IMPACT OF INTEGRATING A PHOTOVOLTAIC POWER PLANT FOR SELF-CONSUMPTION ON THE COMPETITIVENESS OF COMPANIES IN THE METAL SURFACE PROTECTION SECTOR

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Lappeenranta–Lahti University of Technology LUT

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Impact of integrating a photovoltaic power plant for self-consumption on the competitiveness of companies in the metal surface protection sector

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This research focuses on the techno-economic and environmental feasibility of integrating self-consumption through a photovoltaic (PV) system in the metal surface protection industry, which is energy-intensive. Eurosjaj d.o.o. is also used as a case study and closely linked to the two strategic aims of the study to reduce costs and adhere to the emerging European Union climate policies, and specifically the Carbon Border Adjustment Mechanism (CBAM). A quantitative scenario analysis along a 30-year time horizon correlates the baseline scenario with partial and complete integration of PV, i.e., on the grid process of the electricity supply. Technical modelling, including site-specific solar resource, operational load profile, PV degradation profile, and system efficiencies, and finance analysis, including net present value (NPV), internal rate of return (IRR), and levelized costs of electricity (LCOE) metrics, are used. Avoided CO_2 emissions and/or corresponding costs with CBAM cost savings are quantified by environmental evaluation. Findings indicate that total adoption of PV can reduce the cost of electricity by up to 60%, remove over 50% of CO_2 emissions, and reduce the weight of CBAM, thereby generating the most significant economic and environmental benefits. The findings demonstrate the strategic value of decentralised generation of renewable energy within the energy-intensive sector by combining operational resiliency with regulatory compliance.

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SYMBOLS AND ABBREVIATIONS

Units and symbols

%	percentage
°C	degrees Celsius
kWh	kilowatt-hour
MWh	megawatt-hour
tCO_2	metric tonnes of CO_2
gCO_2/kWh	grams of CO_2 per kilowatt-hour
PJ	Petajoule

Abbreviations

AC	Alternating Current
BC	Back Contact
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CO_2	Carbon Dioxide
CVD	Chemical Vapor Deposition
DC	Direct Current
EF	Emission Factor
EMS	Energy Management System
EU	European Union
GDP	Gross Domestic Product
IEA	International Energy Agency

IEC	International Electrochemical Commission
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
NPV	Net Present Value
OPEX	Operational Expenditure
PV	Photovoltaic
ROI	Return on Investment
TCO	Total Cost of Ownership

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DECLARATIONS

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The author, Amina Aljović, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

This thesis explores the techno-economic and environmental solution to the integration of the so-called self-consumption of photovoltaic (PV) systems into the metal surface protection industry, adopting the case study of the company Eurosjaj. The paper involves a discussion of how to resolve the two issues of escalating industrial electricity prices and growing pressure to decarbonise in the face of the European Union's (EU) implementation of the Carbon Border Adjustment Mechanism (CBAM). The volatility of international energy markets conditions the significance of researching the subject matter, the speed-up of the climate policy implementation, which alters the operational and strategic priorities of the energy-intensive industries. More broadly, the work is relevant to help solve the decreased environmental impact and competitiveness-increased resilience in key manufacturing industries that renewable energy integration can bring.

In the past, studies have demonstrated the ability of PV self-consumption to reduce the cost of operations, greenhouse gas emissions, and enhance energy security in various contexts. The declining cost of capital in the solar PV industry and ever-increasing electricity prices have made on-site generation commercially and financially viable, especially in processors with commercial and light industrial buildings. The on-site generation profitability has been proven to be higher, as shown in numerous sector-specific reports. In the heavy industry, control in the PV generation during somewhat constant load daytime operation has been demonstrated in case studies. It provides a considerable amount of cost savings and emission reduction. In addition, three policy incentive schemes have been implemented to cut grid charges, and rooftop solar subsidies have been found to increase the appeal of investment.

Nonetheless, there are relevant gaps in the available literature. Most research has been conducted on residential or small-scale commercial applications, with little empirical evidence on PV self-consumption in high manufacturing environments characterized by process-driven sectors with large continuous processes and high energy demands. Even in cases where industrial situations are taken into consideration, there is limited research that incorporates regulatory compliance-related factors like carbon costs in the evaluation of economic factors. Furthermore, constraints pertinent to a particular sector, namely process scheduling potential, heat recovery potential, or interactions between electrochemical and

thermal energy demands, are often overlooked in prior studies, which may affect the technical as well as economic consequences of implementing PV. This study fills these gaps by integrating technical performance modelling, comprehensive financial modelling, and environmental modelling with explicit CBAM-related cost implications. The key aim of this thesis statement is to evaluate the economic and environmental benefits of PV-based self-consumption in an energy-intensive metal surface protecting plant.

2 Literature review

In In order to determine the possible profitability of PV deployment in the field of metal surface protection, it is relevant to learn more about the industrial energy environment in which such systems will be functioning. These need to look into the energy demand trends, supply security issues, and policy frameworks that affect industrial energy policies.

2.1 Industrial energy needs and supply security

The industrial sector, which forms one of the largest global energy consumers, acts as a driving force in terms of its contribution to GDP, employment creation, and development of technology, and is thus a pillar of contemporary economies. Contributing more than a third of the final energy consumption in the world, the industry depends on natural gas and electricity as the most potent energy carriers.

In 2023, the consumption of industrial energy in the European Union (EU) was only slightly below 8,990 PJ of energy, accounting for close to 25% of total final energy consumption (Eurostat, 2025a; Eurostat, 2025b). Figure 1 demonstrates the end-use of energy in 2023, by industrial sector, at the EU level. Although this means a decrease over the previous year, it reflects the high energy demands of the sector, particularly on energy-intensive operations like metal surface treatments.

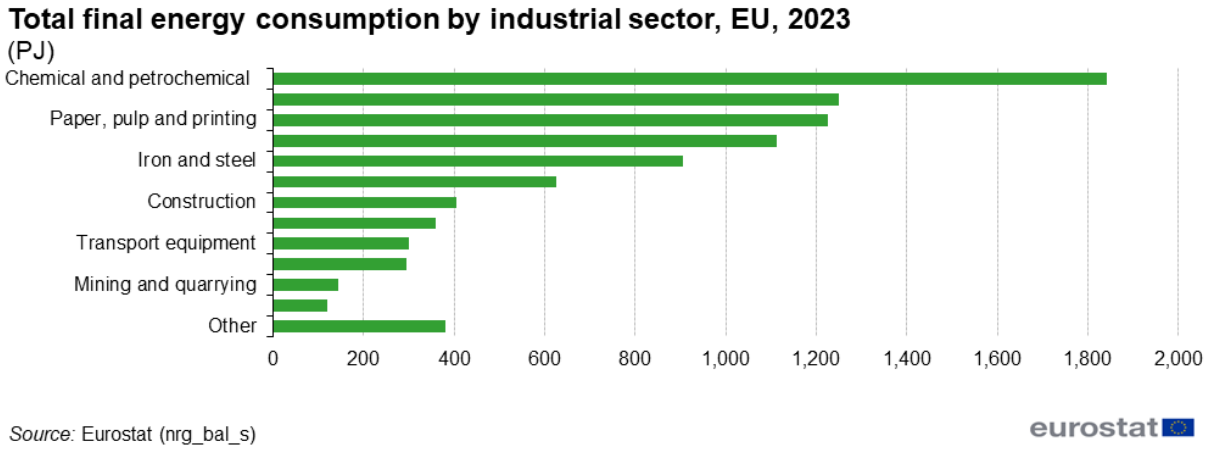

Figure 1: Total final energy consumption by industrial sector (Eurostat, 2025c)

Metal finishing processes are also susceptible to the continuous flow of energy through the utilization of controlled electrochemical and thermal environments to maintain an efficient product. The power in such processes not only forms a huge part of operating cost, but also has a direct impact on throughput and defects. Energy security plays a vital role in the daily operations and the strategic competitiveness since disruption may lead to equipment failure, and loss of production (Thomas et al. 2022; Månsson, 2014). This can result in higher costs and low operational reliability.

According to the significance of such processes and sensitivity to energy instability, the issue of energy supply security becomes particularly acute in this frame. Energy supply security refers to the capability of an energy system to provide reliable, affordable, and adequate amounts of energy in any given situation (Gnansounou, 2008). This would be in terms of continuous supply of energy sources, immunity to market changes, and the ability to withstand the impacts of geopolitical conflicts or natural calamities.

Impacts of disruptions have been particularly devastating in metal finishing because of the sensitivity of the process. Voltage instability in electrochemical systems may cause inconsistent deposition, defective products, or even entire production batches to have to be scrapped. Electricity is also required in heating elements, in the establishment of ventilation systems, and in wastewater treatment. On-site renewable energy generation can greatly improve the stability of the systems and introduce the element of resilience in the operations, and reduce the exposure to risks (Booth et al., 2019). They allow facilities to be less vulnerable to grid failure because they make use of their energy production and storage, hence improving the quality of products and lessening financial losses.

Most industrial companies have resorted to investing in decentralized energy systems to increase their resilience. Metal finishing operations are especially appropriate to take advantage of decentralized energy solutions because energy load and requirements are relatively steady during the day, and on-site system renewable systems are viable. PV facilities with battery storage offer companies a solution to partially or fully decouple themselves from the grid, and gain resilience against the volatility of market prices and overall improved operational continuity. Microgrids, which provide support to these systems, and advanced energy management platforms enable a more efficient load balancing procedure and enable the firms to align consumption to self-generated energy availability (Booth et al., 2019). These combined systems are becoming known not only as methods of

energy saving but even more, as strategic benefits of business continuity and regulatory compliance.

Energy resilience planning has gradually shifted to new levels beyond previous plans of backup systems to complex resilience of system adaptability and recovery capacities. The energy-resilience aspect suggests absorptive, adaptive, and transformative capacity, which enables systems to persist following, throughout, and following shocks (Schmitz et al., 2025) through the addition of renewable energy to systems of monitoring and control to limit the impacts of either rapid or gradual shocks. In addition to increasing the resilience of the industry, the changes will be aligned with the more general policy and market trends of decarbonization and energy autonomy (Amaglobeli, 2024, Nunzi, 2025).

2.2 Self-consumption and photovoltaic integration in industry

Self-consumption means taking direct advantage of the electricity produced on the site (typically PV) in order to cover internal energy demand, rather than exporting energy to the grid. Due to the reduction in solar energy costs, growing interest in self-consumption, and the need to avoid electricity rate volatility, the technique is rising in popularity in industrial settings (Pedrero et al., 2021).

2.2.1 Drivers of self-consumption

The main reason behind the development of industrial self-consumption is the sharp rise in electricity prices worldwide. In some countries, such as Turkey, industrial electricity tariffs have exceeded 500% over the past few years, significantly reducing the payback period of PV investments to between 2.5 and 5 years (Tüzün, 2024). The trends are mostly the same in the European manufacturing hubs. The recent rise in retail prices has encouraged energy intensive industries, such as the metal finishing industry, to consider on-site generation and self- consumption systems as a way to reduce energy costs (European Commission, 2025a; Pedrero et al., 2021).

Concurrently, falling prices of the capital costs of the PV systems improve he economy at large through self-consumption within a business setting. The levelized cost of energy

(LCOE) of electricity generation in a utility-scale solar PV decreased by about 89% globally between 2010 and 2022. The increase in retail electricity tariffs and the decrease in feed-in tariffs, along with a significant reduction in costs, promote the competitiveness of the self-consumption model and the mass implementation of PV (IRENA, 2023; Arnold et al., 2021).

SMEs are heavily involved in the installation of PVs in order to curb the rise in energy costs. In other places, such as Germany, where policy incentives, including lower grid fees on self-generated electricity and subsidies on rooftop solar systems, boosted commercial PV installation, most of the capacity was reportedly installed in 2023 with self-consumption in mind (Reuters, 2024; Clean Energy Wire, 2025).

2.2.2 Photovoltaic Integration Strategies and Technologies

The integration of PV systems facilitates several approaches within industrial facilities. Rooftop-mounted solar arrays are the most prevalent method that arrays utilize unused factory roof space. Designed to align generation with peak daytime consumption to maximize self-consumption rates and reduce dependency on the grid, where feasible, ground-mounted systems and building-integrated PV are also installed (IEA PVPS, 2023; Luthander et al., 2015).

Battery energy storage systems (BESS) are becoming more linked with PV installations in order to increase self-consumption even more. However, even though battery prices remain a barrier to implementation in certain industries, combining PV and storage gives the facilities the ability to store solar energy that is not currently generating during non-operating times (Wang et al., 2023; Migliari & Cocco, 2025). State-of-the-art energy management (EMS) enables the anticipation of energy demand and the PV generation, dispatch optimization, and finer adjustments to the difference between production and consumption (Duran et al., 2024).

On-demand side management strategies to improve self-consumption are production schedules that have been adapted to conform to the time when solar is high. Studies indicate that industrial settings and reduced grid electricity use can be increased by ~41% with self-consumption (Miranda et al., 2024).

Nevertheless, industrial parks with communal PV infrastructure and a private-wire network are one of the new approaches to small and medium-sized businesses without rooftop capacity that can apply the shared benefits of decentralized renewable generation (FIMER, 2021; European Commission, 2025b).

2.3 The Carbon Border Adjustment Mechanism and Industry Implications

CBAM is a potential regulatory measure that will support the EU climate ambitions and help ensure the integrity of the European Union Emission Trading System (ETS). The main goal is to avoid so-called carbon leakage, which is a situation where industries move their production to countries with less stringent climate requirements. Consequently, this would reverse the effect of emissions reduction in the EU (European Commission, 2021a). Under the implementation, specific imported commodities would be subject to a carbon price that would otherwise be cheaper since the same climate policies are not implemented in their home countries.

CBAM is initially to be used in carbon-intensive industries, namely cement, iron and steel, aluminium, fertilizers, hydrogen, and electricity. These sectors were selected because they have a high profile in terms of emissions and are susceptible to emissions relocation due to trade. The policy is being enacted in stages. On a reporting-only basis, between 2023 and 2025, the only requirement imposed on importers during the transitional reporting-only period will be able to provide quarterly reports providing the information on the direct greenhouse gas emissions in the imported goods, with no associated financial costs. After 2026, however, importers will have to purchase and surrender certificates under CBAM in a manner that will look similar to the carbon price that would otherwise have been in play had goods been imported within the EU ETS (European Commission, 2023).

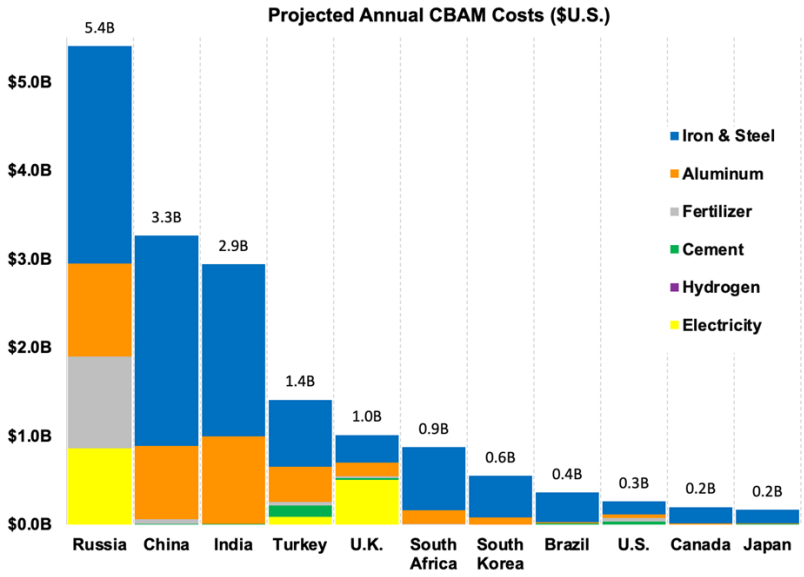

Figure 2: Projected Annual Costs (Hoenig, 2024)

Figure 3 presents the projected annual CBAM costs across major exporting countries, highlighting the highest impacts. The major classifications of the benefits of the CBAM are that it can evolve a territory of a game in the competitive environment where manufacturers located in the EU, which are exposed to carbon expenses through the ETS, and non-EU manufacturers are located, which are not faced with similar costs. Such matching reduces the risk of carbon leakage that may encourage the movement of cleaner production practices to other sites that are safely regulated in the world. Also, CBAM facilitates increased transparency in emissions reporting and allows for the inclusion of carbon pricing in the standards of international trade (European Commission, 2025c).

CBAM presents huge difficulties and prospects for non-EU nations. Future upgrades of the emissions monitoring and reporting infrastructure and, possibly, cleaner technologies can be considered by exporters who want to retain access to the EU market. Nevertheless, there is a risk that some countries that do not have strong climate policies perceive CBAM as an obstacle, which can become the source of trade tensions (Cosbey et al., 2019). However, CBAM provides insight into modernization by encouraging decarbonization in economies that export and want to stay competitive within the EU market.

For the metal surface protection sector, CBAM has direct and significant implications. The industry heavily relies on steel and aluminum, two of the core materials covered under CBAM, and uses energy-intensive thermal and chemical processes. Many coating and finishing firms import semi-finished metal components or raw substrates from outside the

EU. These imports may face a cost increase of 5% due to the carbon intensity of upstream production when sourced from regions lacking strong carbon regulation, especially once CBAM enters its complete phase in 2026 (Orgalim, 2025). Particularly for first operators on thin cost differentials, these increases could tighten profit margins and challenge global competitiveness.

Companies in the metal surface protection sector, as a strategic response, are increasingly exploring self-generation solutions, mainly PV systems, for on-site energy use. Using solar energy to power drying, curing, and heating processes, firms can reduce their emissions, those linked to purchased electricity, by more than 50% (Martínez-Rodríguez & Fuentes-Silva, 2021). It lowers the number of CBAM certificates they need to surrender and reduces their carbon footprint, providing a financial advantage and improving their green credentials in the supply chain.

CBAM mandates the deployment of robust (measurement, reporting, and verification) systems. Embedded emissions will also be mandatory to track correctly, making companies invest in life cycle assessment programs, digital carbon accounting services, and verification services. Companies will enhance their position among investors who take a climate-related approach by becoming active in internal carbon transparency creation and will be able to easily comply with CBAM (Armourenriques & Wetzer, 2021; 4C PL, 2025). Finally, CBAM heralds a paradigm shift in the world of global trade, where carbon performance has become one of the defining factors of industrial performance and viability over time.

3 Metal Surface Protection Sector

Metal surface protection is a convergence of high-technology engineering and materials science with environmental sustainability, and its industry is a key enabler in industries where constant reliability and performance are mandatory requirements. In order to evaluate the success of its economic competitiveness and its ability to meet emerging regulatory and environmental demands, it is crucial to understand its operational structure and energy requirements.

3.1 Sector Characteristics and Energy Demand

The metal surface protection industry enhances corrosion protection, mechanical integrity, and aesthetics, which is why it is applied in the auto industry, aerospace industry, construction business, shipbuilding, and the renewable energy industry (Trzepiecinski & Najm, 2024; Dosta et al., 2024). Having more strict environmental and durability standards and more demands on high-performance materials that can withstand harsh conditions is what led to the development of such an industry.

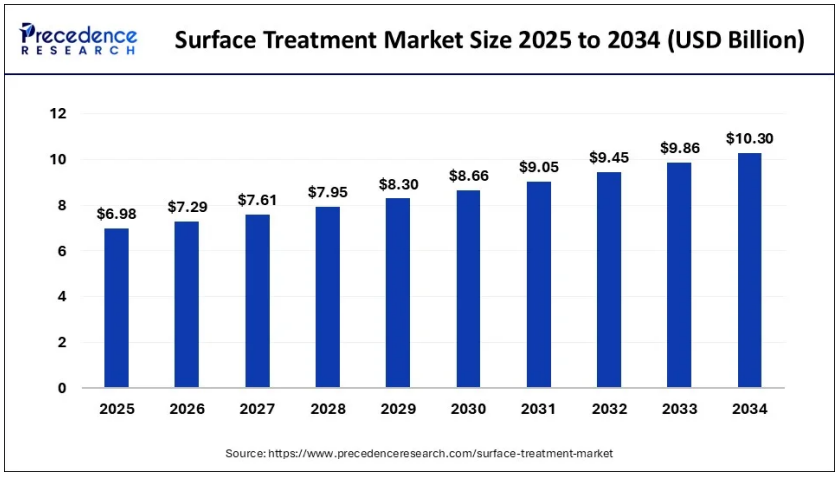

Figure 3: Market size of surface treatment (Precedence Research, 2025b)

The global surface treatment market is estimated to be approximately USD 6.68 billion in 2024, and is likely to reach USD 10.30 billion in 2034, as presented in Figure 4. Previously, the compound annual growth rate (CAGR) will be 4.43% between 2025 and 2034 (Precedence Research, 2025a). Additionally, the broader market of surface treatment

chemicals market was estimated at USD 7.19 billion in 2024, and it is forecasted to reach the value of USD 17.40 billion by 2034, with the anticipated CAGR during 2025 to 2034 constituting 9.24% (Precedence Research, 2025b). To be specific, the estimated revenue of metal surface treatment chemicals, in 2023 will be USD 3.97 billion, which will continue to rise annually, reaching USD 6.19 billion in 2033 (GlobeNewswire, 2025). These figures revolve around the consumption of energy. The production of many types of surface treatments necessitates much heat and electrochemical activity.

Energy requirements are driven by the need for higher temperatures and electrochemical processes in this industry, such as the hot galvanizing process that requires baths to be kept at 450°C. Together with auxiliary heating, drying, and pretreatment, the total energy consumption may reach up to 0.3-0.7 MWh of energy per ton of galvanized steel (Chavan, 2006). Since in powder coating, the process is carried out over a sustained (approximately 10-15 minutes) period, a substantial volume of thermal energy is used to ensure that the polymer is sufficiently cured (Yuan et al., 2023).

High on the list of energy-intensive techniques is thermal spraying, the most commonly used are plasma and high velocity oxy-fuel spray techniques. Every spray gun is required to make particles harder than 10,000°C, which means that the power requirement varies between 50 and 100 kW based on the feed rate of materials and the desired thicknesses (Venkatachalapathy & Udayabhaskar, 2023; Oerlikon Metco, 2022).

An outdated rectifier, inefficient insulation, and insufficient automation of the processes contribute to thermal loss and increasing inefficiencies in the electrical loads of many plants. According to the research, up to 20 to 30% of the energy input may vanish due to system inefficiencies (Papapetrou et al., 2018). That loss is a huge opportunity to reduce expenses with upgrades to cheaper energy-efficient rectifiers, higher-quality thermal insulation, and the harvesting of waste heat.

The other great catalyst is regulation. The Energy Efficiency Directive of the European Union (2012/27/EU) requires large businesses to carry out energy audits and take action based on the results (European Commission, 2021). In addition to this, the CBAM drives exporters into the EU, ensuring they maintain their carbon intensity below the threshold. This induces PV systems, low-carbon heating sources, and enhanced monitoring technology.

All that means that the metal surface protection sector faces an energy-intensive process, and there is pressure to minimize emissions and operational costs, operating under a regulatory burden. Nevertheless, the amount of energy used intensively brings with it the risk of the introduction of cleaner technologies and renewables. The continuously increasing pressure on three treated metals would see energy optimization play a significant role in keeping pace with competition as well as fulfilling environmental requirements.

3.2 Typical Surface Protection Processes

The metal surface protection industry employs an array of process types that are designed to increase the useful life of the metallic parts that we use in our world by inhibiting corrosion, increasing the surface hardness, increasing the wear resistance, and strengthening the aesthetic quality. Such processes are broadly divided into mechanical processes, chemical coating processes, electrochemical processes, and physical or organic coating processes. Determination of the method depends upon the nature of the base material, the level of durability required, exposure to the environment, and the desired appearance, depending on cost factors and other requirements of the industry rules (QA-Group, n.d.).

Popular kinds of chemical surface treatment are phosphating and passivation. Phosphating is a process that coats steel parts in a solution of phosphates to form a phosphate conversion coating that has an enhanced level of paint adhesion and an initial level of corrosion protection. Its everyday use lies in the automotive and appliance industries, where it is used as a pretreatment prior to painting or powder coating (Best Technology, n.d. a; Vintureanu et al., 2023). These stainless steel surfaces, however, are frequently exposed to acid passivation, which eliminates surface iron and improves the durability of the protective oxide of chromium (Best Technology Inc., n.d.b).

Such electrochemical processes as electroplating are characteristic of the surface engineering industry. Electroplating can be defined as the application of an electric current using an electrolytic solution onto a conductive surface to apply a metal layer over it. As an example, nickel plating may result in wear resistance and enhancement of cosmetic features of the parts, and zinc plating can provide the property of corrosion sacrifice protection in the steel components (Ahmad, 2006). Electroless plating, in particular electroless nickel plating, is another process in which no external source of power is employed. Instead, it employs a

chemical reducing agent to create a homogeneous layer of nickel phosphorus, with complexly shaped components as well (Paunović & Schlesinger, 2006).

Hot-dip galvanizing is one of the strongest thermochemical processes where metal parts are put into a melt of zinc at around 450°C. The procedure creates a stack of layers of zinc-iron alloy, which is bonded to the substrate by a metallurgical process, with exceptional corrosion protection, especially in outdoor and marine settings. Hot dip galvanizing is applicable and widely employed in the construction, infrastructure, and energy industries, due to its ability to perform well even under severe corrosive conditions (Ahmad, 2006; American Galvanizers Association, 2012).

Organic and powder coatings have become commonly accepted, especially in light of environmental laws that focus on the volatile organic compounds (VOCs). The process of powder coating is an electrostatic coating technology by which a thermoset or thermoplastic powder is applied, then later cured under heat to the part to fuse it into a coating. They are excellent against abrasion, corrosion, and UV degradation as well.

Short treatment of surfaces, which takes the form of shot peening treatment and abrasive blasting, is employed as a pre-treatment work or as a stand-alone protection mechanism. Shot peening provides compressive stresses at the surface of the metal parts, which improves their resistance to fatigue and the component lifetime, especially concerning the aerospace and automobile industries (Totten & Howes, 2006). Abrasive blasting instead strips away rust, scale, and old coating to form a rougher surface profile, promoting improved adhesion of the coating.

There are advanced techniques like physical vapor deposition (PVD) and chemical vapor deposition (CVD), also in high-performance industries such as aerospace, biomedical engineering, and electronics. PVD is the technique linked to the vaporization of coating materials under vacuum, which are deposited on the substrate to form thin films with a thickness of 0.1-5 μm. CVD, on the other hand, utilizes chemical reactions of our gaseous precursors to form a solid coating on the surface. The techniques are very efficient in producing extremely adherent and wear-resistant coatings, which can be nitrides, carbides, or oxides of titanium, chromium or aluminum (Mattox, 2010).

Newer developments in surface engineering are nano coatings, laser surface alloying, and plasma-enhanced chemical treatments to provide additional functionality with a lower

environmental impact. Moreover, this has been coupled with the changes in the whole industry where the chromium environment has changed to become less hazardous (hexavalent chromium processes moving to be trivalent), less polluting the environment (from solvent-base to water-based processes), and harmonized health, safety, and environmental regulations, such as the REACH directive and compliance with the RoHS (Prabhakar et al., 2021; Guillon et al., 2023).

3.3 Chemical and Thermal Requirements

Use of accurately formulated chemicals and tight control over heat are significant factors in the surface protection process in the metal finishing industry, which ensures effectiveness through proper chemical interactions and reliability of the process. These parameters are fundamental to the high quality of the coating used, the consistency of the process, and the safety to the environment. Chemical and thermal treatments need to be modified based on the type of surface treatment that is being used, which can either be phosphating, anodizing, electroplating, electroless plating, powder coating, or hot dip galvanizing.

Electrochemical processes like zinc electroplating and electroless nickel plating require strict control of electrolyte compositions and bath conditions. Surface defects (blistering, dullness, or non-uniform quantity of the position) in zinc plating are possible, based on the deviation and concentration of Zn^{2+} or pH. This results in ineffective corrosion protection (Anwar et al., 2018).

Regulation of contaminants in chemical baths is also of vital importance. The presence of impurities, either introduced by drag-out, the solutions of anodes, or external sources, may hurt bath performance and product quality. It is necessary to periodically assess the bath by chemical analysis, use filtration systems, and plan regular replenishment to maintain long-term stability of the bath (Nickel Institute, 2023; Berg, 2004).

Thermally, most surface treatment processes are deemed to be energy-intensive since they involve the application of heat during pre-treatment (e.g., degreasing and pickling), primary treatment (e.g., molten zinc baths), and post-treatment (e.g., drying and curing). Coating Zn-Fe substrates in the form of a multilayered Zn-Fe intermetallic coating (according to the requirements of ISO 1461) is carried out in the hot-dip galvanizing, where the steel substrate

is coated by immersion in molten zinc at 440°C to 460°C (Hempel A/S, 2023). However, powder coating systems need to go through curing ovens with temperatures of 160-210°C within 10-20 minutes to reach the full cross-linking of the polymer and guarantee mechanical properties and corrosion resistance (Mafi et al., 2008; Yuan et al., 2023).

Powder curing may also be overheated, thus resulting in possible discoloration, embrittlement, or coating degradation, or be underheated, affecting poor adhesion and mechanical failure. As such, automated temperature regulation systems, real-time process control, and intelligent feedback control are the criteria that are being integrated into modern surface protection facilities to allow the achievement of optimal thermal efficiency (Abid et al., 2007; Li, Shi, & Christofides, 2005).

The industries are using waste heat recovery systems like recuperative burners, heat exchangers, and thermal insulation to improve energy efficiency and reduce heat loss, thereby enhancing the overall energy balance. As an example in galvanizing processes, the flue waste heat can be recycled to preheat the incoming atmospheres or even decreasing tubs, thus reducing fuel energy (Sapmaz et al., 2014). Additionally, the future of surface treatment facility operation is being overtaken by the incorporation of renewable sources of energy, such as PV and solar thermal collectors, as more facilities shift toward large-scale decarbonization, as well as the increasing environmental requirements and carbon pricing policies (Tasmin et al., 2022).

The interaction of the chemical formulation and thermal regulatory processes is at the heart of the technical and environmental performance of the surface protection steps. The potential improvements in process control technology, energy recovery technology, and renewable integration are avenues towards making processes more efficient and also meeting the global sustainability targets.

3.4 Environmental and Regulatory Challenges

The metal surface protection industry is under rising scrutiny, given its high level of environmental impact, namely, large water resources consumption, the use of unsafe chemicals, and the energy-intensive nature of the business. Electroplating, anodizing, phosphating, and hot-dip galvanizing can result in the production of plating baths, acid and

alkaline effluents, and solid wastes like sludge and blasting media. Such waste flows frequently include toxic and carcinogenic substances, including hexavalent chromium, nickel, copper, and complexing agents, which pose serious risks to both human and environmental health in case of improper waste management (Kowalik-Klimczak, 2025).

One of the highest environmental issues with surface finishing processes is water pollution. Heavy metals and persistent organic pollutants may pollute surface and ground waters in the case of poorly dealt with rinse water and spent solutions. To address this, most facilities have incorporated advanced wastewater treatment systems, which include chemical precipitation systems, ion exchange systems, membrane filtration, and biological oxidation systems. These investments are essential to achieve regulatory needs stated by controlling authorities such as the European Union and the national environmental protection agencies (Kowalik-Klimczak, 2025; European Commission, 2019).

Another serious problem is air missions. Painting, galvanizing, and chemical conversion coating processes generate VOCs, acid mists, and metal aerosols, which pose occupational hazards and stress on the environment. Regulatory apparatus such as the U.S. Clean Air Act, or, in the European Union, the Industrial Emissions Directive (IED), place strict upper standards and requirements to adopt best available techniques of air pollution abatement. As a result, industries have shifted more to water-based and powder-based coatings rather than solvent-based ones, which has drastically reduced the quantities of VOCs to less than 100 g/L level (European Commission, Joint Research Centre, 2019; European Commission, Joint Research Centre, 2020; Government of Canada / Environment & Climate Change, 2022).

To overcome these multifactorial issues, the industry is becoming increasingly involved in green innovations through green industry development that supports principles of the circular economy and environmental compliance. Such may involve closed-loop water systems that reduce wastewater effluent, zero-liquid-discharge systems, and the use of biodegradable surface treatment chemicals. Unlike more capital-intensive short- to medium-term initiatives, these sustainable practices have long-term payoffs, including cost savings, regional regulatory compliance, risk prevention, and enhanced corporate image (Friede et al., 2015; World Bank, 2024).

The use of an environmental management system (EMS), life cycle assessment tools, and online monitoring guides would also help in transforming industrial process, as these tools

would enable resource optimization and their real-time monitoring (Tan et al., 2023; Frias-Cacho et al., 2022). In this ever-evolving landscape, an increasingly business-centric view of environmental-related stewardship that is proactive as opposed to compliance-driven is emerging as a strategic imperative, rather than being purely regulatory.

4 Metal Coatings in Solar Panels

The conductive coatings of metal are the key factors that guarantee the efficiency and lifespan of solar modules and thus have a significant impact both on the electrical characteristics of a module and the durability of a cell in hostile weather conditions. The choice of coating material and processes must consider conductivity and corrosion resistance, mechanical stability, and costs to ensure overall system performance.

4.1 Types of Metal Coatings in Solar Panels

PV systems use a metal coating, which plays several essential functions in advancing the performance, resilience, and life of solar modules. The coating is applied to many components of solar-powered systems, including the actual surface of the solar cell, the frame holding the solar module together, and is chosen based on its electrically conductive properties, corrosion resistance, adhesion, optical properties, and cost effectiveness.

4.1.1 Solar Cells and Electrical Component Metal Coatings

Silver (Ag), aluminium (Al), copper (Cu), tin (Sn), and zinc (Zn) are some of the most commonly applied metallic coatings in conventional crystalline silicone(C-Si) solar cells. Silver front contact fingers are widely used in devices due to their high electrical conductivity (6.3 x 107 S/m) as well as compatibility with the screen printing process.

Although it is less conductive than silver, copper is more economically feasible and is used in the interconnect ribbons and recently in higher-end architectures like TOPCon and heterojunction cells. It is associated with a tendency to diffuse and, as such, is frequently coated together with nickel as a barrier layer.

Nickel and tin may be applied in multilayer metallization stacks, with use as either a solderability layer or a diffusion barrier. Although zinc coatings are not directly used on solar cells, they are extensively utilized in support frames and mounting structures,

especially using a hot-dip galvanization (American Galvanizers Association, 2009; American Galvanizers Association, 2012) method to provide cathodic and barrier protection.

New thin-film PV solutions (cadmium telluride (CdTe), copper indium gallium selenide (CIGS)) have a wider variety of metal coatings. They consist of molybdenum (Mo) as back contacts and transparent conducting oxide (TCO) like indium tin oxide (ITO) or aluminum-doped zinc oxide (AZO), whose deposition leads through PVD to high transparency and conductivity (Ong et al., 2018; Patel et al., 2024).

4.1.2 Protective Coatings for Structural Elements

Metallic structural elements of PV systems, like mounting rails and frames, need to be powder-coated to resist tens of years of environmental exposure. The industry standard material that would be used in such applications is galvanized steel, which has zinc coated on a material through the process of hot-dip galvanizing. Such coatings provide two levels of protection: barrier protection and sacrificial anodic protection. The prevalence of zinc coating weighs up to 1200 g/m^2 in the pure zinc and 1000 g/m^2 in zinc-magnesium (ZM) alloys, long exceeding standard requirements (American Galvanizers Association, 2012; Steel Mills of the World, 2013).

On the same note, anodized aluminium can be adopted where structural components are involved because of the improved hardness of the surface, thick oxide film, and resistance to corrosion attributed to the electrochemical process (HLC-MetalParts, 2024).

The thin-film solar modules require TCO coatings. Such materials as ITO and AZO offer a rare situation of both high optical transmission and low sheet resistance, so they can take the place of both front contacts and let the sunlight through.

4.2 Chemical and Physical Properties

Metal coatings have a direct relation to the chemical composition of the sample, its microstructural stability, and physical properties, all of which influence the functional performance of coatings on PV modules. These properties have a role in determining such features of solar panel performance as electrical conductivity, resistance to corrosion, optical

properties, mechanical strength, and compatibility with other parts of the modules at various temperatures.

Chemical properties of coatings depend on elemental composition, crystal phase, and behavior at the interface with a substrate. High electrical conductivity is a key performance factor in metallic-based coatings like silver, aluminium, copper, and so on.

Although it has lower conductivity (3.5 x 10 ^7 S/m), aluminum offers one of the best alternatives in terms of oxidation resistance because it is covered with an oxidation protective oxide layer of aluminum oxide (Al2O3). Copper, a near equal of silver (5.96 × 10^7 S/m), is used in advanced cell designs, especially in dual damascene technology, but needs nickel barriers to prevent diffusion into the silicon substrate (Engineering Toolbox, n.d.; Li et al., 2022; Li et al., 2020).

Intermediate metallizers commonly used in the multi-layer metallization environments are nickel and tin. The metallurgical gradients that form in protective coatings, like hot-dip galvanization, are mostly zinc-based.

Silicon nitride (SiNx:H) is widely used as part of the non-metallic functional coating. It has been deposited by PECVD and is composed of silicon-nitrogen bonds with hydrogen added to increase its passivation. Titanium dioxide (TiO2) coatings, especially in the anatase form, are photocatalytic materials capable of self-cleaning and anti-reflective behaviour, owing to their large band gap (3.2 eV), encouraging the formation of photo-generated electron-hole pairs by UV irradiation (Mannai et al., 2025; Omotosho et al., 2024).

To ensure the life and durability of solar panels due to environmental stresses, the mechanical/thermal response of the coating is critical. Anodized aluminum consists of a strong oxide layer that is bonded chemically to the base metal, thus, outstanding scratching response and delamination can be avoided.

Silicon nitride coatings are highly thermally stable and have good mechanical adhesion, as PECVD synthesizes them and can be tuned in terms of composition. Zinc-based galvanized paint is protected by a multi-layered corrosion resistance mechanism, which includes protection by the barrier, the catalytic reaction, and intermetallic bonding with the steel undercoat.

4.3 Role in Corrosion Resistance and Environmental Behaviour

Metal coatings on PV modules are key to durability, performance stability, and environmental resiliency of the system over the life of the solar panel. The weather conditions, such as ultraviolet radiation, wet, salty environments, temperature changes, and industrial pollution, require the use of strong defence measures to protect electrical units as well as building materials (Rana et al., 2025).

The main process of degradation of solar panels in the environment is atmospheric corrosion, and moisture and atmospheric pollution promote the destruction of unprotected metals (Rana et al., 2025). Metal coatings are important defense mechanisms; they develop physical barriers or make sacrificial protection possible and prevent the start of corrosion. The coatings of galvanized steel, which are popular in solar mounting construction, have two productive functions. Zinc is used as a barrier and also as a sacrificial anode, which continues to protect the underlying steel in case of scratches (severe damage) or any mechanical chip (American Galvanizers Association, 2009; American Galvanizers Association 2012). Zinc galvanic action increases the surface life and supplies localized protection to areas that are prone to damage.

Galvanized coatings have a high dependence on the effectiveness of their thickness, as well as that of all alloying. Generally, pure zinc coating is effective to guarantee a reliable corrosion resistance of more than 50 years in moderate environments, and advanced zinc-magnesium alloy is more adaptive to corrosion resistance in hostile or seashore conditions because of its adhesive and self-healing properties (American Galvanizers Association, 2008; Qiao et al. 2024). All these alloyed surfaces react with atmospheric components to form stable forms of corrosion whose products seal off the surface further, thereby preventing corrosion.

Nickel is commonly used in multi-layer applications, often in conjunction with copper, to act as a corrosion and diffusion barrier, as well as a diffusion barrier and corrosion-inhibiting interlayer. Silver is a noble metal that is always prone to tarnishing in some environmental conditions. It is therefore coated with a multilayered polymeric coating inside the module to give protection against atmospheric effects and maintain its reflectivity and conductivity over time (Aliofkhazraei et al., 2021; Zhang & Xue, 2019).

4.4 Performance Contribution and Material Choice

Metal coating plays a critical role in enhancing the energy conversion efficiency of the PV modules, structural strength, minimizing long-term maintenance, and achieving economy. The properties of coating materials will affect the thermal stability and environment, as well as the optical and electrical performance of solar cells. The right balance of performance, sustainability, and economics leads to the rationale of choosing the materials.

The use of metal-based coatings and the manner of treating the surface considerably influence the energy output of the PV systems. Anti-reflective coatings (ARCs) are one of the most direct improvements as they reduce the amount of sunlight reflected off the surface of solar cells and increase the capture of photons (Ji et al., 2022).

Absolute levels of efficiency have also shown measurable improvement by these systems, such as a 0.21% cell-level increase that is carried to the module level (Galiazzo et al., 2015). Such coatings are advantageous, particularly with the changing conditions of sunlight, where a uniform energy is produced.

Also, self-cleaning coatings, containing hydrophobic or photocatalytic components, help maintain the specified results by preventing the accumulation of dust and organic substances. Dust layers may reduce the generation capacity by 10 to 25% over long periods, therefore, the coatings are of the utmost importance in the retention of energy in the long term, especially in arid regions or polluted territories (Quan et al., 2022).

The aim of coating materials must be carefully selected based on several key criteria, including optical properties, thermal and chemical stability, availability of coating process, coating costs, and ecological factors. Materials, in an anti-reflective application, have an appropriate range of refractive index and extinction coefficient, compatibility with high-throughput deposition methods, and long-term environmental exposure.

In conductive applications, silver is the standard in the industry used as a front-side metallization with the highest possible electrical conductivity, leading to minimum resistive losses. However, there is current PV research involving copper as a cheaper alternative, especially in emerging countries.

The frames of the solar panel, back contact, and back surface field layer are commonly made of aluminium as it is lightweight, resistant to corrosion, and can be anodized. The durability and mechanical properties coupled with the anodized aluminum surface have since been proven to be the best surface for use on rooftops where the weight and corrosion are particularly high (Olkowicz et al., 2023).

High-performance coatings have immense economic advantages because of their material benefit concerning the lifetime of a PV. The use of self-cleaning coating, though it is expensive at the onset, will reduce the amount of cleaning necessary to the system, especially in dusty zones, which continues to keep the system efficient and reduce operation cost (El-Mahallawi et al., 2022). Supporting structures are also proven economically viable over the long term with the aid of protective coating. This obviates the cost of repainting or structural repairs, thereby saving a significant amount in the lifecycle (American Galvanizer Association, n.d.).

4.5 Coating Techniques Used in PV Panels

Surface coatings during and after the production of PV modules play an important role in defining the performance and durability of these modules. These coatings can perform a wide variety of functions, including anti-reflective, electrical conductivity, corrosion resistance, and structural protection. There is a broad spectrum of coatings used within the PV industry, such as CVD and PVD, wet chemical techniques, electrochemical techniques, and classic galvanizing. The choice of what technology to use rests on the compatibility of the technology with current substrates, performance requirements, scalability, and economic viability of the technology.

4.5.1 Electroplating and Electroless Plating

The deposition processes used in the manufacture of multilayered contacts and barrier coatings, in particular those using nickel and copper, are electrochemical processes such as electroplating and electroless plating. These factors can be attributed to the fact that they can work with selective planning and patterning technologies, as well as an upsurge in the

miniaturization and accuracy trends in the PV fabrication (Cheng et al., 2018; Meziani et al., 2023).

4.5.2 Hot-dip Galvanizing

Hot-dip galvanizing is used in deep PV mounting structures to protect the steel. However, it cannot be applied to the solar cells directly, but the PV mounting structure is critical. The mechanism of action involves dipping steel parts in molten zinc, forming a syngenetic coating through metallurgical bonding, which provides a durable, long-term sacrificial means of corrosion protection. The method provides structural stability and minimum maintenance, particularly in rough atmospheric conditions (American Galvanizers Association, 2009).

Galvanizing is a good example of a cross-industry technology where companies such as Eurosjaj may consider transferring their structural coatings expertise to the metal treatment services that focus on PV.

4.5.3 Surface Treatment and Preparation

All coating techniques should have proper surface preparation. Notably, in contrast, metal substrates, e.g., mounting frames or backplates, may require mechanical cleaning, chemical etching, or flux treatment (Pre-Coating Surface Preparation, n.d.).

Chemical bonding between the substrate and functional coatings is usually reinforced with advanced in-process treatments, e.g., primer coatings or saline-based adhesion promoters, e.g., APTMS (Pan et al., 2023). Such techniques are instrumental where an assembly includes multiple materials and where delamination of the coating can be particularly hazardous because of the variation in thermal and mechanical characteristics.

4.6 Sustainability and End-of-life Considerations

With the spread of PV systems and technologies and with increased volume of production, the sustainability of the employed materials and, especially, the metal coating, gains particular importance.

4.6.1 Resource Recovery and Material Recyclability

The use of metal coating of PV modules and supporting structures, e.g., galvanized steel, is not only essential to ensure that the module is not susceptible to corrosion but also that recycling and recovery of resources are facilitated. As such, galvanized steel makes the ideal material to use in PV as part of a circular economy approach. This makes the recycled item commercially viable, given the inclusion of zinc, which sets it apart in more ways than one from the uncoated steel product and lowers the total environmental cost incurred in the making of raw materials (American Galvanizers Association, 2024).

The complexity of multilayered materials and thin layers of coatings on laminated or encapsulated substrates is one of the significant challenges in PV recycling because those materials are frequently tough to separate by a mechanical route. In a bid to deal with this, scientists are studying the development of environmentally friendly delamination processes.

Moreover, there has been a recent trend of extracting silicon from end-of-life solar panels, which has proven to recycle waste into valuable materials. These forms of upcycling take sustainability a step further by upcycling retrieved materials to even more valuable uses. A potential opportunity to improve sustainability is the creation of a biodegradable coating.

4.6.2 Environmental Impact

There is an increasing usage of life cycle assessments, which aim at quantifying the environmental performance of metal coating over its life cycle. Hot-dip galvanized coating layers and others provide significant lifecycle benefits as they do not require recoating and maintenance over time, thus decreasing the emissions, work, and resource consumption

levels (American Galvanizers Association, 2024). The coated mounting structure has a long operational life.

Besides, anti-reflective and functional coatings increase the efficiency of energy output by PV modules. In this regard, coatings can play an indirect role towards the emissions reduction targets, they help to maximize output without increasing the footprint of the system.

Higher recycling solutions integrated in thermal, chemical, and mechanical processes have been effective in the recovery rates of the materials (85% and more), particularly when designed to be considerate of the end-of-life conditions.

5 Design and Integration of PV Systems

The engineering of PV systems cannot be treated in isolation, as it needs to be considered in terms of technical performance, economic viability, and regulatory constraints. The proper integration means that energy production should align with the consumption assumption, as well as offer the highest level of efficiency and the sustainability of industrial activities in the long run.

5.1 Technical Overview

The PV plant that is used in this self-consumption model is a facility that serves to produce electricity directly at the consumption site and thus reduces reliance on external electricity grids, increases energy independence, and improves long-term operational stability. The design and arrangements of such systems are composed of various interdependent parts, which require equal effort in assuring the safe, effective, and reliable energy production.

The key energy-converting aspect of the system is the PV modules. These units consist of two or more interrelated solar cells, usually of monocrystalline or polycrystalline silicon, that generate direct current (DC) electricity by harnessing solar energy to electricity via the PV effect. Mass-produced monocrystalline modules have efficiencies of between 22 and 24%. Still, the available models with the highest efficiency can now soar up to 24.4% especially modules with advanced back contact, heterojunction, and tunnel oxide passivated contact technologies (Fraunhofer ISE, 2023). The high-efficiency modules are strongly beneficial where industrial rooftops are considered. In such situations, output per unit area becomes one of the most critical design considerations.

The inverter serves as the focus point to make the conversion. It takes the DC electricity generated by the PV modules and converts it to alternating current (AC), which industrial loads and the grid can use. The choice of inverts is size and architecture dependent as well as sensitive to shade. String inverters are most typically used on medium-sized installations, central inverters on large-scale plants, microinverters or power optimizers on systems with different module orientations or partial shade. The newest generation of so-called smart inverters combines artificial intelligence (AI) and machine learning (ML) algorithms to

improve maximum power point tracking, improve performance over a wide range of conditions, enable real-time operation, and facilitate predictive maintenance, as well as support more advanced grid-interactive functions (IEA, 2022).

The mounting structures have the purpose of keeping PV modules fixed and orienting and tilting mounted modules to maximize energy generation in rooftop systems. In industrial settings, ballast-mounted systems can be employed on flat-roofed buildings, or fixed tilt rack systems can be used on pitched roofs. In contrast, ground-mounted arrays can be used where there is no available rooftop real estate. All mounting structures should be certified against internationally recognized engineering and safety standards, including IEC 61215 and IEC 61730, which require tighter mechanical load testing and limits on the degree of degradation of the mechanical structure, which have been lowered to 5% and 8%.

Electrical protection and safety devices protect personnel and equipment. These are surge protection devices, fuses, circuit Breakers, and residual current devices. DC isolators are also necessary in high-power industrial PV installations to maintain safe procedures. Protective systems are required to operate and meet IEC 60364 design requirements and become incorporated in the electrical architecture of the plant to provide detection and prompt de-energizing when needed.

Industrial self-consumption applications can only be successful with monitoring and control systems that allow a real-time overview of the generation, consumption, and performance indicators. The state-of-the-art systems use predictive analytics to identify anomalies before failures, compare past production data to current production, and adjust operational strategies that maximize matches between PV generation and load profiles (Dimitrova-Angelova et al., 2025).

Although battery energy storage systems (BESS) are not critical to grid-tight self-consumption systems, they can significantly expand the on-site PV share of consumed PV energy. The current large BESS solutions cover up to 500 kWh to several GW-hours of capacity with lithium-ion chemistries playing a dominant role because of high energy density, efficiency, and scalability. Altogether, the planning of an on-site PV plant must strike a balance of technical feasibility, site-specific conditions, economic feasibility, and compliance with the regulations.

5.2 Grid Connection vs. Island Mode

The operational mode of the PV system is also an important design parameter that directly determines the technical architecture, cost plan, and resilience of operations of such a system. Generally, self-consumption PV plants may exist in three types of configurations: grid-connected, islanded (off-grid), or hybrid, which, in addition, incorporates the characteristics of the first two and ensures the highest rate of reliability and flexibility.

Grid-connected PV systems are physically connected to the public electricity grid, which allows two-way power. Any excess energy produced over the instantaneous requirement of the site is exported to the grid. In contrast, any deficit in PV production can be supplied by the importation of electricity. This gives a continuous power supply and, to a very great extent, diminishes the need for large-scale vivid store inventory. Grid connectivity allows operating flexibility in industrial facilities, where load is frequently relatively constant during daylight hours, and enables high levels of utilization of the PV generation.

Innovations in inverter technology have also enhanced the grid-connected capabilities. Recent advances in inverters now provide inverters with grid-support features, including frequency regulation, voltage stabilization, and reactive power control, enabling PV systems to adapt to grid variations (NREL, 2021/2020).

Island mode operation, in contrast, involves no longer being connected to the utility grid at all, no longer providing the local loads, which are fully self-sustained with a combination of PV generation and a BESS. Such systems are technically more demanding in their design and operation. They must optimise load balancing, redundancy planning, and have highly oversized storage capacity to remain reliable during periods of low solar irradiance or after dark. Off-grid systems are designed to include auxiliary power sources, e.g., diesel generation or gas turbines in industrial applications, to keep production alive when the forecast indicates long periods of low solar (Hidalgo-León et al., 2022).

Another trend in PV deployment has become the emergence of hybrid systems, able to switch between being connected to the grid and operating as an island. Such resilience can, in the manufacturing or process industries, avoid expensive production shutdowns. Additionally, hybrid systems provide the opportunity to proactively balance the incoming and outgoing energy flow among PV modules, storage, and grid, allowing hybrid systems to

take part in demand response and other grid-interactive initiatives, opening new streams of revenue (Mohamed, Khan, & Malik, 2022).

Economically, the grid-tie PV system tends to be cheaper to implement initially when compared to fully islanded systems, which require the installation of large-scale battery banks. Island or hybrid mode may represent better long-term value in areas of uncertain grids, high electricity tariffs, or those where energy security is a strategic priority. Overall, the grid-connected, island, and hybrid modes of operation as selected need to realize a reasonable evaluation of technical feasibility, economic trade-off, site-specific conditions, and reliability needs.

5.3 Policy and Administrative Aspects

The successful implementation of the self-consumption of PV through a technically sound design depends not only on the navigability of regulatory, administrative, and policy frameworks. These structures that are developed at an international, national, and regional level have the potential to shape the feasibility of projects, the amount of capital required, the duration of construction, and the level of profitability in the long term.

The first step in planning often includes a technical and economic feasibility study, which involves the evaluation of available roof or land space, solar isolation profiles, patterns of electrical loads, and the system size that is possible. That is followed up by a conceptual design and a lay-in of the financial analysis with the capital expenditure (CAPEX), operational expenditure (OPEX), and return on investment (ROI) projection. In self-consumption deployments, the sizing approaches typically effectively aim to maximize the time matching the PV generation and local demand to minimize excessive exports to the grid and maximize the resulting costs of avoided electricity purchases (Rodríguez-Martínez & Rodríguez-Monroy, 2021; Garabitos Lara & Vallejo Díaz, 2024).

The administrative process is jurisdiction-specific, but it is typically typified by facilitated interaction with regional and local permitting jurisdictions and grid operators. In the European Union, the Renewable Energy Directive 2018/2001 (revised in 2023 with the introduction of a binding 42.5 per cent renewable energy target by 2030) requires Member States to be able to administer simpler and proportionate procedures to small- and medium-

sized renewable projects (European Union, 2018; European Union 2023). The most important actions are fast-tracking permitting and having uniform grid connection requirements, as well as shortening technical documentation on projects that are below the thresholds.

New forms of regulation have then included introducing flexible grid connection contracts, especially in areas of grid-constrained grids. At the same time, capacity allocation practices by grid operators that demand the publishing of real-time grid constraint information and advanced network development plans have been adopted in multiple EU member states, which have augmented transparency and trust of investors.

The compliance requirements have also changed the technical aspects. The international standards that cover large-scale and industrial PV plants are also being revised: IEC 61215:2023 (performance qualification) and IEC 61730:2023 (safety) now require more extreme requirements about high-voltage components, fire resistance, and mechanical stability.

The role of policy in promoting the use of PV self-consumption is another area that cannot be diminished, as this financial incentive makes decisions. Investment grants, fast depreciation schemes, exemptions or reduced taxation (e.g., 0% VAT rate in Austria and Germany on systems <35kW), and favourable financing arrangements are available through the EU. The direction of policy has shifted away from traditional feed-in tariffs and towards self-consumption incentives and energy sharing, aligning with EU priorities of focusing on decentralized, local energy utilization.

Reaching a policy milestone in 2024 with the introduction of energy sharing frameworks is a critical moment. Such frameworks allow sharing surplus self-generated electricity between consumers under contract, avoiding individual self-consumption among apartment-housing consumers and within energy communities within the same vicinity. Such processes take advantage of price differences to encourage the shifting of loads to reduce congestion in grids.

Overall, streamlined administrative procedures and a favorable regulatory environment form the most important facilitators of the PV market. Effective policy design can smooth the process of project development, reduce the financing risks, and increase the competitiveness

of the system. In contrast, bureaucratic hang-ups or regulatory ambiguity can serve as a considerable obstacle to deployment.

6 Methodology

In this chapter, the methodological framework to assess the economic feasibility and environmental impact of PV integration to self-consumption at Eurosjaj d.o.o. is described. The research is a quantitative scenario case study-based research involving technical simulation, financial modeling, and environmental impact study. The combined solution ensures that both economic and sustainability factors are considered, which is appropriate given the company's dual strategic goals: reducing and complying with emerging climate-related regulations.

6.1 Research Approach and Design

Methodological design is based on applied research concepts, namely the application of a single-case quantitative research method that provides the ability to analyse in detail a given industrial case based on the real operational data. The three scenarios being compared in the study are as follows, with a 30-year analysis horizon:

1. Baseline Assessment - Establishing the current energy demand and cost profile of the company without PV integration (Scenario 1)
2. Current Integration Evaluation - Assessing the operational and financial performance of the existing PV plant installed in August 2024 (Scenario 2)
3. Full PV Expansion Projection – Modeling the performance and financial viability of an expanded PV system covering nearly 100% of electricity demand (~5 MWp) (Scenario 3)

The scenario method enables the quantification of both absolute and relative advantages. A PV degradation rate of 0.5% per year is applied in technical modeling, as this is the current record of achievers in modular crystalline silicon (Jordan & Kurtz, 2013). Financial analysis is determined at a discount rate of 6% taken as the median weighted cost of capital in industrial renewable energy projects in the Western Balkans (Steinbach & Staniaszek, 2015).

This is an uncertainty-supportive comparative structure adopted to aid in decision-making. It allows the management to evaluate incremental benefits, assess risk exposure, and

formulate phased investments. Moreover, with a case of maximum adoption, the analysis can identify the upper economic and environmental potential.

6.2 Data Collection and Validation

The analysis dataset is a combination of primary operational data and secondary reference data of Eurosjaj d.o.o., as well as official and peer-reviewed resources.

Monthly records of high- and low-tariff electricity consumption, starting in August 2023, are used as primary data. Additionally, the objective output measures of the active PV installation, technical specifications of PV modules and inverters, investment cost data records, and notes on maintenance expenditures are considered.

On the other hand, secondary data are market cost benchmark values for the installation of PVs, Solar radiation data provided by the European Commission Photovoltaic Geographical Information System (PVGIS), grid emission levels supplied by the European Environment Agency, and estimated eventual carbon pricing provided by the European Commission CBAM policy information.

6.3 Analytical Framework and Environmental Impact Calculations

The technical part evaluates the performance of PV systems, which incorporate electricity production, self-consumption, capacity use, and system degradation during the lifetime of the system. The calculation of the annual energy generation is done as:

$$E_t = P_{installed} \times Y_{specific} \times (1 - d)^{t-1} \quad (1)$$

Where:

E_t - energy generated in year t

$P_{installed}$ - installed PV capacity

$Y_{specific}$ - specific yield per kWp

d - annual degradation rate

This enables us to measure the percentage of PV contribution to the total electricity demand as well as system efficiency over a period of time.

A Total Cost of Ownership (TCO) based financial analysis is used, with typical investment appraisal ratio standards. The TCO reflects all costs incurred in each of the scenarios in the present values of costs over the project lifetime:

$$TCO = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{2}$$

Where:

C_t - includes CAPEX, OPEX, replacements, and electricity purchases

r - the discount rate

n – project lifetime in years

The Net Present Value (NPV) measures overall project profitability, and it is calculated as:

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{3}$$

Where:

B_t - total benefits in year t, including avoided electricity costs and carbon costs

C_t - total costs in year t

A positive NPV implies that the PV investment makes a profit in a greater amount than the discount cost, which implies its application from an economic point of view.

The discount rate r, which makes this true, is called the Internal Rate of Return (IRR) and is calculated as:

$$0 = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{4}$$

IRR provides the annualized effective return of the investment and is compared with the company's cost of capital to assess viability.

Levelized Cost of Electricity (LCOE) calculates the average cost per unit of electricity generated, and for the PV system, is calculated as :

$$LCOE = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \quad (5)$$

Where:

E_t - electricity generated in year t accounting for degradation.

The LCOE describes the cost as the generation of each unit of electricity and enables comparison with the generation of grid electricity over time.

The environmental component evaluates the avoided CO_2 emissions due to PV self-consumption:

$$Avoided\ Emissions\ (tCO_2) = \sum_{t=1}^{n} E_t \times EF \quad (6)$$

Where:

E_t - annual PV electricity generation in MWh

EF - grid emission factor in tCO_2/MWh

The monetary value of avoided emissions is calculated by applying projected carbon prices:

$$Carbon\ Value = \sum_{t=1}^{n} \frac{E_t \times EF \times P_{CO_2,t}}{(1+r)^t} \quad (7)$$

Where:

$P_{CO_2,t}$ - projected carbon price per ton in year t

This combination will harmonize ecological advantage with cost evaluation, indicating the risk of being subjected to measures like CBAM.

Using these technical, financial, and environmental formulas jointly, the framework offers the full (scenario-based) estimation of the adoption of PV systems in a way that enables decision-making about uncertainty, in addition to the main aspects of trade-off and optimal pathways of investment (IRENA, 2019; Almulhim, 2023).

Despite the various financial and environmental formulas that are being applied, the NPV is the most pressing formula for decision-making. Unlike the payback period, which only regards the time period over which the money invested in the undertaking is recovered, NPV addresses the problems concerning the time value of money, the total profit of the specific investments, and all the expenses involved. This will help the management to know whether, besides being payable, the investment in PV will leave a surplus to be used elsewhere. NPV is the value-creating measure of the final value, which is primarily applied to capital-intensive businesses where opportunity cost is high. As an example, the fact that the NPV is sufficiently high in the conservative expectation signifies that the PV project will even be viable under a less favourable market scenario. The consistency of all technical, financial, and environmental formulas in the chapter makes it possible to make a direct comparative analysis of economic and sustainability consequences in all three scenarios.

6.4 Methodological Validity

The methodological foundation is paired with the suggestions of the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA). It integrates standardized formulas, transparent assumptions, and validated data sources. The dilemma here is that scenario consistency is obtained by using the same financial and technical assumptions in all cases, and this is possible, and hence strong comparisons are made.

The rigorous technical modelling combined with financial and environmental valuation helps to test, in a solid manner, the long-term strategic benefit of adopting PV at Eurosjaj d.o.o. By doing so, this methodology will ensure that the recommendations associated with

the analysis will be quantitatively assessed and will be consistent with operational reality and strategy objectives.

Other limitations are considered by the methodology, such as fluctuations in production and energy provision, assumptions in modeling the system's performance, and simplifications in financial forecasting.

7 Case Study

The case study has examined the techno-economic and environmental implications of incorporating the use of PV electricity generation in operating Eurosjaj d.o.o. production operations. The manufacturing processes, such as galvanizing and coating processes, demand a regular and continuous supply of power. Hence, the electricity costs present a significant impact on the overall operational cost. In addition, the company's high level of export orientation to the EU exposes it to direct compliance under the CBAM.

Self-consumption through PV integration has several possible advantages that include reduced dependence on grid electricity, reduced risk to energy price fluctuations, reduced CO_2 emissions, and, finally, a simplified kitchen with a carbon tax compliance shutdown in the EU. In addition, the process of PV succession is also consistent with the company's long-term decarbonization strategy that incorporates the application of systematic energy efficiency audit, personnel training, and the intended expansion of renewable energy capacity.

The scenario analysis contained in this chapter is carried out over 30-year operational period and analyzes the economic and environmental performance of three different energy supply situations.

7.1 Company Background

Eurosjaj d.o.o. Began its operation in 1996, among the first joint venture enterprises in Bosnia and Herzegovina, and established itself as one of The Pioneers of metal surface protection businesses. It has over 540 employees and it works in several international markets. The firm provides leading surface treatment technologies, and there are 26 different processes available for surface protection, including zinc plating, decorative nickel plating, chromium plating, copper plating, and special coating applications. Although its manufacturing facility is installed in the industrial zone of Konjic, in Bosnia and Herzegovina, its key export destinations (Croatia and Austria) involve it firmly in the European regulatory system.

Metal surface protection industries are energy-intensive industries by nature, with the amount of electricity used in similar industrial sectors making up to 40% of the total operating expenditure. Continuous power is required in large volumes because of the electrochemical reactions involved in galvanic treatments, as well as heating and climate control of the production plant. The strategic significance of cost optimization testifies to sustaining the competitive position in the domestic and international markets, which is reflected in this energy profile.

7.2 Current Energy Profile and Operational Characteristic

To give a precise evaluation of PV system integration, it is imperative to have a comprehensive picture of the existing energy profile. The subsection provides a quantitative and qualitative account of the electricity usage pattern and energy requirements of the production process in the facility, which has been developed as a benchmark for evaluating the outcomes of the scenarios.

7.2.1 Electricity Consumption Analysis

The electricity load characteristic in the facility indicates that the metal surface protection processes are energy-intensive. The average monthly consumption experienced in the firm is 530,648 kWh or roughly 6.37 GWh in a year. This makes it one of the major users of electricity in industries within Bosnia and Herzegovina.

Purchase of electricity is based on the dual tariff charge regime, whereby the high tariff charges are pegged at 0.12 EUR/kWh, and the low tariff charges lie at 0.08 EUR/kWh. Peak and off-peak demands have been replicated in this structure, which is very common in the electricity market of Bosnia and Herzegovina, and the expensive period is during the day when there is more activity in the manufacturing sector, coinciding with general demands.

7.2.2 Production Process Energy Requirements

The major drivers of energy consumption are lines 4, 5, 6, 7, and 8, which involve most galvanic processes, including hot zinc plating and special coating procedures. They need

fine temperature regulation, high amounts of electrochemical energy, and the maintenance of auxiliary systems around the clock with high volumes of ventilation, pumping, and unloading.

Because of the electrochemical nature of the processes, high DC demand occurs, and supporting heating systems need to maintain optimum operating temperatures in the range between 25°C and 75°C. More energy is required to heat baths, operate controlled facility environments, fume extraction systems, and transport equipment. The systems being dependent on one another offer prospects of efficiency gains that will have a ripple effect through the production process.

7.3 PV System Integration Status

PV systems have emerged as an increasingly relevant option in industrial energy planning, addressing cost aspects, decarbonization, and energy security. In the case of Eurosjaj d.o.o., the application of the PV installation decision was motivated by both the goal of increasing the organization's independence from grid electricity and the goal of reducing exposure to fluctuating electricity market prices. Besides the economic justification, the system is a strategic investment in the long-term sustainability goals of the company and ensuring compliance with the rising EU climate measures, including the CBAM. The subsections below outline the existing PV infrastructure installed, the design and performance features that form the operational efficiency of this infrastructure.

7.3.1 Existing PV Infrastructure

The PV system is a two-step,grid-connected PV 830kWp system consisting of a first 600 kWp and a second 230 kWp that is commissioned on 1st August 2024. The system is configured to be entirely on-site self-consuming with no battery storage or export settlement to the grid, meaning that the generated solar electricity is used directly by the facility to eliminate the daytime demand, especially by the energy-intensive activities like hot-dip galvanizer and production line 4-8.

In summer, the installed PV system contributes about 10% of the instantaneous power load of the facility. When seasonal generation rates are considered, effective self-consumption is estimated at 573,100 kWh, or approximately 9% of the total electricity demand of the plant, on an annual basis. This level shows continuity against this damaging summer coverage because higher solar resource in Bosnia and Herzegovina (1,300-1,400 kWh/ m² per year) makes PV-based production sensible (although less in winter months).

The technical lifetime of the plant is defined as 30 years, and the degradation rate of the modules is 0.5% yearly. Operation and maintenance is estimated to be 511.31 EUR in the first year and increasing by 2% every year.

Based on the PV self-consumption of approximately 582,676 kWh/year, the system yields annual savings of roughly 57,471.21 EUR. Such operational configuration places the PV system as a cost-optimization intervention on one hand and a decarbonization strategy in the other hand, which are essential in reducing long-term energy costs and greenhouse gas emissions.

7.3.2 System Design and Performance Characteristics

In the current study, the grid-average CO_2 emission factor in Bosnia and Herzegovina is taken to be EF=0.585 tCO_2/MWh (585gCO_2/kWh). It is consistent with the numbers produced in national inventories within the United Nations Framework Convention on Climate Change (UNFCCC) and the IEA. It is a humble number that can be justified as a regional policy evaluation because published data in national inventories and global databases are dependent on the year of publication and the methodology used. The possibility of comparing scenarios is ensured by modelling the EU CBAM with a constant real term of 85 EUR/tCO_2 (GIZ & International PtX Hub, 2023).

Depending on regional solar resource conditions, the gross annual generating potential of the system is about:

$$Generation = 830\ kWp \times 1{,}300\ \frac{kWh}{\frac{kWp}{year}} \approx 1{,}079{,}000 \frac{kWh}{year} \quad (8)$$

Nevertheless, only part of the theoretical potential is achieved, resulting in sufficient savings because of the operational limitations (i) the coincidence factor, i.e., how well PV generation coincides with real-time facility demand; (ii) the inability to export power to the grid. The present operational profile of the centre attains 573,100 kWh/year of self-consumption, representing 9% of the total yearly electricity need for the facility.

The seasonal comfort performance in Bosnia and Herzegovina is affected by the variation in solar irradiance during seasons, which generates considerable differences between summer and winter performance. The system is able to take full advantage of PV electricity during times when high tariffs would otherwise be generated, as peak generation in the summer correlates with peak energy-intensive operations of galvanizing. This time-based convergence generates a high level of working synergy, both increasing the potential of the PV system in terms of cost savings and optimizing the environmental performance. The government raised the national emission factor, which expresses the annual tons of CO_2 emissions avoided thanks to PV self-consumption as:

$$CO_2 Avoided = 573{,}100\ kWh \times 0.585 \frac{kgCO_2}{kWh} \approx 335 \frac{tCO_2}{year} \quad (9)$$

This contribution supports Eurosjaj's decarbonization strategy, which includes broader measures for energy efficiency and CBAM compliance. The PV integration thus serves a dual purpose, as a cost-optimization intervention and as a low-carbon technology investment that enhances the company's competitiveness in the EU market for metal surface protection services.

7.4 Scenario Analysis

In an effort to determine the possible effects of adopting a PV system for self-consumption, a thorough scenario analysis is performed. Such an analysis enables a methodical analysis of various operational and financial costs during the lifetime of the project. Variations in energy consumption, electricity prices, and related environmental and regulatory factors are all contemplated in each situation.

7.4.1 Scenario 1

Scenario 1 represents the baseline case, in which all of the company's demand is supplied exclusively from the national grid, without any investment in PV generation. Under this scenario, Eurosjaj purchases electricity at the contracted fixed tariffs, and for a more straightforward calculation, we will assume that the price is 0.098 EUR/kWh. Electricity costs in this scenario are solely determined by the grid tariffs and their annual escalation, without any offset from PV generation. The baseline analysis horizon is 30 years, which aligns with the expected operational lifetime of a potential PV system.

In year 0, the company's annual electricity bill at the electricity tariff and annual consumption equal:

$$Year\ 0\ electricity\ cost = 6{,}367{,}776\ kWh\ \times 0.098 \frac{EUR}{kWh} \tag{10}$$

As previously mentioned, electricity prices escalate at 2% per year so that the 30-year tariff will rise. Considering that, the electricity cost is calculated for 30 years and is presented in Table 1.

Table 1: Calculations for Scenario 1

Year	Annual Consumption (kWh)	Electricity Price (€/kWh)	Annual Electricity Cost (€)	Cumulative Cost (€)	CO_2 Emissions (tCO_2)	CBAM Cost (€)
0	6,367,776	0.098	628,528	628,528	3,725	316,638
1	6,367,776	0.101	641,099	1,269,627	3,725	316,638
2	6,367,776	0.102	653,921	1,923,548	3,725	316,638
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
30	6,367,776	0.179	1,138,492	26,636,681	3,725	316,638

Since this scenario involves no capital investment, the IRR is not applicable, as the IRR is used exclusively for assessing investment projects with defined cash flow series. Therefore, it represents a continuous stream of electricity-related costs without any renewable energy generation. The LCOE, calculated using the company's annual electricity consumption,

electricity price, and CBAM costs, is 0.19 EUR/kWh. This value reflects the effective cost per kWh over a 30-year analysis period, incorporating electricity price escalation, a 6% discount rate, and the inclusion of CBAM expenses.

The lifetime electricity cost, equivalent to the TCO, amounts to 36,452,448 EUR over 30 years. CAPEX is 0EUR because no PV system is installed. Over the same period, total CO_2 emissions from purchased electricity are estimated at approximately 115,480 tCO_2. At current carbon prices, these emissions would generate CBAM liabilities of about 9,815,767 EUR.

In the baseline scenario, the company would spend over 36 million EUR on electricity purchases alone (undiscounted), while bearing full exposure to market price fluctuations and regulatory carbon costs. These results provide a reference point for evaluating the economic and environmental benefits of PV integration in subsequent scenarios.

7.4.2 Scenario 2

Scenario 2 evaluates the performance of the PV system currently operating at Eurosjaj, commissioned on 1 August 2024. The system has a total installed capacity of 830 kWp, consisting of an initial 600 kWp installation supplemented by a 230 kWp array. It is designed primarily for self-consumption, thereby reducing reliance on grid electricity and partially mitigating exposure to both electricity price escalation and regulatory carbon costs.

The annual PV output is derived from observed performance data, assuming that the system covers approximately 9% of the company's electricity demand during peak summer months. Module degradation is incorporated into the projections, leading to a gradual decline in generation over the 30-year analysis horizon. The self-consumed PV electricity directly offsets grid purchases, which in turn reduces annual electricity costs.

Table 2: Calculations for Scenario 2

Year	Annual Consumption (kWh)	Annual PV Output (kWh)	Grid Purchase (kWh)	Electricity Price (€)	Annual Grid Cost (€)	Annual Total Cost (€)
0	6,367,776	0	6,367,776	0.098	628,528	628,528
1	6,367,776	573,099	5,794,676	0.101	583,400	583,911
2	6,367,776	567,383	5,800,392	0.102	595,655	596,166
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
30	6,367,776	493,086	5,874,690	0.179	1,050,333	31,050,845

Table 3: CO_2 emissions and CBAM liability Scenario 2

Year	CO_2 Emissions (tCO_2)	CO_2 Avoided (tCO_2)	CBAM Cost (€)	CBAM Savings (€)
0	3,725	0	316,638	0
1	3,390	335	288,140	28,497
2	3,393	332	288,565	28,213
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
30	3,437	288	292,119	24,519
Year	CO_2 Emissions (tCO_2)	CO_2 Avoided (tCO_2)	CBAM Cost (€)	CBAM Savings (€)
0	3,725	0	316,638	0
1	3,390	335	288,140	28,497
2	3,393	332	288,565	28,213
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
30	3,437	288	292,119	24,519

As summarised in Table 2, the analysis covers annual electricity consumption, PV generation, self-consumption, grid purchases, electricity costs, PV operational costs, and

total annual and cumulative costs. For example, in Table 3, in year 0, the company emits 3,725 tCO_2, avoids no emissions, and faces CBAM costs of 316,638 EUR. By year 1, PV generation avoids 335 tCO_2, reducing CBAM costs by 28,497 EUR. This trend continues with minor annual variations due to degradation, with avoided emissions in year 30 amounting to 288 tCO_2 and CBAM savings of 292,119 EUR.

In energy terms, annual grid purchases are reduced by approximately 573,100 kWh in the first year, corresponding to a reduction in electricity expenditure of about 57,700 EUR compared to the baseline without PV. Over the 30 years, the system has consistently generated at the baseline without PV. Over 30 years, the system has consistently generated cost savings while reducing CO_2 emissions by up to 335 tCO_2 annually. Operational and maintenance costs are minimal at roughly 511 EUR per year, which is negligible relative to the financial and environmental benefits achieved.

From a financial standpoint, the TCO for the PV system is 607,038 EUR. The difference reflects the continued need for significant grid electricity purchases, as the PV system does not cover total demand. The NPV is positive at 600,253 EUR when discounted at 6%, indicating that cost savings from PV self-consumption outweigh the investment and operating costs. The IRR is approximately 13% meaning the system recoups its initial cost within the first decade. The LCOE for PV generation is 0.08 EUR/kWh, highlighting its cost-effectiveness compared to grid prices.

Overall, Scenario 2 confirms that even a moderately sized PV installation can produce substantial long-term economic and environmental benefits, laying the groundwork for expanded PV integration in future scenarios.

7.4.3 Scenario 3

Scenario 3 considers the installation of a PV system with sufficient capacity to fully meet the company’s annual electricity demand of 6,367,776 kWh from the first year of operation. In an ideal case, designed for 100% coverage, the system supplies all on-site electricity consumption directly from PV generation, which would eliminate the need for grid purchases after commissioning. With this degradation, the company would purchase electricity, as it does not have batteries for storage.

Table 4: Calculations for Scenario 3

Year	Annual Consumption (kWh)	Annual PV Output (kWh)	Grid Purchase (kWh)	Electricity Price (€)	Annual Grid Cost (€)	Annual Total Cost (€)
0	6,367,776	0	6,367,776	0.098	628,528	628,528
1	6,367,776	6,367,776	0	0.101	0	6,000
2	6,367,776	6,335,937	31,839	0.102	3,269	9,269
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
30	6,367,776	5,506,265	861,510	0.179	154,022	160,022

Table 5: CO_2 emissions and CBAM liability Scenario 3

Year	CO_2 Emissions (tCO_2)	CO_2 Avoided (tCO_2)	CBAM Cost (€)	CBAM Savings (€)
0	3,725	0	316,638	0
1	0	3,725	0	316,638
2	19	3,706	1,583	315,054
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
30	504	3,221	42,839	273,799

The capital expenditure for this configuration is derived by proportionally scaling investment costs from a smaller reference system in earlier scenarios. The reference case, covering only part of the demand, was approximately 6.4 times smaller in capacity. Accordingly, both CAPEX and OPEX were scaled by a factor of 6.4 to reflect the larger installed capacity and associated operational requirements. This approach ensures realistic modelling of investment and maintenance costs for a system designed to achieve complete self-sufficiency in electricity supply.

By entirely replacing grid electricity, the system avoids the CO_2 emissions of 3,725 tCO_2 per year, eliminating CBAM liabilities. Over the 30 years, this represents a substantial cumulative reduction in emissions and regulatory costs compared to the baseline.

The TCO attributable solely to the PV system is 3,982,589 EUR, covering procurement, installation, and operational maintenance. Financial analysis indicates an NPV of 6,457,396 EUR, confirming the investment's strong profitability when accounting for avoided electricity purchases and long-term savings. The IRR reaches 20%, far exceeding typical industrial benchmarks of 8-15%, and corresponds to a rapid recovery of investment cost. The LCOE for PV generation is 0.04 EUR/kWh. These values highlight the competitive advantage of fixed, low-cost on-site generation that is insulated from market volatility.

The CAPEX of 3,900,000 EUR covers the full investment in hardware, installation, and commissioning. Although the initial cost is significant, it is quickly offset by the substantial operational savings achieved each year. Scenario 3 demonstrates that a PV system sized for complete self-consumption delivers exceptional financial and environmental performance.

7.5 Numerical Results and Economic Assessment

The present analysis evaluates the impact of PV system integration on Eurosjaj's electricity costs, carbon exposure, and overall competitiveness, based on three scenarios: Scenario 1 – no PV installation, Scenario 2 – existing PV capacity of 830 kWp, and Scenario 3 – full PV coverage estimated at approximately 5,300 kWp. The assumptions used in the calculations include an annual electricity demand of 6,367,776 kWh, a grid electricity price in year 0 of 0.098 EUR/kWh, an electricity escalation rate of 2% per year, a real discount rate of 6% a PV yield of 1,200 kWh/kWp/year with annual degradation of 0.5%, and a grid emission factor of 0.585 tCO_2/MWh based on UNFCCC and IEA reporting.

Scenario 1, which is the control condition, that is, no PV installation, shows the largest TCO considering the whole company, 36,452,448 EUR, and lifetime electricity cost. All electricity requirements are obtained through grid purchases, and there is no capital investment, making IRR inapplicable. LCOE is highest at 0.18 EUR/kWh, reflecting full exposure to grid tariffs and the escalating cost of electricity over the 30-year horizon. Scenario 2, representing the current 830 kWp PV system, reduces total electricity costs substantially, resulting in a positive NPV of 600,253 EUR and an IRR of 13%. The TOC PV-only of 607,038 EUR represents the cumulative cost directly attributed to PV investments and OPEX. Scenario 3, representing full PV coverage, nearly 5 MWp, demonstrates the largest financial benefit, with TCO falling to 3,982,589 EUR, an IRR of

20%, and an LCOE of only 0.05 EUR/kWh. CAPEX and OPEX were calculated assuming a proportional scaling from Scenario 2 (OPEX multiplied by 6.4) to account for full system coverage, reflecting the operational costs of the larger PV installation. In Scenario 1, the lifetime electricity cost includes the total cost of electricity purchased from the grid, as there is no PV system installed. In Scenarios 2 and 3, it represents only the cost of the remaining electricity that must be purchased from the grid after self-consumption from the PV system.

Table 6: Summary of economic performance indicators for all scenarios

Item	Scenario 1	Scenario 2	Scenario 3
TCO PV(€)	-	607,038	3,982,589
NPV (€)	16,276,416	600,253	6,457,396
IRR (%)	-	13	20
LCOE (€/kWh)	0.18	0.08	0.05
Lifetime electricity cost (€)	16,276,416	12,611,204	1,611,570
CAPEX (€)	0	600,000	3,900,000

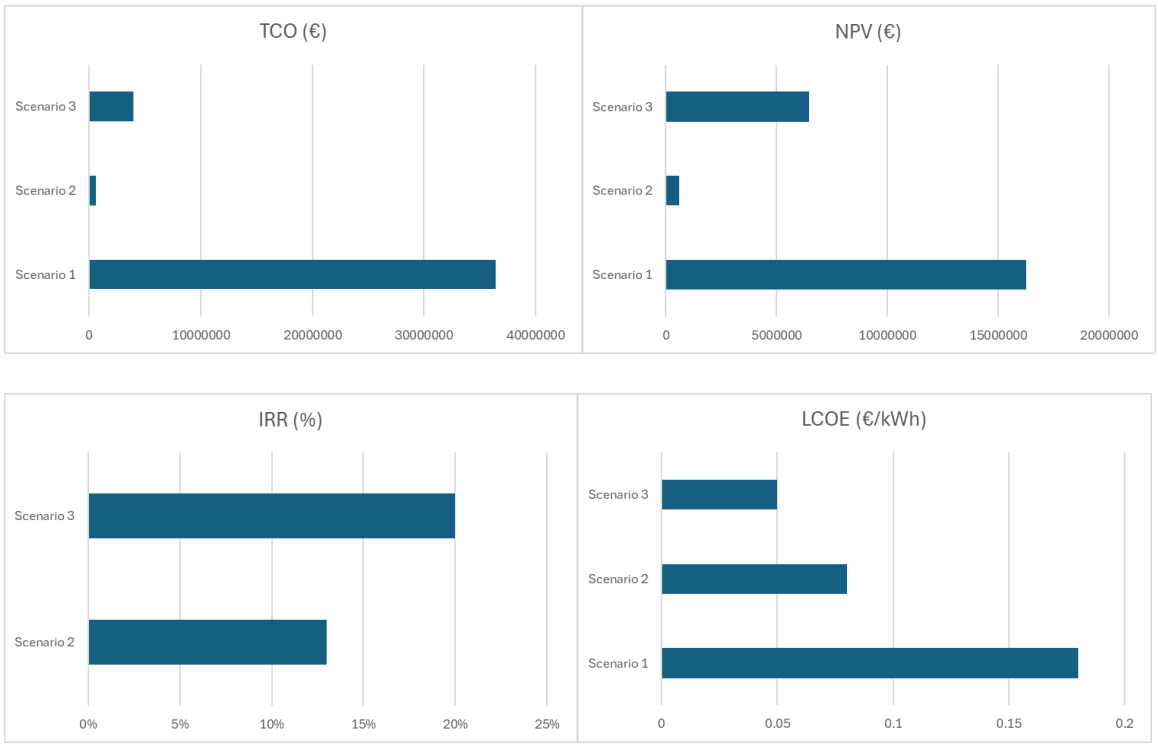

Figure 4: Comparative results of the scenario analysis based on economic indicators

The summary of economic performance indicators for all scenarios is presented in Table 6, while Figure 4 provides a comparative visualization of the scenario results based on TCO,

NPV, IRR, and LCOE. Together, they illustrate the clear financial advantage of increasing PV penetration, with Scenario 3 offering the most competitive long-term outcome.

7.5.1 CO_2 emissions and CBAM implications

The environmental impact of PV integration was assessed using the grid emission factor of 0.585 tCO_2/MWh and CBAM price of 85 EUR/tCO_2. Annual CO_2 emissions, CBAM liabilities, and emissions avoided are summarized in the figures below. Scenario 1 carries full CO_2 exposure with annual emissions of 3,725 tCO_2, corresponding to a CBAM liability of 316,638 EUR. Scenario 2 partially mitigates CO_2 exposure, reducing annual emissions to 3,389 tCO_2 and CBAM costs to 288,140 EUR, with 335 tCO_2 avoided per year. Scenario 3 effectively eliminates all electricity-related CO_2 emissions, resulting in zero CBAM costs and complete environmental compliance.

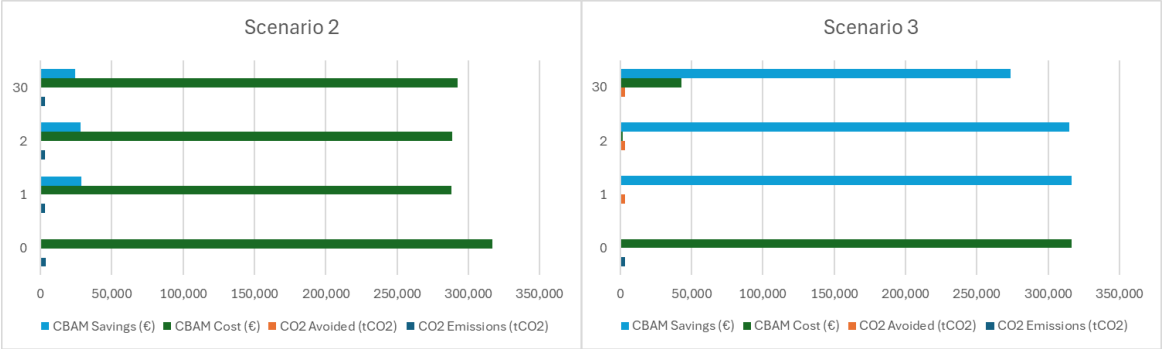

Figure 5: Comparison of CBAM costs and savings, and CO_2 under Scenarios 2 and 3

The results presented in Figure 5 demonstrate that PV integration not only provides financial benefits but also strategically reduces the company's exposure to regulatory CO_2 costs, supporting export competitiveness and sustainability objectives. Scenario 3 achieves full avoidance of CBAM liabilities, providing long-term security against CO_2 price fluctuations.

7.5.2 Comparative Scenario Analysis

A comparative evaluation of lifetime financial and environmental performance highlights the increasing benefits of higher PV coverage. Scenario 1 represents the full-cost baseline, Scenario 2 shows measurable cost reductions, while Scenario 3 maximizes both economic

and environmental benefits. TCO and lifetime electricity cost decline sustainability with PV deployment, IRR increases proportionally with self-consumption, and CO_2 emissions and CBAM costs decrease in parallel with PV output.

These results illustrate that PV self-consumption delivers significant cost and CO_2 savings even at partial coverage, while complete coverage maximizes financial returns and environmental benefits. Scenario 2 serves as an intermediate, incremental step, while Scenario 3 demonstrates the potential strategic advantages of full PV deployment.

7.5.3 Strategic implications and recommendations

Although the numerical study presents a solid argument in favor of the PV expansion, the process requires various strategic considerations in deciding on the issue. A potential solution can be based on the usage of the expansion process in phases, the cost of investments might be smoothed out across the period, and there is a chance of testing its ability and making it worthwhile to continue to expand to a large-scale approach. The company also has the option of exploring friendly financing options, such as green bonds, EU decarbonization funds, or seeking recommendations from Energy Service Companies (ESCOs), to reduce early capital outflows. Additional steps, which could entail specific investments in energy efficiency, e.g., upgrading of motors or recovery of process heat, might further lower electricity consumption and magnify the relative weight of PV production. In the medium term, the added battery storage systems, not considered in the present scenarios, would potentially augment the self-consumption rates and resilience to grid failures. Lastly, the company should actively address EU purchasers, translating the emissions decreases and CBAM conformity to the benefits of the company, and recognize the option of premium pricing in specific market sectors. The present discussion will not substitute the conclusions given in the succeeding chapter; it will only translate the situation findings into practical updates on the company management, linking up the technical analysis done in this chapter with more strategic considerations given in Chapter 8.

8 Conclusion

The study has managed to reach its aim, to find out the economic and environmental viability of large-scale PV integration for self-consumption in an energy-intensive metal surface protection facility. Using the three modelled scenarios, the evidence was found to be consistent across all cases since PV deployment truly lowers the cost of electricity, alleviates the company's burden on carbon liabilities because of CBAM, and aligns with the decarbonization strategy of the company. The complete PV CAPEX (Scenario 3) indicated the best NPV, a competitive IRR over the general cost of capital of the industry, and the LCOE significantly lower than the shown grid tariffs.

The impact on the environment was significant, with over 50% cuts in annual CO_2 emissions and a relative drop in the cost of CO_2 emissions. Relative to past research, which has tended to focus on residential for light industrial applications, the study bears out the idea that PV self-consumption is at least and perhaps better suited where energy demands are consistent and heavy during the day. The finding can also expand the available literature because it clearly establishes an association between PV integration and adherence to carbon pricing mechanisms, indicating that regulatory systems can be applied to improve returns on renewable energy investments in heavy manufacturing on a material basis. Broader in scale, the findings highlighted the importance of decentralized renewable generation as an operational and strategic resource to industrial companies. In addition to providing cost savings, PV integration has the benefit of energy security and resilience against market fluctuations, as well as gaining a competitive advantage at a time when supply chains need to be more carbon-friendly. To policy-makers, the research findings also indicate that industrial energy policy needs to be made consistent with decarbonization rewards to create a faster pace of adoption in high-impact industries.

However, there are limitations. The modelling presumes constant availability of the solar resources, fixed load profiles, and fixed carbon prices, which in reality can differ. It also carries the risk of excluding potential technological disruption, including major scientific developments in battery storage or other forms of decarbonization. Besides, existing designs cannot store battery capacity, reducing the proportion of PV energy that could be used locally, especially in the absence of daylight. On the whole, this research proves that PV

self-consumption is a profitable, environmentally significant, and regulatory-compliant approach to energy-intensive industries. It offers not only a sector-based evidence base but also a methodological framework that can be used in other industrial contexts and thus advances the wider discussion on how manufacturing transitions should be approached.

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