompanied with costs for the workers and their sustenance. The table indicates that the unit cost of the hot wash method is usually higher, mainly because of the specialized equipment used.

Data suggests that manual cleaning has a lower unit cost, but the result may not be effective and may need more frequent cleaning cycles. Hot water pressure washing may be more costly per unit, but it can provide a deeper cleaning that could help prolong the time between maintenance cycles. The choice between these methods would be based on the long-term cost-effectiveness, which took into account the frequency of maintenance needed to eliminate flashovers because of contamination.

Table [2]. Comparative analysis of the costs associated with two different insulation maintenance techniques

Silicone Plating of Insulators

Materials, personnel, and equipment	Unit Cost (S/.)
Industrial Cloth	2.4
Lineman Staff	45
Dow Corning 3099 Silicone Grease	80
Vehicle Cmta 4x4 D/C	25.00
Personal nutrition Líniero	10
Supervisor	10
Supervisor Power	8.33
Cost per 220 kV chain	100.73

Silicone Coating

Materials, personnel, and equipment	Unit Cost (S/.)
Industrial Cloth	2
Lineman Staff	50
Sylgard Silicone Coating	225
Additive	16.67
Motor compressor equipment	16.67
Vehicle Cmta 4x4 D/C	25.00
Personal nutrition Líniero	5
Supervisor	10
Supervisor Power	1.39
Cost per 220 kV chain	351.72

Source: Chemist Doctor Emiliano Barisano, Technical Report, D. Lgs. n. 152/2006, EKD project s.r.l.

The table [2] presents a comparative analysis of the costs associated with two different insulation maintenance techniques: silicone plating of insulators and silicone coat. The categories that are is compared are material, labor and equipment that are involved in each process and their unit costs.

The Silicone Application column contains cost of items such as the industrial wipes, line personnel, and silicone grease (Dow Corning 3099) in a per-unit cost format. Other items are the expenses of vehicles' cost and food for the line workers and supervisors. The total cost of maintenance for a 220 kV line using this technique is depicted.

The silicone coating column has similar line items except that instead of $/L you have specific coating materials such as Sylgard coating and an additive. The costs of the compressor, vehicle and labor power are also detailed. In this case, the unit cost of the coating application is higher than the unit cost of silicone application, which reflects a more resource-intensive process. In case the coating method is to be used for a 220 kV line, a total cost is also given which is significantly higher compared to silicone.

This the-table compared to the preceding one [1] differs only in details of the materials and total costs of one maintenance process. The former table might have discussed different maintenance types like manual cleaning and hot water washing as well as their wrought costs. On the contrary, this table concentrates on two silicone-based maintenance approaches, giving a much more detailed cost analysis and comparing direct costs of more specific maintenance procedures. The large difference between the total costs of these two methods would represent that the higher initial cost is an opportunity cost to the durable and efficient maintenance work conducted.

Table [3]. Different electrical insulator maintenance

	Cost per chain	Number of chains	Period	Quantity Activities in (8) years	Cost S/.
Cleaning	100.73	300	4 months	24	725,280.00
Washing	40.26	300	3 months	32	386,506.67
Silicone	175.39	300	2 years	4	210,466.67
Coating	351.72	300	8 years	1	105,515.67

(For the comparative table, maintenance for 100 suspension structures was considered)

A table [3] gives a cost comparison for various electrical insulator maintenance methods for a term of eight years of expenses over a set of activities. It gives the cost for each rope of cleaning, washing, application of silicone, and coating. Each activity is associated with a specific time interval: all the action types (except drying) occur with high frequency for the shower samples. Cleaning and washing are common, while applying and spreading silicone are less so.

It is the most frequent, least expensive per event, but accumulates the highest cost over eight years. Washing is somewhat less often and is done once in three months. The application of silicone and coating, although more expensive per event, requires much less frequent interventions: silicone application once every two years, and coating application once every eight years. The data shows that traditional cleaning methods cost less per task, but cumulatively are a lot more expensive due to the frequency they are needed. On the other hand, the higher cost of cladding at the beginning is economically justified by its durability and long life which makes it the lowest cumulative cost over an eight-year duration. This economic study is very important for informed decisions that are to be made concerning the most beneficial maintenance strategy of insulation in very contaminated and humidity environments.

The tables illustrate the detailed cost analysis which provides an intensive description of the financial particulars upon which the strategies of electrical insulator maintenance will be based upon in the coastal regions of Peru. These tables are quite helpful in representing the long-term economic advantages of using high-end maintenance technologies such as RTV silicone coatings, in comparison to conventional cleaning and washing methods.

The detailed cost analysis of manually cleaning, hot washing, silicone application and silicone coating reveals that while the new technologies like silicone coatings have higher initial costs, maintenance interventions fall drastically. Such frequency reduction not only reduces the operating costs in the long run, but also leads to improvement of system reliability and decrease in the environmental footprint, as less water and chemicals are used.

To sum up, the data approves of a strategic change to the greater utilization of RTV coatings as more durable and efficient ways of maintenance. Such way of doing things is not only efficient in terms of cost in the long run, but also complies with sustainable practices by reducing environmental degradation and resource conservation. These tables are useful for informative to the policy makers and utility managers about the unique challenges that come with the maintenance of electrical infrastructure in harsh coastal environments and thus help them in planning and implementing more effective maintenance strategies.

3.4.3 Technical insights on maintenance and hydrophobicity

Hydrophobic characteristics of RTV coatings are not lost even when they are kept under exposure of contaminants for longer time. This characteristic is necessary to eliminate the possibility for the humidity and salts to build up, which are the main source of flashover hazards. Moreover, the capability of regeneration of hydrophobicity by RTV silicone is one of the key factors of its efficiency, which actually reduces the overall environmental impact of frequent replacement or maintenance.

The implementation of RTV silicone coatings strategically in the coastal and industrially polluted areas of Peru represents a proactive way of dealing with economic and environmental issues related to service operations. The substantial savings of costs and the improvement of the environment are the values of investment in advanced coating technologies. These insights can be a source of future utility planning that advances the use advanced material solutions, making the process more economically efficient and environmentally sustainable.

3.5 Emissions Control

The impact on the environment from the process of the insulator coating, especially in the usage of RTV silicone coatings comprises several important aspects concerning emissions and resources use. In distribution, and transmission lines, insulators are widely used outdoor insulation. Yet, silicone rubber and other polymeric insulator materials exhibit aging process under the influence of long-term impact of pollution, UV radiation, discharge, temperature, humidity, altitude, and other natural and complex environmental and service factors, which allow them to lose their hydrophobicity as well as electric insulation properties. The operability drastic reducing greatly influences the dependability and safety of the power system.

This section provides the information from the technical report of EKD project s.r.l. which discusses the application techniques, emission control, and environmental precautions related to the RTV silicone coating process applied by them in their industrial situation.

Coating of insulators

Application of protective coatings – RTV silicone treatment and coating.

The VOCs that form during the coating phase will be caught and taken to a treatment plant and discharged through a stack located in the drawing with the designation of E04.

Emissions estimate

The RTV silicone used (see S.D.S.), before the spraying, has a solid part (68. The solvents yielded by the coating process and the drying process will be aspirate, treated in the abatement system and redirected to the outside through the chimney E1.

For quantification of the emission values, a whole work cycle is settled, which is based on execution times, methods of use, consumption of the products, volumes and temperature of the air, which is expelled, and substances during the work phases.

A painting time is assumed to be 60 minutes and the flash off/drying time is 3 days. Let's assume that in spray painting efficiency is approximately 90%, i.e. 10% of the paint product it is overspray which is driven out with the ventilation air. Considering the chemical - physical characteristics of the components, it can be assumed that already at the end of the coating, in addition to the overspray, even the most volatile components have evaporated at a rate of 95% of the VOC residue:

Residual VOC = total VOC - overspray VOC; the 5% remaining will be emitted in the next 3 days. So, the total mass of VOC involved in the emission into the atmosphere is equal to. So, the total mass of VOC involved in the emission into the atmosphere is equal to:

a. Overspray painting (95% of the residue)
b. painting (95% of the residue)
c. withering / drying (5% of the residue)

Tabulated are the calculations and emission values.

Table [4]. Emissions

Description	Unit	Data
Air Flow Rate	m^3/h	13,500
Quantity of Product Sprayed per Hour	kg	3,000
Duration of Work Cycle	minutes	480
Composition of Coating Product		
Product		
Paint	kg	3,000
Composition	%	100
%VOC	%	31.2
VOC Weight	mg	936,000

Description	Unit	Data
Total Product	kg	3,000
VOCs from Overspray	kg	0.300
Overspray VOCs	mg	93,600
Residual VOCs (Total VOC - Overspray VOC)	mg	842,400
5% of Residual VOCs		42,120
Emissions During Coating		
Coating VOCs (95% of Residual VOCs)		800,280
Drying VOCs (5% of Residual VOCs)		42,120
Total VOCs Emitted in One Cycle (60 min.)	mg	978,120
EMISSIONS DURING THE COATING PHASE		
Air Volume Expelled During Coating Phase	m^3	13,500
VOC Concentration (Overspray + 95% Residual VOCs)	mg/m^3	69.33
Filtration Efficiency	%	90
VOC Concentration at Outlet	mg/m^3	6.93
Mass Flow Rate	kg/h	0.094
EMISSIONS OF PARTICULATES DURING THE COATING PHASE		
Particulates in Overspray	mg	206,400
Particulate Concentration During the Cycle (1h)	mg/m^3	15.29
Filtration Efficiency	%	90
Particulate Concentration at Outlet	mg/m^3	1.53
Particulate Mass Flow Rate	kg/h	0.021

Table [5]. Abatement Plant

Section	Dry Abatement of Overspray Particulates	Active Carbon VOC Abatement
Nominal Throughput	13,500 Nm^3	13,500 Nm^3

Section	Dry Abatement of Overspray Particulates	Active Carbon VOC Abatement
Filter Type	Fabric mat	Cartridge
Filter Material	Fabric	Mineral-based activated carbon in cylindrical pellets
Filtration Efficiency	>90%	>90%

Source: Chemist Doctor Emiliano Barisano, Technical Report, D. Lgs. n. 152/2006, EKD project s.r.l.

The characteristics of filtration shall meet the requirements of DGRC no. 243 of 08/05/2015 as changed and supplemented by DGRC no. 465 of 18/07/2017 and in any event the above-mentioned systems for the abatement processes shall guarantee an abatement efficiency of over 90%.

Polymerisation cabin

After the cabin, the elements are then transported by the conveyor to a curing oven fired by an LPG gas burner, and the combustion fumes are emitted into the atmosphere through a chimney with the code Id 03 on the plan. The thermal capacity will amount to 0.100 MW.

The polymerization vapours will be led into the same paint processing plant and freed into the air by the same stack marked on the plan with the abbreviation E04.

Table [6]. List of Raw Materials and Auxiliary Items

Processing / Operation	Finished Products (Type)	Quantity	Unit
Laser Cutting	Flat Elements	800	kg
Plasma Cutting	Profiles	10	kg/week
Steel Sheet Cutting	Structures	200	kg

Processing / Operation	Finished Products (Type)	Quantity	Unit
Aluminum Sheet Cutting	Structures	100	kg
Steel Welding	Structures	20	kg/week
Panel Assembly	Structures	120	kg
Metal Element Coating	Structures	240	kg
Ceramic Insulator Coating	Ceramic Insulators	60,000	pcs/year

Table [7]. Raw Materials for Specific Processes

Processing / Operation	Material	Average Annual Quantity	Unit	Storage Method
Panel Assembly	Polyester Base Paint	44	liters	Covered Storage
Panel Assembly	Polysiloxane Base Primer	100	liters	Covered Storage
Panel Assembly	Polyurethane Adhesive	1,300	liters	Covered Storage
Metal Element Coating	Polyurethane Resin Paint	3,000	kg	Covered Storage
Metal Element Coating	Catalyst	600	kg	Covered Storage
Metal Element Coating	Paint Thinner	150	kg	Covered Storage
Ceramic Insulator Coating	RTV Silicone	5,000	kg	Covered Storage
Ceramic Insulator Coating	Diluent	220	kg	Covered Storage

Source: Chemist Doctor Emiliano Barisano, 29 November 2023, Technical Report, D. Lgs. n. 152/2006, EKD project s.r.l.

The tables provide an organized system of material types and quantities used in different manufacturing processes and their storage means, which depict every lean concept of resource management and inventory control.

From the predicted consumption, considering the VOC content of paint products and solvents and thinners, we calculate. From the predicted consumption, considering the VOC content of paint products and solvents and thinners, we calculate:

Coated product consumption: 80% paint - 16% hardener - 4% thinner - 3750 kg/year average % VOC - 0.36. 9

Total VOC: 1384 Kg/year

RTV silicone consumption: Mass of VOC – 5000 Kg/year average % VOC – 31. 2

Total VOC: 1560 kg/year

RTV thinner silicone consumption: 220 kg/year, average percentage of VOC is 100.

Total VOC: 220 kg/year

TOTAL VOC: 140 lbs/year however the weight is thrown. 164 tonnes/year.

It should be mentioned that the emission values given in the previous tables are estimates and they are calculated by algorithms developed by Dr. Chimico Emiliano Barisano, and his related variables are based on literature data, safety data sheets of raw and auxiliary materials, technical data sheets of the abatement plants, and where available, hourly mass flows of raw and auxiliary materials, processing times per phase accompanying the

Since the parameters listed are very variable, the values of emissions that the calculation gives in terms of concentration and mass flows are only indicative and should not and should not represent the authorized values.

So, tables of the emissions for the authorization request are suggested in that regard.

Table [8]. Emission Point E4 Details

No.	Description	Details
1	Origin	RTV Silicone Coating
2	Equipment Involved	Coating and Drying Cabin
3	Nominal Capacity	13,500 Nm^3/h
4	Duration of Emission	8 hrs
5	Emission Frequency	Continuous, 24 hrs
6	Continuous / Intermittent	Continuous
7	Temperature	20°C
8	Pollutants Present	Total Dust, VOCs, other
9	Pollutant Concentration in Emissions	Total Dust <3 mg/Nm^3, VOC <50 mg/Nm^3, etc.
10	Mass Flow of Pollutants in Emission	Total Dust 0.39 kg/h, VOC 1.950 kg/h, etc.
11	Emission Stack Height	10 m
12	Chimney Dimensions	Diameter 500 mm, Height from base 1.1 m
13	Chimney Construction Material	Steel
14	Type of Abatement Equipment	Activated carbon filters
15	Emission Point Coordinates	40°58'32" N, 14°58'50" E

Source: Chemist Doctor Emiliano Barisano, Technical Report, D. Lgs. n. 152/2006, EKD project s.r.l.

The designed filtration and abatement systems to meet environmental requirements to have emissions within the permissible levels. This method greatly decreases the influence of the pollutants on the eco-system.

3.6 Results

Environmental and economic consequences of the RTV silicon coating technology used in insulation production, described in the EKD s.r.l. Project. report, depict a sophisticated method in achieving operational effectiveness and environmental responsibility. Introduction of high-efficiency particulate filters (HEPA) and activated carbon systems allows to cut volatile organic compounds (VOCs) and particles release complying with tough environmental requirements. This also reduces the environmental footprint of the business and promotes green manufacturing practices.

Regarding economical aspect, the initial costs concerning advanced abatement systems are neutralized by the long-term savings due to the reduction in the fines, improved relations with society and eventual tax benefits for compliance. Operational efficiencies including low downtime and high equipment life also add to the economic reasons for such the investments. An effective resource management characterized by detailed green control and material utilization optimization cuts down on wastage and material cost factors responsible for competitive product prices.

In the future, the continuous investments in the research and development of green materials and search for renewable energy sources could lead to better and economic results. These initiatives would facilitate further cutting down of VOC emissions and thus diminishing the coating processes' impact on environment.

To sum up, the practices used by EKD Project s. r. l. offer an example of environmental protection being incorporated into the corporate strategies, which guarantees sustainability and profitableness. This way of proceeding does not only remove ecological pressures, but also reinforces a company's leadership role in the environmentally friendly production in the coatings industry.

CHAPTER 4

EKD PROJECT CASE STUDY

4.1 EKD Project: Company Overview

ekd project (EKD) was established in 1999 as ekd Italy, a traditional engineering company involved in the study, research, design, and development of new mechanical and electrical systems. The review of the history and mission of EKD is given, its competence, and the innovative technological solutions that are used in the process of the improvement of the quality of the RTV coating in sense of the thickness homogeneity, adhesion and hydrophobicity. In addition, such solutions ensure safety of workers, silicone waste and environment pollution reduction.

It is situated in the South of Italy and works in design and manufacturing of industrial automation, automotive sector, application of RTV silicone on Insulators by automatic systems (realized in house).

In this regard, EKD (Engineering, Know-How, Design) stands for being able to design and implement integrated solutions that come from the needs of each customer with a consolidated technical/engineering product and process expertise. The production reality consists of the following business units:

Engineering: development, research, and implementation of innovations in products and processes.

Coating: Coating of high voltage insulators and components for power lines and subtraction with RTV silicone.

Manufacturing: making of prototypes and production of parts and assemblies primarily for the automotive industry.

Research and Development: the research and implementation of new solutions for the development of automatic systems and cutting-edge products, consulting research centres and universities.

It has a team of 60 persons so far, the team contains of technicians, skilled workers, engineers, and employees. The team works with Universities and Consultants. The personnel comprise mechanical, electric, and electronic technicians and engineers, specialized in automotive area, reverse engineering, rapid and virtual prototyping, and machinery and plants design and construction.

The management is dependent on an essential contribution from a large female part, which has always been in the context of the company, to imbue the management actions with force and vitality.

EKD has always believed in the importance of giving space to young people and new generations: The company has been dedicated to the education of promising youth for many years. The development of the skills of the 'new generation' represents a two-way exchange: the organization provides an avenue for skills' acquisition; they offer zest, zeal, fresh ideas, and creativity. This is why they have been working with schools and training organisations for years and including students in vocational training by means of offline classes, internships, and apprenticeships. The competence developed in RTV silicone coating, automatic mobile systems for HVI RTV silicone coating are demonstrated.

Due to its experience and the inherent desire to develop business process robustness and the technological novelties EKD organized International Workshop in Avellino on 11th – 12th October 2018, aimed to analyse the current situation and to make an outlook. The event was attended by more than 50 participants representing 20 Countries from insulators manufacturers, RTV silicones producers, utilities, RTV silicone coating service providers, consultants. This paper outlines the elements of the R&D activities to enhance the quality of HVI RTV coating and the prospects.

In the end, conclusions are made about the necessity of the process standardization coating.

4.2 Evolution in Automated Pre-Coating Techniques

During the last 35 years, several types of RTV silicone have been introduced into the area of high voltage insulation, and from the 90s, the first applications at industrial level have started. However, the development of application techniques was slower than advancement of silicon products. The primary applications were executed using crude methods and ignoring essential factors associated with the high voltage environment.

Recently, pre-coating solution, coating process performed in factory on new insulators, is actually being considered as one of the possibilities to be taken for insulation solution in harsh environment, either for new installation or to substitute insulators with poor performance. Exponentially, they are used even much more and today it is estimated that there are more than 7 million pre-coated cap and pin insulators are installed on the overhead lines around the world. The same solution is also widely used for insulators of a power station.

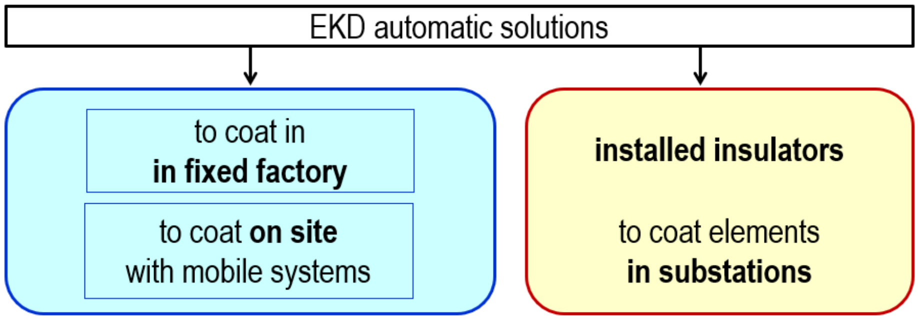
The paper discusses the pre-coating process development from manual to a complete automatic solution. Fully automated pre-coating system improves the quality and productivity thus ensuring the uniformity of the coating thick-ness and repeatability of the process. Moreover, a system of automatic operation operates in the clean environment due to which a silicone waste and contact of the operators with the chemicals is minimal, what results in environmental pollution, production costs and risks for workers.

4.2.1 Coating Automatic Solution

EKD was contracted by SEVES – Sediver to apply RTV silicone on its glass insulators for TERNA, Italian leading electrical utility more than 18 years ago. Initiating from the late 2004, EKD used to apply silicone coating manually in the beginning. Having finished a first series of around 1000 pieces, EKD initiated a creation of automated solutions that would ensure more efficient application of RTV silicone to different types of insulators. This development was led by the aim of minimizing the residue of the product, cutting down the number of human resources, increasing productivity, and maintaining a constant quality of covering.

From 2005, EKD has coated over 3,000,000 overhead line (OHL) insulators. This involves delivering over 1,600,000 number coated insulators to TERNA for use in Italy and over 50 countries globally, respectively. All such insulators have proved the severe tests and are installed rendering good results.

Figure [21]. EKD Automatic Solutions



Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

The technological advances of EKD have not only made the process of coating more efficient but also have been adjusted to requirements of critical installations. In 2008, EKD has applied its robotic systems to coat over 3,500 insulators of the substations located in highly polluted and coastal areas of Italy, which are washed at least twice a year, with fully automatic systems. TERNA, Enipower, ABB, Enel in Italy and several other major utilities and companies in other countries were the clients for these projects, which demonstrate EKD's willingness to deal with particular environmental issues.

EKD still strives to develop better and new coatings solutions indicating its commitment to technological innovation and excellence in insulators servicing in both awaiting and installed states.

Figure [22]. Installations in Terna

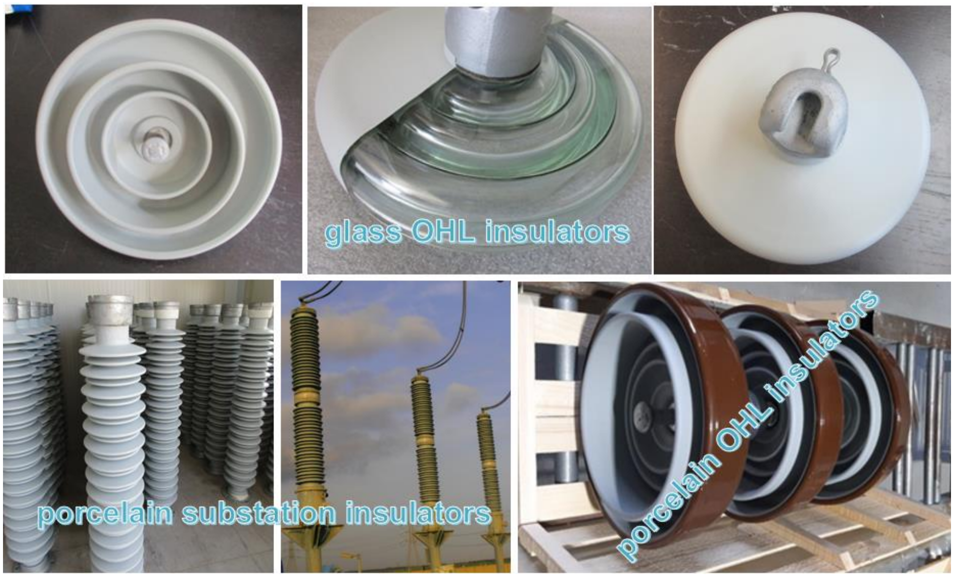
Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

4.2.2 Advanced Coating Techniques for Insulators

Their system is technically designed to evenly coat different types of silicone RTV coatings resulting in a uniform finish conforming to different quality standards of their clients. They give precedence to the process repeatability in the homogeneity of all items by the uniformity of the product batches. A major part of their activity is in reducing over-spray and preventing silicone and solvent emissions in the environment, which just goes to show how they are committed to environmental protection and safety of the workers.

With a large production capacity, they can meet the tight delivery schedules demanded by some customers, thus, satisfying customers' needs in time. In addition, their advanced coating technology allows targeted insulator area application without the need of masking the neighbouring sections. Such method allows to get the uniform thickness of the covering, even in very thin layers, over any surface of the insulator. This improves the product functionalism and life, which proves their technology advanced ability in insulator coating solutions.

Figure [23]. Some types of insulators



Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

4.3 SWOT Analysis

In the dynamic scenario of the global power transmission and distribution industry, the use of Room Temperature Vulcanizing (RTV) silicone coatings on electrical insulators is considered as a major technological innovation that targets at improving the efficiency, reliability, and life of electrical systems. The player in question is EKD Project SRL, and it was set up in 1999, and it is the most important player. It provides innovative solutions, drawing the attention to the most difficult problem of insulator maintenance in polluted or aggressive environment. This complete SWOT analysis endeavours to critically analyse EKD's standing within the industry, its internal capabilities and the external forces that are in control of its operational environment. The analysis represents the foundation for comprehension of EKD's opportunities for development, creativity, and sustainability in accordance with the dynamics of electricity utility field and other areas.

Strengths

Innovative Technology Implementation: Automation processes of the RTV silicone coating that are the forte of EKD lead to increase of efficiency, uniformity and at the same time, make the company an innovator. This technological leadership is a demonstration of EKD's approach to going beyond conventional ways and thus leading the way for improved insulator's performance and reliability.

Comprehensive Expertise: Covering engineering, coating, manufacturing, and R&D, EKD's wide range of knowledge helps in the complete implementation of projects from idea to reality. This interdisciplinary concept has an enabling role in the process of creating innovations and solutions of the highest quality that fulfil detailed requirements of the world market.

International Reach and Recognition: The global presence of EKD, which can be seen in more than 50 countries, confirms its high-quality standards and ability to satisfy various market needs. This global recognition further affirms EKD's reputation as a reputable ally in the electric utility industry globally.

Environmental and Safety Commitments: Environmental sustainability and worker safety commitment is demonstrated by implementing strategies aimed at siloxane waste minimization and occupational hazard reduction, what reflects EKD's commitment to corporate social responsibility. There values are in tune with the increasing focus of the global business environment on environmentalism and social responsibility.

Strong R&D Orientation: The collaborative initiatives of EKD with academic institutions and research centres reflect its focus on continuous improvement and innovation. By concentrating on R&D, this strategic approach guarantees that EKD continues to be a leader in the development of the best technological inventions in this industry.

Weaknesses

Specialization Risk: Specialization in RTV silicone coatings and related technologies is both a distinguishing characteristic and a risk factor of EKD in that it is associated with adaptability and diversification risks. EDK's competitive advantage could be threatened by rapid technological changes or the appearance of new materials, which has always been the case.

Market Dependency: The operational concentration of EKD on the utility sector especially high-voltage insulators makes it sensitive to sector-specific fluctuations. Opposite economic trends or changes in energy policy may affect demand for EKD's products.

Challenges in Scaling Production: The custom nature of EKD's solutions and the dependence on specialized equipment can limit the ability of the company to quickly adapt production to market demand. This constraint can impact the agility of EKD in seizing emerging opportunities.

Opportunities

Growing Renewable Energy Sector: The substantial transformation to renewable sources of energy on a global scale, requiring large-scale electrical infrastructure development, offers EKD a great number of chances to apply its innovations in new and growing markets.

Technological Advancements: The constant development in the field of materials science provides EKD with opportunities to create innovative coating formulations and methods of application that may become industry standards.

Partnerships and Collaborations: Forming strategic partnerships with other industry players and academia could stimulate radical innovations that would improve the product line and its competitive edge.

Threats

Intensifying Competition: The introduction of new players having advanced technologies or cost advantages poses a danger to EKD's market share and profitability. To stay in front, constant innovation and strategic market placement is necessary.

Supply Chain Volatility: Unpredictability in both availability and pricing of critical inputs, for instance silicone, might render production costs and timelines erratic, thus reducing the operational efficiency and profit margins of EKD.

Regulatory Changes: Continuous changes to EKD's processes and products are due to dynamic environmental regulations and industry standards in various jurisdictions. Adapting to the changes in regulatory frameworks would require significant investments and adjustments.

4.4 Business Model

Core Value Proposition

The key to the business paradigm of EKD Project SRL is to propose the new efficient, durable, and reliable solutions for improvement of the electrical insulators using the RTV silicone coatings. This proposal has many dimensions, being addressed not only to the operational requirements of the electric transmission and distribution sector but also highlighting the demands of environmental stewardship and occupational safety. EKD products are designed to improve operational efficiency, standardize application, and reduce the need for regular maintenance benefiting utility and other stakeholders in the energy sector that need to reduce operational interruptions and extend the useful life of their infrastructure assets.

Customer Segments

Insulators, electrical utilities and the operators of the electrical transmission and distribution systems are some of the main clients of EKD. In satisfying the needs of these four but interconnected industries, the company is involved in an essential yet very specific segment of the world's energy market. Through the delivery of specialized products that adhere to the specific requirements of the diverse markets and environmental regulations, EKD is indeed capable of addressing the complex requirements of its customers.

Channels

Firm proceeds with a direct interaction model, using its online trail together with the industry's existing networks to connect with both potential and existing clients. By means of channels like technical seminars, industry-related seminars, and joint research initiatives, EKD promotes relations with the participants in the energy sector. This approach allows for an understanding of their needs and limitations. Thereafter, this approach enables the firm to tailor its products, ensuring they are in line with its clients' requirements and the current trends within the industry.

Customer Relationships

The customer relations culture of EKD is based on the foundation of competence, reliability, and team spirit. Adaptable solutions and continuous communication with its clients are what EKD banks on to guarantee the relevance and adaptability of its offerings to the dynamic needs of the energy sector. The company's persistent support of research and development activities emphasize the company's dedication to long-term partnership relations rooted in pursuit of technological innovations and ecologically responsible methods.

Revenue Streams

The income structure of EKD is mainly based on providing specialized services in coating and producing automated systems for application. This includes that proprietary equipment is commercialized, alongside consultancy and maintenance services related to application of RTV silicone coatings. The approach that the organization applies is the innovation and the customization of its solutions, which enables the use of premium pricing strategies reflected in the added value that these solutions provide in terms of improving performance and efficiency of operations.

Key Activities

The operational activities of EKD are primarily characterized by generation, development and realisation of solutions related to the RTV silicone coatings. Among these activities is the implementation and production of automated application systems, as well as research and elaboration of new materials and methods. Moreover, firm offers specialized consulting services. Cooperation with academic establishments and industrial partners in joint projects increases the innovative potential of EKD, widening its range of technological advances.

Key Resources

The basic assets of the company are a group of engineers, technicians, and experts in the niche, whose shared experience is the basis of the company's technological and innovative power. Moreover, the company facilities of production as well as the R&D, equipped with the state-of-the-art technical equipment, are crucial in the creation and production of the proprietary machinery and coating solutions.

Key Partnerships

The commercial approach of EKD is supported by the alliance of the organization with the scholarly bodies, research institutions, and some critical industry players. These types of synergistic cooperation stimulate the propagation of knowledge, initiate innovative processes, and lead to the creation of advanced solutions specifically tailored to the sophisticate needs of the electric power industry.

Cost Structure

The general overhead costs that are directly traceable to the operation of EKD include costs on research and development, costs of manufacturing and production, and marketing and customer relations costs. Moreover, one can point out the appropriations for technological changes, and the enhancement of the workforce as fundamental aspects of the financial structure of the EKD, which is critical for achieving the organization's market competitiveness, as well as promoting the innovation.

The business model of EKD is a synergy of technological creativity, deep sectoral expertise, and commitment to ecological sustainability. Being focused on the development of customized interventions for the electrical utility domain, EKD not only helps to resolve the critical operational dilemmas but also relates to the broad target of environmental protection and the minimization of energy consumption. The continuous striving for the advance of technology, combined with a deep understanding of customer demands, identifies EKD as the foundation entity in the global system of energy infrastructure.

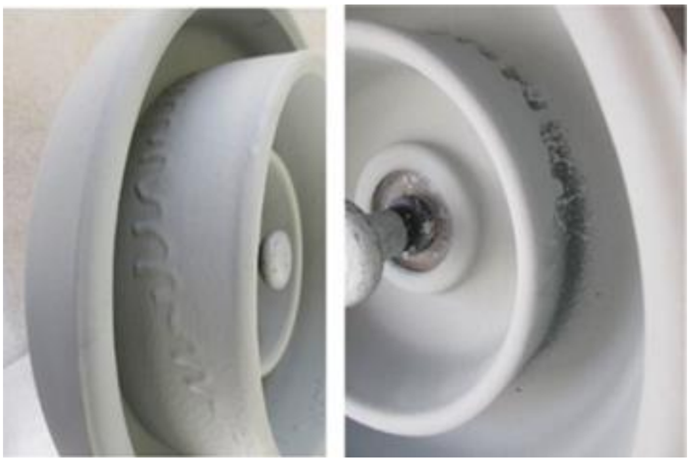
4.5 Challenges of Manual RTV Coating Applications

At first, upon the silicon supplier direction, the application process was done manually, with the product placed on a stand, and the operator who used a spray equipment to do the application (see figure 24). The quality of the product and the productivity of the operator's manual/skill were considerably influenced. Many pieces were reworked for non-compliance: lack of homogeneity and controllability of the thickness of the silicone layer, as well as inaccessibility of some areas of the product that were not coated. The curing was performed in big areas. Typical non-compliance obtained from manual applications is shown by Figure 25. More than 40% of the method resulted in the waste of silicone, what leaded to the safety and environmental costs of the workers. The output was very poor (140-300 pcs every 8 hours), and the fulfilment of delivery dates demanded by customers was not possible.

Figure [24]. Manual coating – 2004

Rendina, R., et al. "First experience with factory coated glass insulators on the italian transmission network.", 2007.

Figure [25]. Example of non-compliance caused by manual application of RTV silicone. On the left, lack of coverage in the recess, difficult to access manually. On the right, insulator with significant silicone thickness variation.



Rendina, R., et al. "First experience with factory coated glass insulators on the italian transmission network.", 2007

4.5.1 Automatic Pre-Coating for Insulators

2005 – First Semi-Automatic System: The first machine had a semi-automatic spraying system and was produced in a more controlled area, which only require the control of environmental characteristics, which decreased the unevenness in the thicknesses, and increased the capacity compared to manual application (up to 450 pcs every 8 hours).

2008 – Second Semi-Automatic System: The following phase was to enhance the quality of the application. Application tools were also newly added to increase coverage and uniformity in hard-to-reach places. The output capacity was boosted to 700 pcs per 8 hours.

2011 – Third Automatic System: After a radical reconfiguration to the facility lay out for the purpose of increasing production capacity to 1,000 pcs every 8 hours, washing system, transfer system and curing area where included (see figure 26)

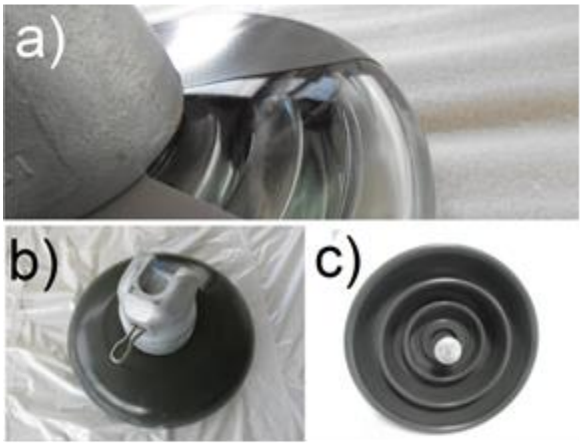
Figure [26]. Elements of industrial system dedicated to HVI automatic RTV coating.

Rendina, R., et al. "First experience with factory coated glass insulators on the italian transmission network.", 2007.

2014 – Fourth Automatic System: This amendment has resulted to a more perfection with the decrease of all volumes. The operator's mission is confined to loading and unloading operations, while the coating area is supervised by qualified technicians who mainly monitor the start-up phase as well as the correct execution of the process. The process is carried out in a limited area with controlled access, minimizing the contact between the technician and the RTV silicone. This design modification enhanced once again the production capacity (1200 pcs every 8 hours) and minimized the labor force. This automatic system gives very uniform thickness and has decreased non-compliant products.

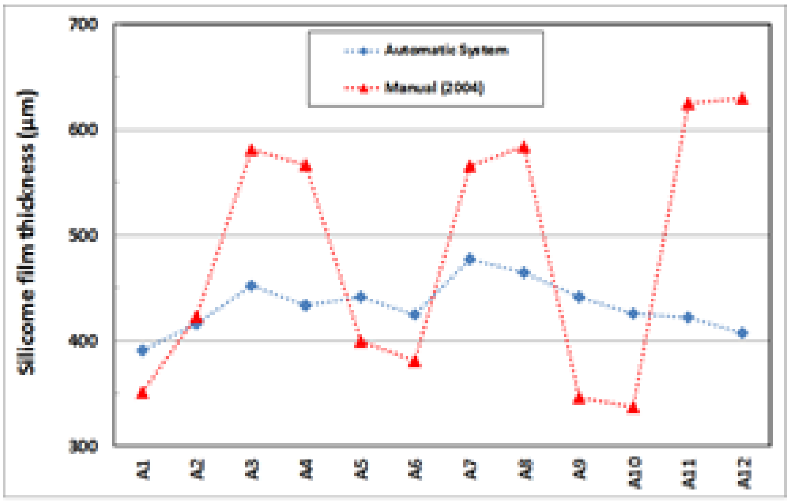
The figure 27 indicates even coating surface without any presence of uncovered areas, no dirt nor bubbles, no drops, no silicone accumulations applied via last automatic system. Silicone thickness variation as measured in figure 28 on 12 samples removed in radial direction from the top half of a couple of coated isolators of the same kind in 2004 and 2014. In 2004 (by manual process) the thickness variation is much higher than in 2014.

Figure [27]. OHL insulator coated. (a) Part of the coating was removed to show the uniform thickness achieved by the automatic coating system. (b and c) Similar insulator seen from different sides.



Rendina, R., et al. "First experience with factory coated glass insulators on the italian transmission network.", 2007.

Figure [28]. Thickness variation in radial direction on top half of the insulator, showing the reliability of the automatic system.



Rendina, R., et al. "First experience with factory coated glass insulators on the italian transmission network.", 2007.

2018 – Fifth Automatic System: The spray booth is fully automated and controlled environment, with PLC Systems (Programmable Logic Controller) that ensures uniformity of the thickness and of each coating lot, thanks to repeatability of the process; for each type of insulators and of RTV silicone there is a specific program, also considering customer specification requirements. One skilled worker is the head, who oversees set up, of checking the start-up production and control an appropriate work of the system, respecting the set-up parameter.

Cleaning area is clean and automatic of the system to ensure the surface to be coated should be clean and dry to prevent glass contamination before the coating.

The curing area is an environmental control system to ensure the proper curing of the RTV silicone, taking into account silicone TDS, and is designed to prevent coating damages during the handling of the product This system, once more, increased the production capacity (up to 1,300 pcs every 8 hours).

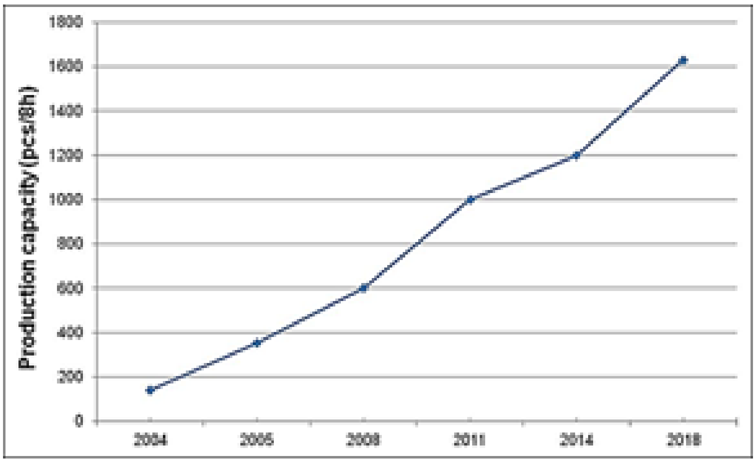
2019-2020 – Next Automatic System: Having full automated solutions that resulted in more advantages. This also decreased silane utilization and the number of necessary workers.

The new solution is able to apply the RTV silicone both on OHL and Substation Insulators, keeping the same spray booth.

These new solutions are researched and implemented in sections that are quick to assemble and portable. The last system also provides the opportunity of production capacity to rise by 1,400 pcs per 8 hours (see figure 29), being limited by the minimum skin over time of the RTV silicone used.

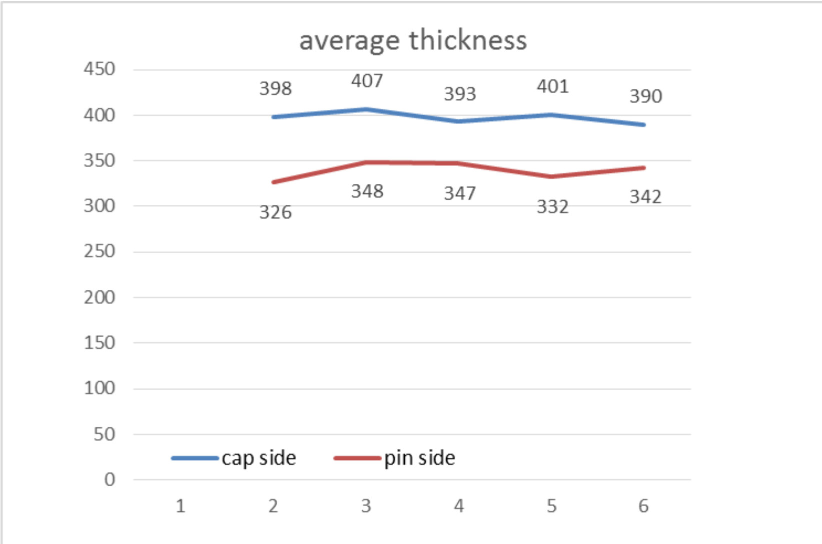
Homogeneity of the production batches is increased, which decreases the standard deviation of the average thickness (as displayed in figure 28).

Figure [29]. Production capacity increase over the years with different evolution of the automatic systems.



Rendina, R., et al. "First experience with factory coated glass insulators on the italian transmission network.", 2007.

Figure [30]. The graph above shows the average thickness measured (in µm) on no. 5 different coated OHL cap and pin insulators on upper and bottom sides. The standard deviation is very low.



Rendina, R., et al. "First experience with factory coated glass insulators on the italian transmission network.", 2007.

4.5.2 Automatic System for Long Rod Coat

In late 2007, the EKD constructed the first prototype of robot.

With such solutions, between 2008 and 2012, applications for various clients such as TERNA, Enel, ABB/EniPower were done. During the period from November 2011 to May 2013, EKD studied in partnership with Terna and improved its Robot for testing and validating its use on Post Insulators in operation in the vicinity of live lines. EKD has already passed with positive outcome all certification tests and concluded the activities at Brindisi Sud (in 2013) in a very short time, in full compliance to requirements of the Terna specifications. EKD have researched and entered into prototyping of new solutions that bring more improvements to the CRP with regards on productivity, quality, and worker safety. The new system will also be lighter and more universal, as it can cover insulators mounted on the apparatus on which accessibility of platforms and equipment for sprays are restricted.

Engineered Solutions

The ongoing process of optimization of operations, the plants adaptable to various situations as well as customizing of products and services make it possible to supply a comprehensive range of services that are all the way from application at the end of the insulators production line, to application on site, always with product efficiency and quality.

Solutions of EKD is in Automatic Application System, designed and made in house. Below are de-scribed the different systems and the type of insulators each system is able to coat. So far, over 2. Over 2 million OHL insulators (delivered to over 50 countries in the World) and installed at over 1500 post insulators have been automatically coated. The characteristics of the systems are:

- uniform application of a variety of different RTV silicones on high voltage insulators according to several Customers' specifications.
- repeatability of the process and uniformity of the batches.
- a decrease of overspray respecting the environment and the health of workers.
- great production volume to meet the short delivery times that some Customers demand.

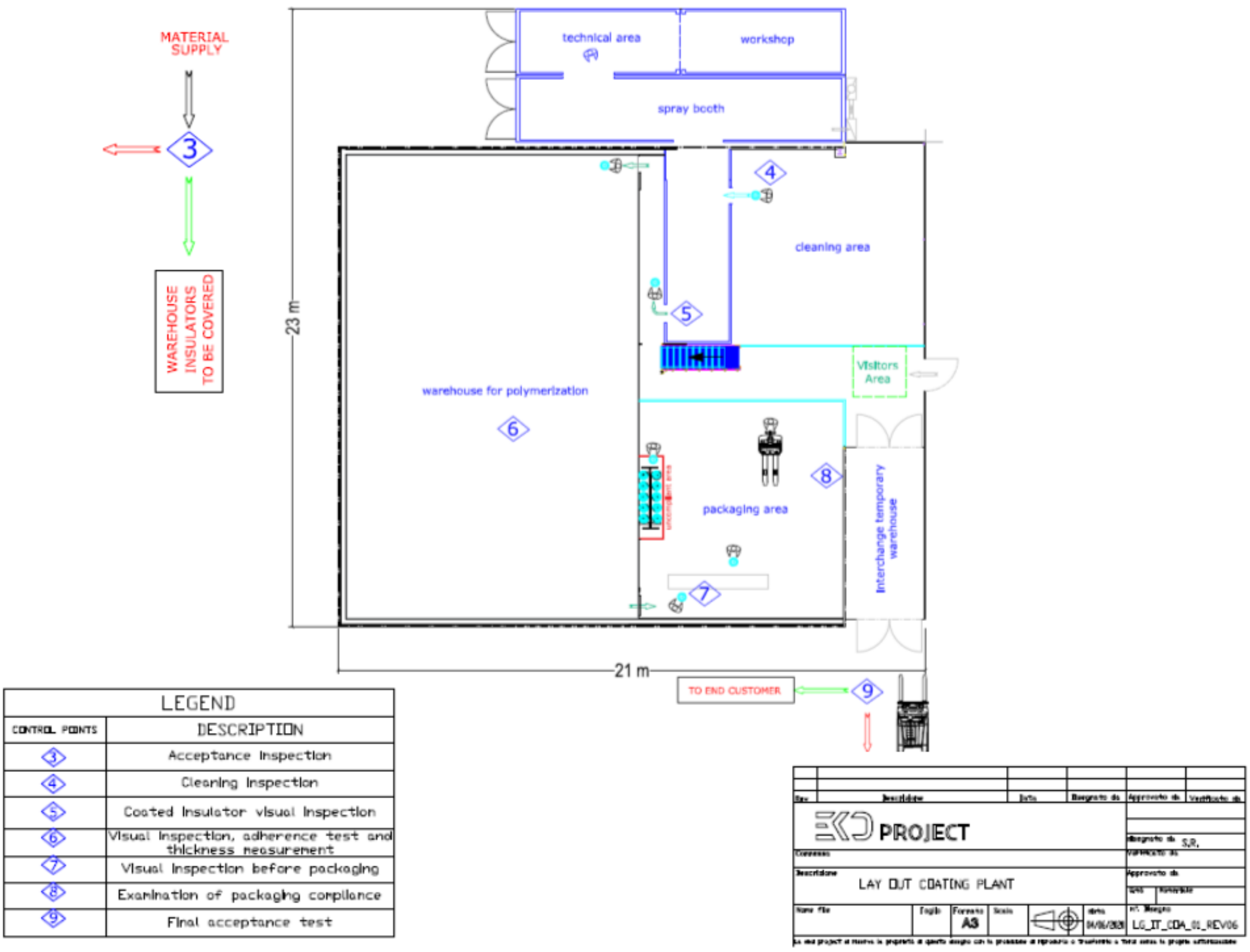
4.5.3 EKD Automatic CFF (EKD's Coating Fixed Factory): plan the construction

EKD's Fixed Factory: Application is made in a pre-determined Factory. Equally, it is best used for a great production requirement, provided there is enough equipment and facility, bigger curing area and all trained skilled workers were available. However, the expenses of packaging and transport of the final insulators are higher than in other described options. In particular, coated insulators should be protected with special packing, which will prevent the damage of the RTV silicone layer, during long distant transport.

Spray booth is full automatized and controlled environment, with PLC Systems that ensures the uniformity of the thickness and of each lot of coating, thanks to process' repeatability. Each type of insulators and of RTV silicone has its specific program, considering customer specification requirements.

One highly skilled operator is responsible for the set-up of the spray booth, start up production checks, and system functionality checks as well as that the setup parameters are being followed.

Figure [31]. A schematic of EKD's Coating Fixed Factory



Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

4.5.4 EKD Automatic CMF (EKD's Coating Mobile Factory): Salient Features

EKD's Mobile Factory: This novelty, in-built for quick transportation and painless setup near the customer's warehouse or another strategic point near the insulators' target, greatly simplifies the processes. Support tasks are done by local labor and this helps to reduce the costs of equipment transportation and set-up expenses and also greatly reduces packing expenses associated with shorter haulage distances. As a result, it allows the finished products to be delivered directly to the storage facility of the customer or the assembly team, eliminating the packing costs of the final products.

The dimensions and design of the Containerized Mobile Factory (CMF) are customized for daily insulator coating requirements. This mobile automatic system for cap and pin insulators consists of modular containers that allow the relocation of the system as a whole or its sections. Its mobility makes it possible to be quickly used at any place.

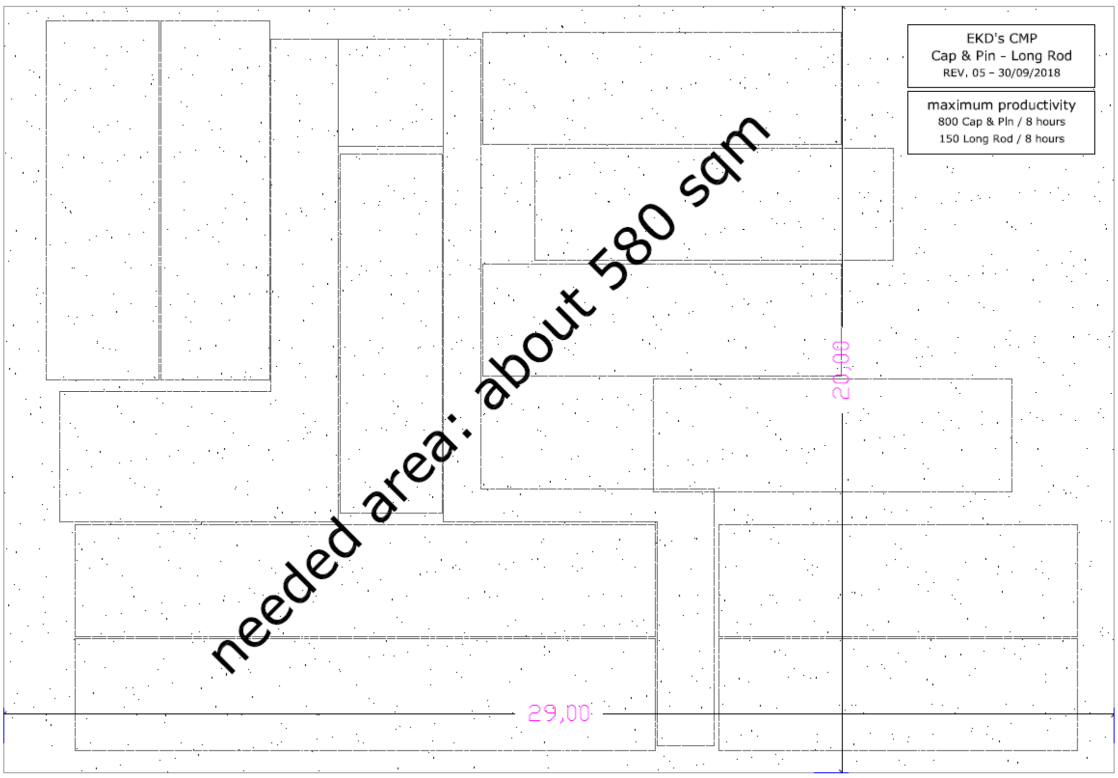
It is furnished with a completely automatic environmental controlled paint booth that is similar to the ones found in stationary factories and integrated with Programmable Logic Controller (PLC) systems. The systems provide thickness uniformity of each coating batch by repeating the process accurately. A technician EKD is in charge of the booth's set-up, attends the beginning of the production, and follows the system's functionality and compliance with the setting parameters. Though the spray booth provides production capacity comparable to what can be achieved in a permanent facility, it is worthy to note that the curing area size will limit the actual output.

Figure [32]. Coating Mobile plants parts

Source: P. Graziosi, M. Morella, S. Simonluca, 2019, “*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*”

EKD's Mobile Plant: Mobile in concept these fully automated spray systems, containerized, are moved from one work area to another by truck up and down the line, in places with no infrastructure whatsoever. The systems are capable of coating insulators near their positioning towers, which significantly speeds up the process. Workers are told only to unbox the insulators, to put them onto the system, and to watch the subsequent application of coating. This arrangement allows to not only operate on the site but also removes the necessity to make use of a lot of packaging itself by providing for the direct loading of insulators into the equipped containers. The capacity of these revolutionary systems is defined by the size of the mobile curing unit, and in general, they can process approximately 1,400 pieces per 8-hour shift.

Figure [33]. Coating's plant

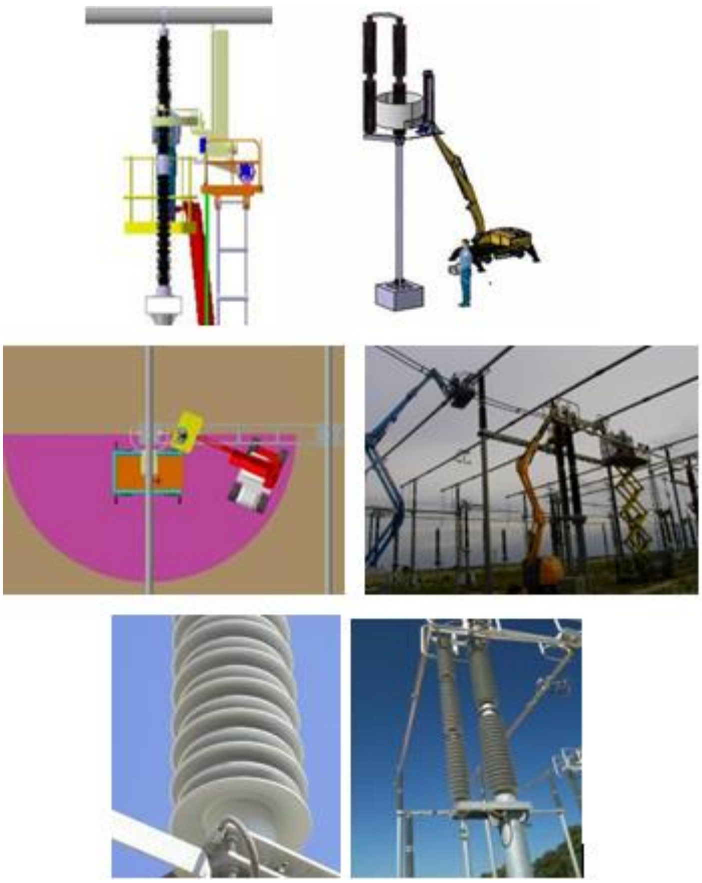


Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

4.5.5 EKD CRP (EKD’s Coating Robot Post Insulators)

Long Rod coating system before installation and Post Insulators, either before or after installation. This system may be used to apply silicone in the various conditions; EKD CRP is easily transportable and can be installed within a platform to apply the coating directly on the installed insulators. A robot is made up of a chamber cylindrical in shape that encompasses the insulators and step motors direct spray nozzles to apply even coat. After the initial positioning and alignment are done, the operator proceeds with the complete security which keeps him away from the high tension. The reduction of over-spray is more than significant due to a suction mechanism and therefore the dispersal of silicone in the environment is very minimal. A smaller and lighter version is under development to make possible the coating of parts of substations that are difficult to reach while keeping the worker safe.

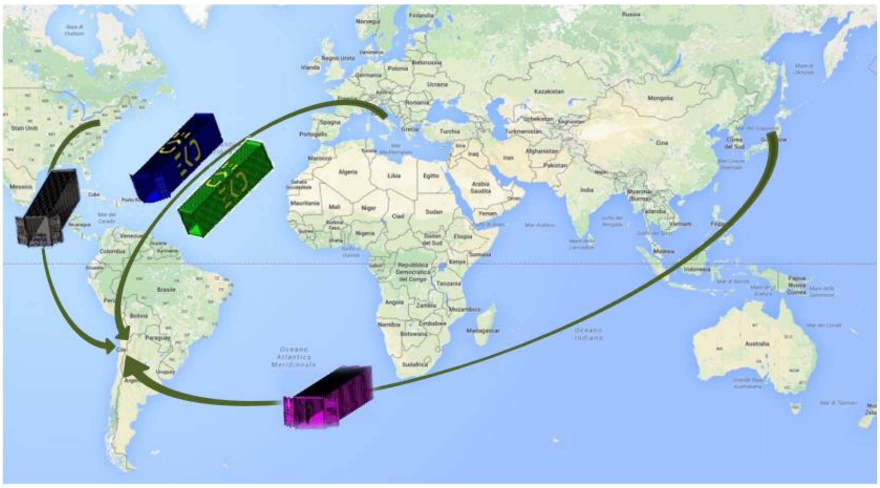
Figure [34]. EKD’s Coating Robot Post Insulators and ex-ample of finished application (bottom)



Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

4.5.6 Example of activity (Chile Project) - Coating Mobile Plant (EKD CMP)

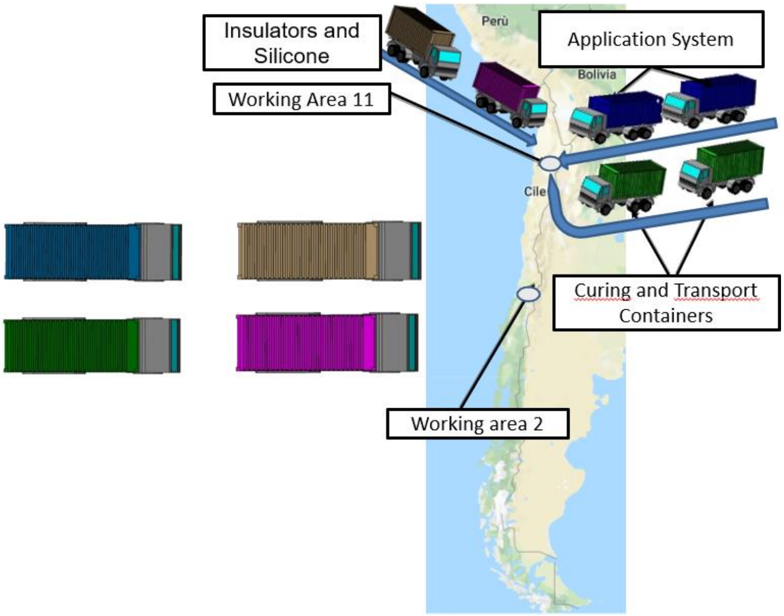
Figure [35]. Global Coordination in Motion: Preparing for the RTV Silicone Coating Process



Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

The insulators intended to be coated are sometimes shipped from a country such as Japan, in which they are produced, to the first working area, or right into the clients' warehouse. At the same time, the specialized equipment of EKD is shipped from Italy, and the equipment goes to the same starting point of the project. Further, unerring RTV Silicone, vital to the application process, is shipped from its origin point, which could be somewhere in North America, to the first cell. This process of coordination among materials and equipment from different parts around the world forms a scene for the beginning of the coating process displaying international cooperation and logistics of getting ready for the task.

Figure [36]. Efficient Insulator Coating Operations: On-site Application and Streamlined Logistics

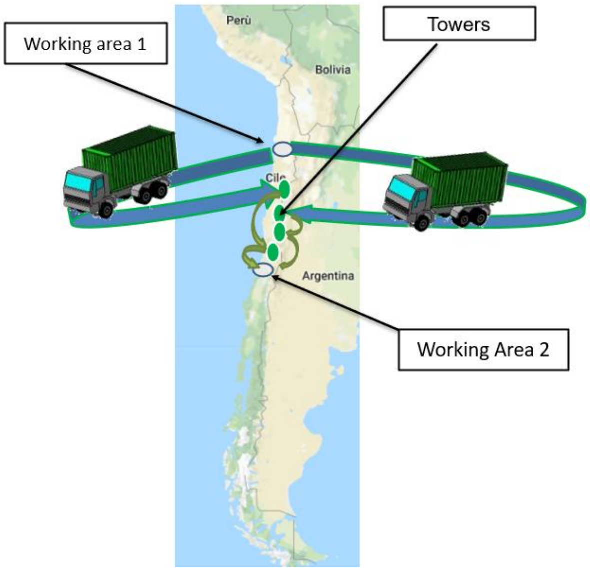


Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

It permits to paint insulators right at their installation tower; the cost of shipment of finished products is very low and there are no other packing costs.

The coated insulators are delivered to customer's warehouse or to the area of the towers. After the delivery of the coated insulators the trucks with empty containers move to the next workplace, prepared to be filled with other coated insulators.

Figure [37]. Seamless Transition: Moving from Working Area 1 to 2 for Continuous Insulator Coating and Delivery

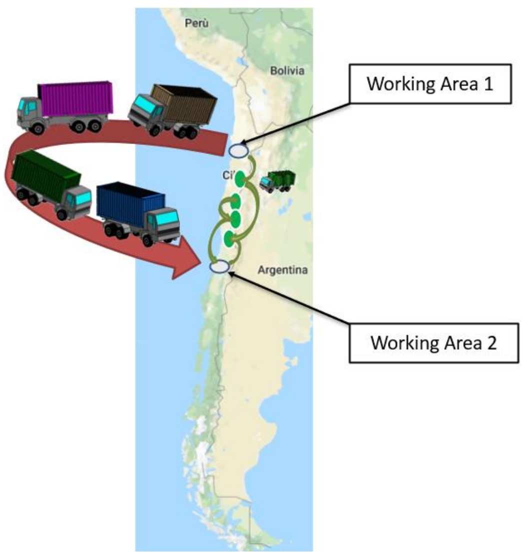


Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

Upon the application of the silicone, EKD's Equipment, RTV silicone and insulators to be coated are moved from working area 1 to working area 2.

The trucks in the meantime carry the coated insulators to the places of application.

Figure [38]. Final Stage: Insulator Coated and Delivered



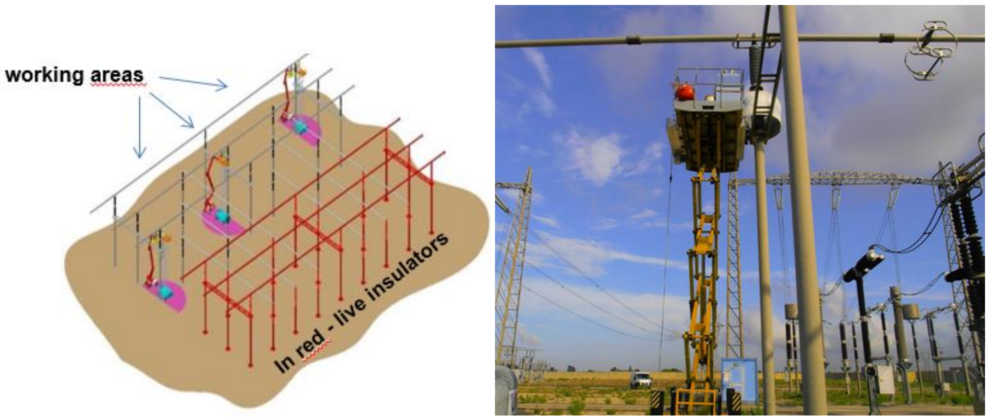
Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

4.5.7 EKD Automatic CRP (Coating Robot Post Insulator): Main Characteristics

Coating Robot Post Insulator: This equipment is characterized by its being portable and the possibility of fixing it to a platform, thus making it possible to apply coatings directly to installed insulators. Housed within a cylindrical enclosure around the insulators, the device uses stepper motors to move the spray nozzles for even coating.

The mechanism is aimed to be utilized on insulators located near the energized sections (approximately within a 5-meter radius), which creates a safe environment for the personnel. The marked decrease of the overspray and the incorporation of a suction element makes the elimination of silicone into the environment minimal.

Figure [39]. Innovative Robotic Solution for Safe and Efficient On-Site Insulator Coating



Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

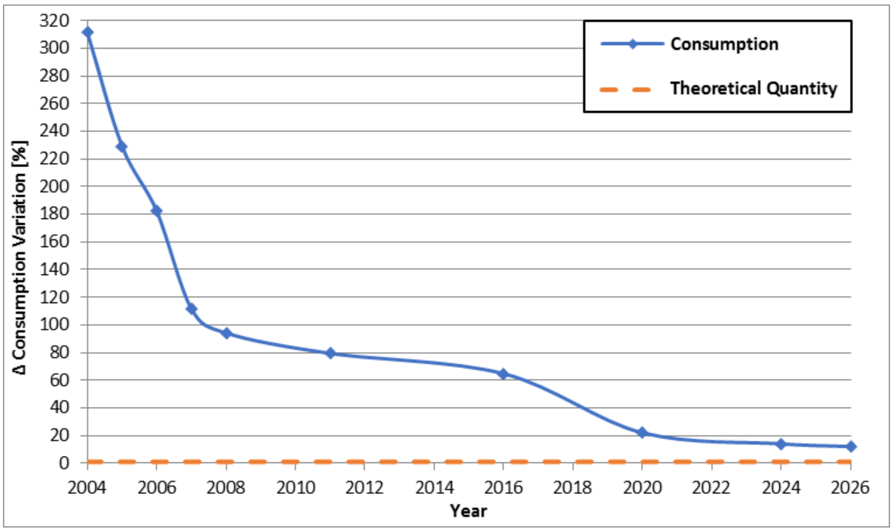
4.6 Future Outlooks

In the historical development of silicone technologies and their deployment methodologies, the evolution of silicone materials and the improvement of application processes was frequently separated.

Now, the collaboration between Midusn and EKD opens up the era of synergy, offering opportunities for further improvement of both application systems and the efficiency of silicones performances. This collaboration facilitates the generation of materials and technologies that are to increase the quality of the final product. Particularly, custom silicone compositions can be purposely designed to suit the peculiarities of the different insulator shapes, so as to eliminate the possibility of material gathering and dropping, and thus simultaneously simplify the process of applying and curing. These improvements would improve production capabilities, at the same time, reducing the space requirements for operations.

In addition, this partnership guarantees efficient use of silicone materials which minimizes the usage and amount of waste generated. This strategic mode, in fact, is not just a leap in the approach of technological development of the silicone applications but also a bright example of collaborative innovation that has the potential to redefine the industry standards and practices.

Figure [40]. Trend of RTV silicone consumption compared to theoretical value, considering Solids by volume 57% and solids by weight 70%.



Source: P. Graziosi, M. Morella, S. Simonluca, 2019, "*RTV Silicone Application on EHV/UHV Ceramic Insulators: State of the Art and Future Developments*"

4.7 Considerations

The story of EKD Project SRL is a testament to the changing influence of innovation and knowledge in the electrical utility sector. The strategic focus of firm on technological progress, an integrated approach, and global market coverage places EKD well in the competitive environment.

Despite the paradoxes of specialization, market dependence, and production scalability, agility should be the critical factor in EKD's future growth and prosperity. Again, company should seize the growing renewable energy prospects, adapt to the unending technological change, and build strong strategic partnerships to fully unleash its potential. Against the challenges of competition, supply chain uncertainties, and regulatory swing, the EKD must be agile, proactive, and resilient. In the end, EKD's course will be determined by its capacity to innovate, modify, and cooperate in a dynamic world energy context.

CONCLUSION

This thesis has presented a comprehensive study of Room Temperature Vulcanizing Silicone on High Voltage Insulator Coatings, and the role that they play in the improvement of the reliability and performance of electrical power transmission systems. Through analysing historical context, material properties, technological exploits and economic aspects, the study has underscored the great advantages of RTV silicone coatings in preservation of insulator performance up to any kind of environmental conditions.

The quantitative analysis, which is being shown in detailed tables and graphs, shown the economical and operational benefits of the RTV silicone coatings. The data simply shows that good initial application cost aside, RTV silicone coatings provide significant long-term savings because of their longevity and the reduced amount of work required to keep the coat in good condition. Cost comparisons reveal that RTV-coated insulators save much higher cumulative maintenance cost compared to traditional methods in the long run. It is mainly the cost efficiency of RTV coatings, which are very long lasting and therefore require maintenance interventions less frequently and allow resource allocation to be optimized. Charts presented maintenance cost over time also further support economic efficiency of RTV silicone coatings. These graphical illustrations show an almost constant decrease in the total maintenance costs of insulators treated with RTV silicone with respect to the conventional methods. Moreover, the statistical treatment of the leakage current suppression and hydrophobic recovery rates prove the better performance of the RTV silicone coatings. The data demonstrates that RTV silicone coatings are continuously hydrophobic and leakage current preventers even in severe environmental conditions defined by high pollution and extreme weather.

The case study of the EKD Project has given practical insight into the technological advancements and operation improvements, which were achieved in maintenance of high-voltage insulators. The transition that EKD went through over the years from manual coating processes to completely automated ones is a good example of the quality and consistency improvements as well as the environmental sustainability that is brought by the technological innovation. Development of robotic systems using RTV silicone coatings has allowed EKD to reach the highest level of coating quality, reduce silicone waste and improve worker safety. The latter has made the process of coating more effective and sustainable which is an example for other companies and other industry stakeholders.

In addition, the study of regulatory drivers and environmental stewardship has emphasized the role of regulatory frameworks and policies in determining the adoption strategies for RTV silicone coatings. The thesis has pointed out that compliance with the regulation on advanced coating technologies as well as environmental sustainability targets can lead to the adoption and implementation of the technologies. The partnership of utilities with the technology suppliers appears to be an important factor in mitigating barriers to adoption and maximizing the performance of insulator coatings. The fact that RTV silicone coatings are capable of meeting strict environmental legislations and supporting sustainability goals has been widely covered, highlighting their importance in contemporary power distribution infrastructure.

Cost-benefit analyses with detail support the economic and environmental benefits of RTV silicone coatings. As an example, comparisons of costs of manual cleaning, hot washing, silicone application, and RTV silicone coating show that, although, the initial costs are higher RTV silicone floods provide the lowest of all costs throughout the long time. It is because of their long lifetime and low maintenance requirements. Graphs of RTV silicone coatings performance metrics, such as their ability to suppress leakage currents and retain their hydrophobicity, help to provide evidence of their performance superiority. The study demonstrates that RTV silicone coatings are capable of surviving heavy pollution and environmental stress and still preserving their protective function. The practical case studies, and detailed analysis of EKD's experience, provide real-world examples of application of RTV silicone coatings, in different environments and geography. The case studies offer convincing proof that the coatings are useful in controlling pollution flashovers and improving the performance of insulators. The knowledge gained from these case studies represents very important lessons for utility companies and other stakeholders that are interested in the deployment of RTV silicone coatings that show great increases in operational efficiency and environmental sustainability.

Finally, the thesis emphasizes that the above approach is the only way of dealing with the challenges of environmental contaminants and diverse climatic conditions. The systems-based analysis of management, economic, and technical items offered practical recommendations for industry practitioners and stakeholders. The results support the functional integration of RTV silicone coatings in improving the reliability, efficiency and sustainability of power transmission systems. This research has provided a detailed analysis supported by robust quantitative data and practical case studies that make a strong case for the wider adoption of RTV silicone coatings. The findings of this study will inform future research and implementation strategies to ensure resilient and efficient power transmission systems under changing environmental and operational scenarios.

The detailed data analysis and graphical presentations have delivered evident proof of the economic and operational advantages of RTV silicone coatings, and so, there is a strong case for their strategic incorporation in power transmission infrastructure. The case study of EKD Project illustrates benefits of the application of RTV silicone coatings in the aspect of practical developments and operational improvements. Regulatory impacts and environmental stewardship, consequently, also emphasize the need of these coatings to help achieve sustainability objectives and improve environmental performance of power systems.

In Summary, this thesis showcases the critical role of RTV silicone coatings in modernizing and ensuring that electrical power systems are future-proof. It is the strategic integration of these coatings that is crucial for the reliability and efficiency of power transmission infrastructure and such a measure empowers the power systems to efficiently react to and withstand environmental contaminants and adverse climatic conditions. The findings and recommendations introduced in this thesis serve as a strong basis for industry professionals, policymakers, and researchers to push forward the adoption and optimization of RTV silicone coatings, thereby, playing a role in the creation of a more sustainable and resilient electrical power infrastructure.

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