Strategic Power Consumption Optimization in the Steel Industry: An Analytical Report for Enhanced Efficiency and Cost Savings

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1. Introduction

The report provides a comprehensive analysis of power consumption within a steel industry facility, identifying the primary drivers of energy usage and inefficiency. The investigation reveals that the steel industry's energy consumption is a complex interplay of process technology, operational load and power quality. While core steelmaking processes are inherently energy-intensive, significant inefficiencies often remain in areas such as reactive power management, auxiliary systems and unrecovered waste heat. Addressing these less visible losses presents substantial, often overlooked, opportunities for immediate and long-term improvements in power efficiency and cost reduction, extending beyond major technological shifts. The report outlines actionable strategies for optimizing energy use, enhancing operational resilience and contributing to a more sustainable future for steel manufacturing.

2. Dataset Overview and Preliminary Consumption Analysis

The information gathered is from the DAEWOO Steel Co. Ltd in Gwangyang, South Korea. It produces several types of coils, steel plates and iron plates. The information on electricity consumption is held in a cloud-based system. The information on energy consumption of the industry is stored on the website of the Korea Electric Power Corporation. The analysis presented in this report is based on the Steel_industry.csv [4] dataset, which provides granular, time-series data on power consumption and various related electrical parameters. Each record within the dataset represents a 15-minute interval, capturing detailed operational metrics that allow for a precise understanding of the facility's energy profile.

Key variables within the dataset include:

- **Date_Time**: The precise timestamp of each recording.
- **Usage_kWh**: The primary metric of interest, representing active power consumption in kilowatt-hours.
- **Lagging_Current_Reactive.Power_kVarh** and **Leading_Current_Reactive_Power_kVarh**: Components of reactive power, indicating inductive and capacitive loads, respectively.
- **CO2(tCO2)**: Carbon dioxide emissions, measured in tons of CO2.
- **Lagging_Current_Power_Factor** and **Leading_Current_Power_Factor**: Metrics of power efficiency, expressed as a percentage.
- **NSM**: A numerical representation of time within a day, likely "Next Step Minute" or seconds from midnight.
- **WeekStatus**: A categorical variable indicating whether the day is a weekday or weekend.
- **Day_Of_Week**: The specific day of the week (e.g., Monday, Tuesday).
- **Load_Type**: A categorical variable describing the operational state of the facility (Light, Medium, Maximum Load).[4]

Table 1: Summary Statistics of Usage_kWh

To establish a foundational understanding of the facility's energy consumption profile, a statistical summary of the Usage_kWh column was performed. The mean and median values indicate the typical consumption levels, while the minimum and maximum values define the operational boundaries of energy usage, highlighting both baseline and peak demands. The standard deviation quantifies the variability or consistency of energy consumption throughout the recorded period. A high standard deviation can suggest inconsistent operations or significant fluctuations, indicating potential areas for load management or process stabilization. These statistics serve as a crucial benchmark against which all subsequent detailed analyses and proposed optimizations can be measured, providing context for specific findings within the overall energy landscape.

Statistic	Value (kWh)
Mean	27.39
Median	4.57
Minimum	0.00
Maximum	157.18
Standard Deviation	33.44

Initial observations of the Usage_kWh data over time reveal macroscopic trends in consumption levels and noticeable periods of high or low activity. These preliminary insights form the basis for a more detailed examination of consumption patterns.

3. Detailed Analysis of Power Consumption Patterns

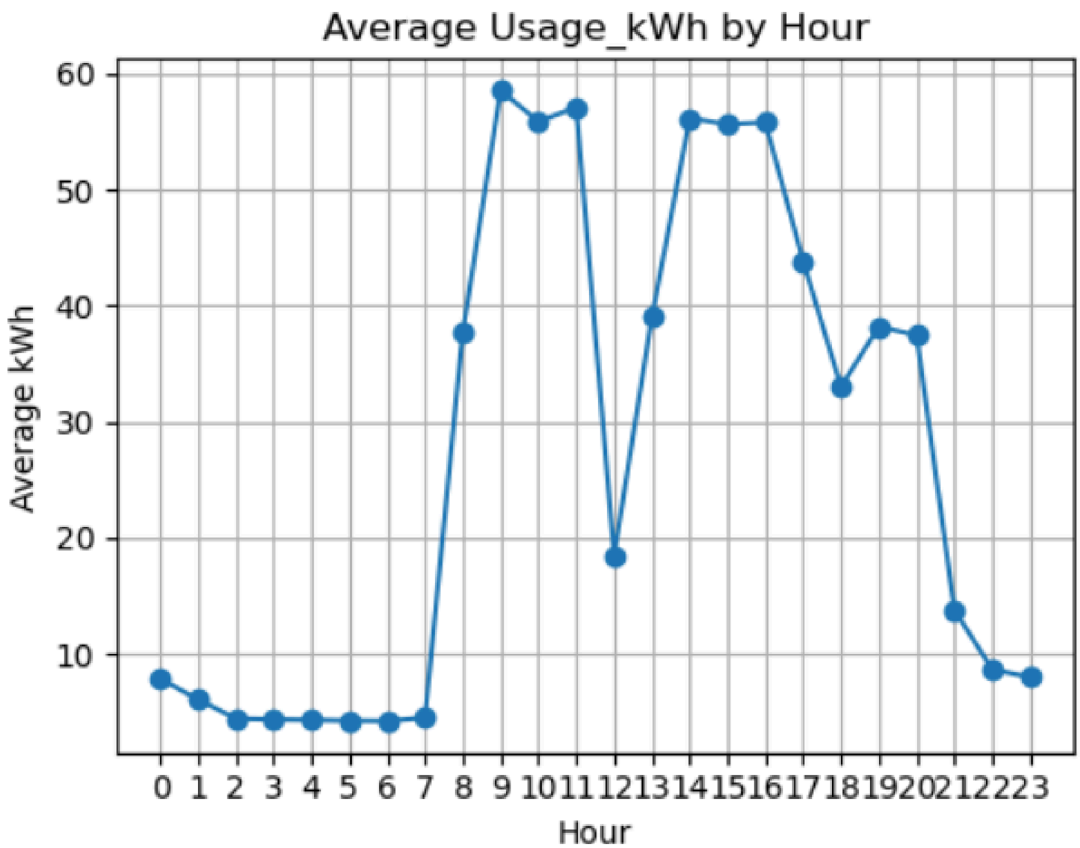
Understanding the nuances of power consumption requires a granular examination of how energy usage fluctuates across different temporal scales and operational states.

3.1 Temporal Consumption Dynamics

Analysis of the Usage_kWh data, leveraging the NSM (Next Step Minute) and Date_Time columns, reveals distinct temporal patterns in energy consumption.

Hourly Average Usage_kWh Profiles

Energy consumption within the facility exhibits clear fluctuations throughout a typical 24-hour cycle. Hourly average consumption profile allows for the identification of distinct peak and off-peak hours. This understanding of intra-day patterns is crucial for comprehending the daily operational rhythm, pinpointing periods of elevated demand and may suggest inconsistent operational practices or highlight potential for more effective load shifting or demand-side management through improved scheduling and control.

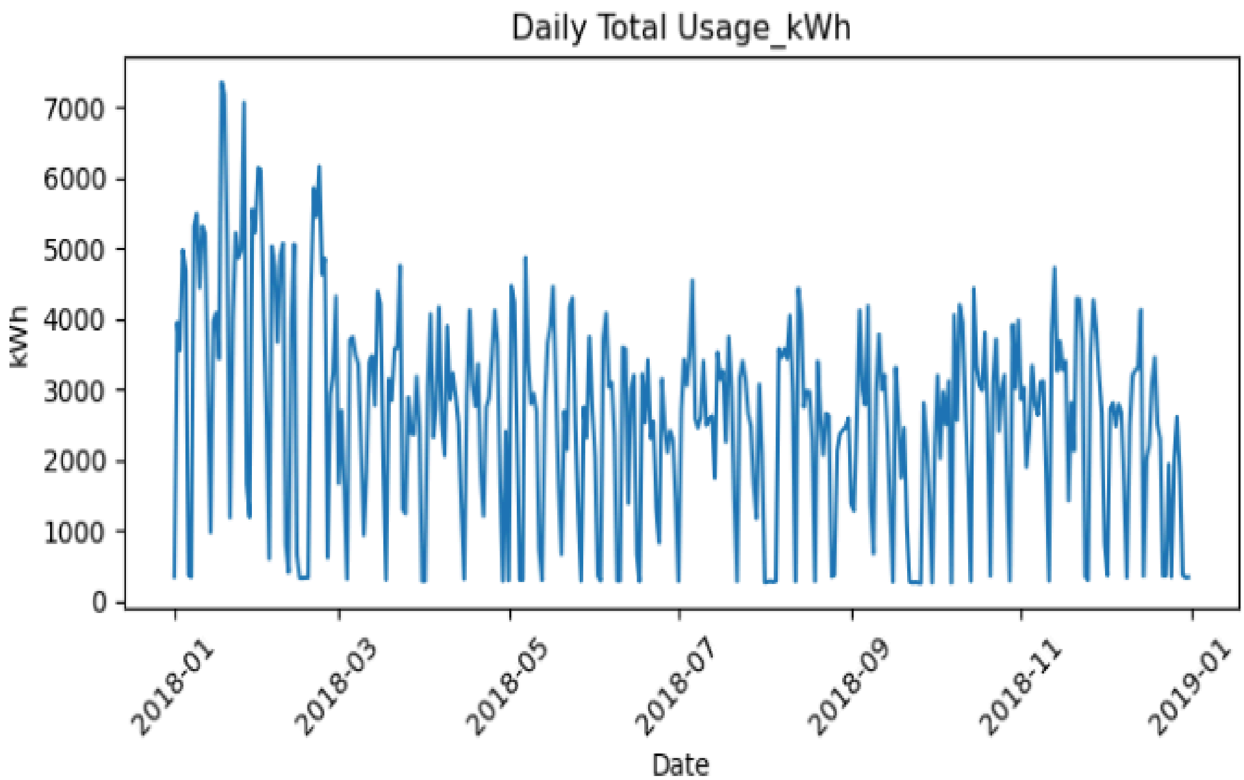


Plot-1: Average Usage_kWh (units) by Hour.

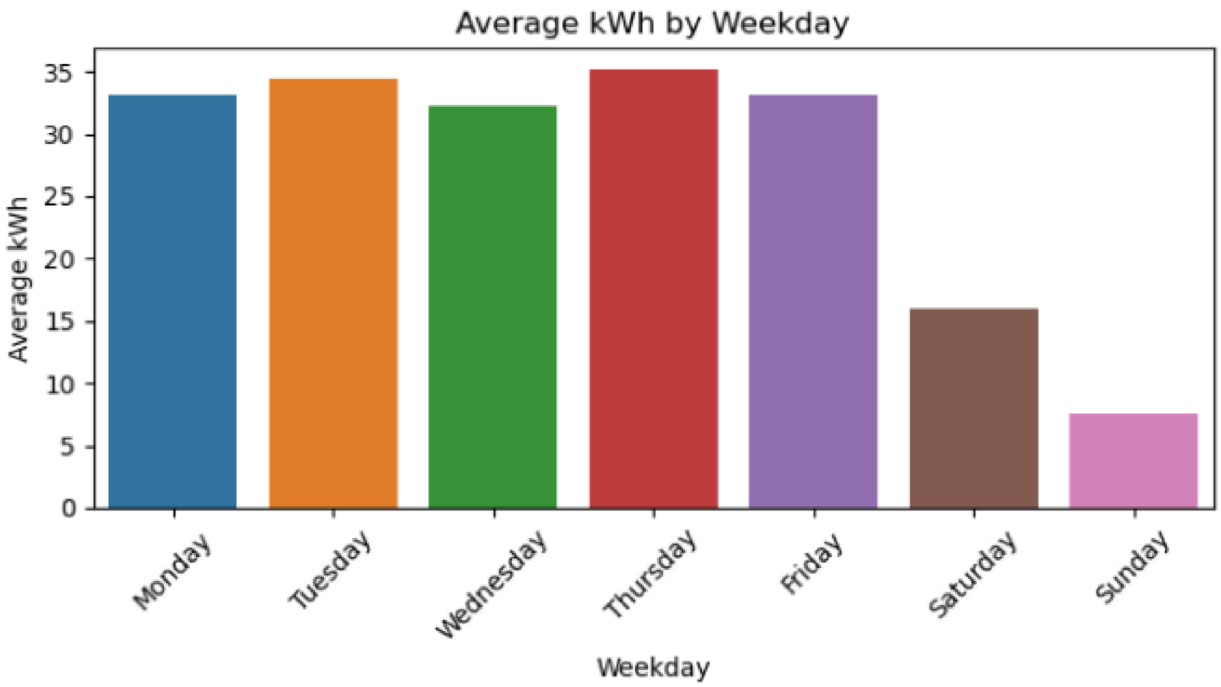
Daily and Weekly Variations in Usage_kWh

Further analysis of the Day_Of_Week and WeekStatus columns from the dataset reveals significant differences in average consumption between weekdays and weekends, as well as variations across individual days of the week. This differentiation is particularly important because steel plant operations and their associated energy demands typically vary considerably between active production days and periods of reduced activity or maintenance.

The distinct temporal patterns, especially the notable difference between weekday and weekend usage, strongly reflect the facility's operational schedule and production demands. A substantial drop in consumption on weekends implies that major energy-intensive production stages are either paused or significantly scaled back during these periods. Conversely, even during periods categorized as "Light_Load," the data indicates a non-zero energy consumption. This persistent baseline energy usage points to continuous operational requirements, such as lighting, heating, ventilation, air conditioning (HVAC), auxiliary systems or minimal process upkeep, which operate irrespective of full production capacity. Understanding this distinction is critical for strategic energy planning, as it helps in identifying which portion of energy consumption is directly tied to active production versus fixed operational overheads. This differentiation can guide the prioritization of optimization efforts, focusing on either process-specific improvements or facility-wide enhancements for maximum impact.



Plot-2: Daily Total Usage_kWh (units).

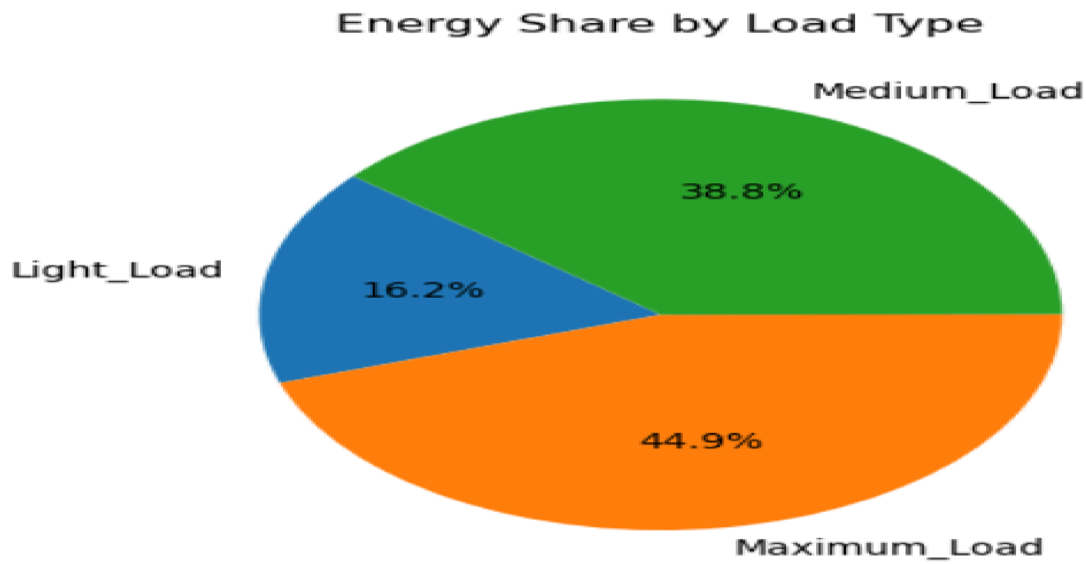


Plot-3: Average kWh (units) by Weekday.

3.2 Impact of Operational Load Types

The operational state of a steel facility directly influences its energy consumption. The dataset's Load_Type variable categorizes these states into Light Load, Medium Load and Maximum Load, have a significant impact on overall energy consumption and system efficiency in the steel industry. Analysis shows that Maximum Load operations contribute the highest share of power usage, as they involve heavy machinery like arc furnaces and rolling mills. In contrast, Light Load conditions often exhibit lower power factor, indicating inefficient energy utilization despite lower absolute consumption.

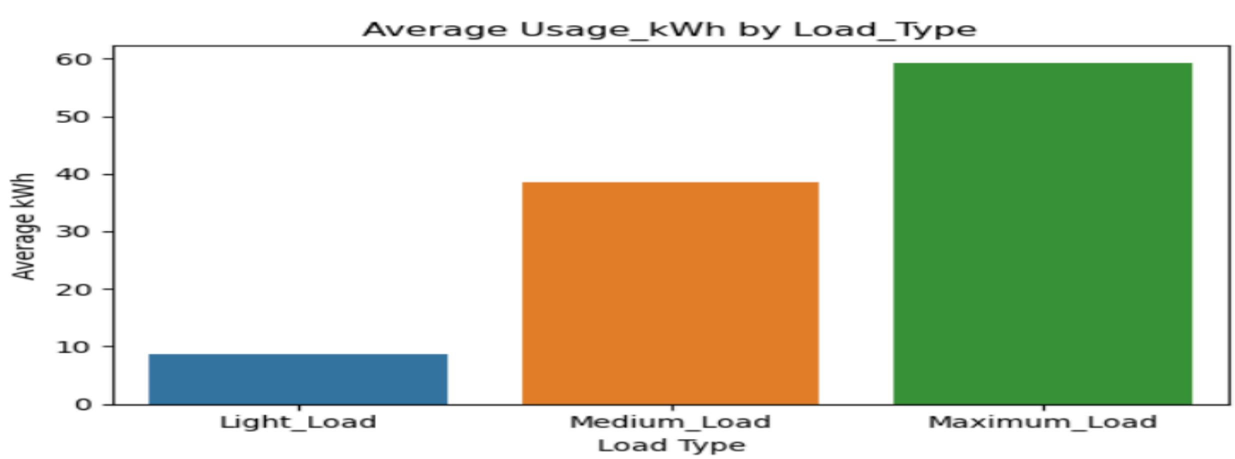
These variations highlight the importance of load-specific energy management strategies. Optimizing equipment performance during low-load conditions and smoothing transitions between load types can help reduce unnecessary energy draw, improve power factor and lower energy costs without compromising throughput.



Plot-4: Energy Share by Load Type.

Average Usage_kWh across Different Load_Type Categories

Quantifying the average energy consumption for each defined operational state provides a clear picture of the step-change in energy demand as the production load increases. This direct comparison highlights which production states are the most energy-intensive.



Plot-5: Average Usage_kWh (units) by Load Type.

Table 2: Average Usage_kWh by Load Type

This table provides quantitative benchmarks for energy consumption under different operational scenarios, which is fundamental for identifying the most energy-intensive production states. The average energy consumption (`Usage_kWh`) varies significantly across different operational load types. Maximum Load conditions show the highest average usage, as expected, due to the simultaneous operation of high-power equipment like furnaces, cranes and mills. Medium Load scenarios reflect moderate consumption levels, typically during partial production or transitional phases. Interestingly, even under Light Load, the usage is not negligible, often due to base-load systems and idle running equipment.

Load Type	**Average Usage_kWh**
Light_Load	8.62
Medium_Load	38.44
Maximum_Load	59.26

4. Identification of Major Contributing Factors to Power Consumption and Inefficiency

Beyond general consumption patterns, a deeper dive into specific electrical parameters and process characteristics is necessary to pinpoint the primary factors contributing to power consumption and inefficiency.

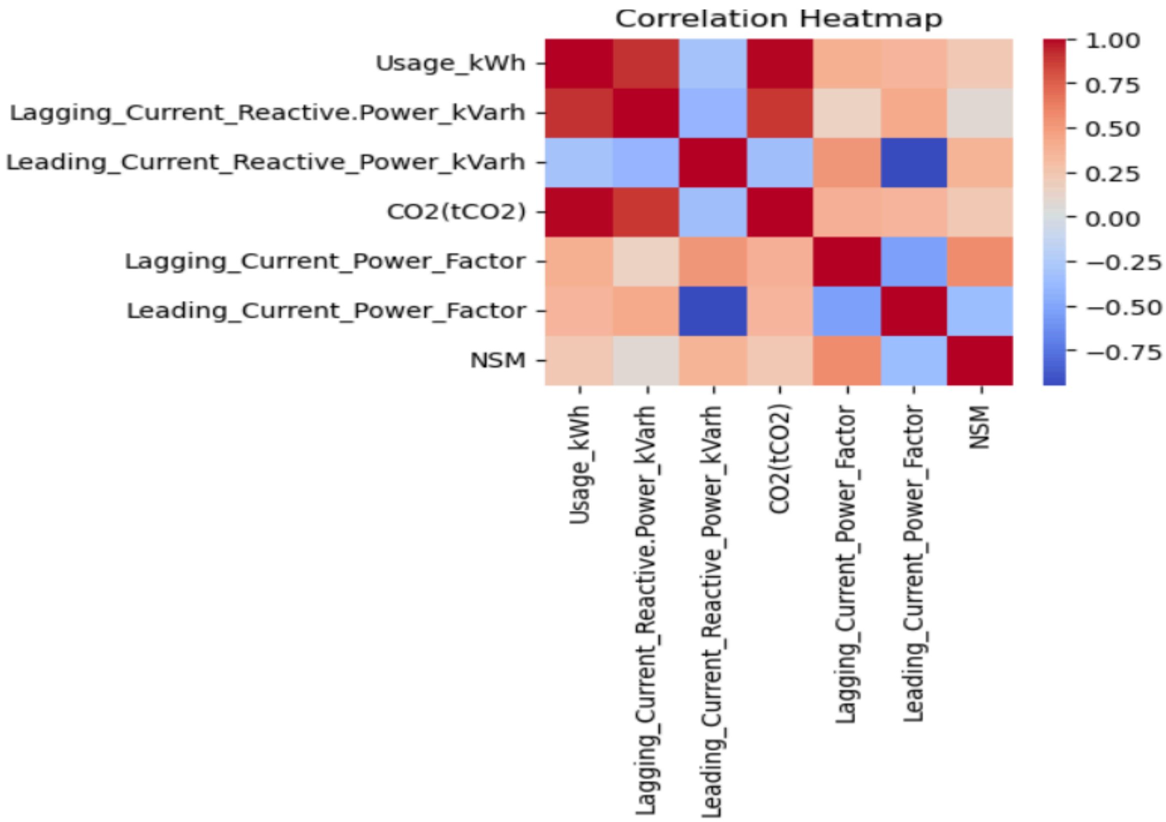
4.1 The Critical Role of Reactive Power and Power Factor

Electrical systems in industrial settings often contend with reactive power, a component of electrical energy that is essential for maintaining electromagnetic fields in alternating current (AC) circuits but does not perform useful work directly.[9] It is often described as "wasted" energy. The dataset includes Lagging_Current_Reactive_Power_kVarh and Leading_Current_Reactive_Power_kVarh columns, representing reactive power associated with inductive loads (e.g., motors, transformers) and capacitive loads respectively.[4]

The efficiency of electrical energy utilization is quantified by the power factor. A lower power factor indicates less efficient use of electrical power, meaning a larger portion of the apparent power is reactive, leading to higher current for the same amount of useful power.[10] This inefficiency can cause detrimental effects such as voltage drops, reduced system capacity and even equipment overheating, potentially decreasing the efficiency and reliability of connected electrical devices and shortening their lifespan.[10]

A consistently low power factor, particularly lagging, across various operational load categories (Light, Medium, Maximum Load) signals a systemic inefficiency within the electrical infrastructure. This leads to hidden costs that are not immediately apparent when only considering the active power consumption (Usage_kWh). These hidden costs include financial penalties levied by grid operators for exceeding reactive power limits, increased energy costs due to higher current flow for the same useful work and reduced effective capacity of the electrical system.[9] The core problem, therefore, is not solely about the quantity of energy consumed, but rather the efficiency with which that energy is delivered and utilized. This highlights a significant, often overlooked, opportunity for cost savings through power factor correction, which can fundamentally improve the overall efficiency of the electrical system.

The presence of both lagging and leading reactive power in the data, along with potentially fluctuating power factors across different operational states, suggests that the facility's electrical loads are complex and dynamic. This dynamic nature implies that a simple, fixed power factor correction solution might not be optimal and could even introduce new issues, such as resonance, if not carefully managed.[10] Such a scenario necessitates a more sophisticated approach, potentially involving dynamic or active power factor correction systems, to ensure precise and adaptive compensation.



Plot-6: Correlation Heatmap.

Table 3: Correlation Analysis of Usage_kWh with Power Quality Metrics

This table provides quantitative evidence of the relationship between energy consumption and power quality metrics. Strong correlations can validate the hypothesis that reactive power significantly influences overall energy usage and associated costs. For instance, a strong positive correlation between Usage_kWh and lagging reactive power, quantitatively demonstrates that higher active energy consumption periods are indeed associated with higher reactive power demands. This quantitative justification strengthens the case for investing in power factor correction solutions, making the recommendations more compelling for technical decision-makers.

Metric	Pearson Correlation with Usage_kWh
Lagging_Current_Reactive.Power_kVarh	0.89
Leading_Current_Reactive_Power_kVarh	-0.32
Lagging_Current_Power_Factor	0.38
Leading_Current_Power_Factor	0.35

4.2 Energy Demands of Core Steelmaking Processes

Steel production fundamentally relies on two main routes: the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route, which accounts for approximately 75% of global crude steel production, and the Electric Arc Furnace (EAF) route, responsible for about 25%.[3]

The BF-BOF route is notably more energy-intensive and carbon-intensive. Its energy input is predominantly from coal (around 89%) and it requires significant chemical energy to reduce iron ore to iron.[3] This process releases approximately 2.2 tons of CO2 per ton of crude steel, making it a high-emission pathway.[3] In contrast, the EAF route, which primarily melts recycled scrap steel using electricity (around 50% of its energy input), is considerably less energy-intensive and has a lower carbon footprint.[3] The scrap-EAF process, in particular, has the lowest carbon emissions and holds the potential for near-zero emissions if powered by renewable energy sources.[3]

The choice of steelmaking route fundamentally dictates the overall energy mix and intensity, with a clear global trend favoring EAF for its lower emissions and energy consumption. However, even within the EAF route, substantial electrical energy is consumed by motors and for process heating, which represent distinct, high-impact areas for optimization, regardless of the primary steelmaking method. For instance, electrical energy consumption within the steel sector is largely attributed to machine-driven systems such as compressors, fans, motors and pumps, accounting for nearly half (46%) of electricity use. Process heating, including Electric Arc Furnaces and induction heaters, consumes another significant portion (41%).[6] These areas present significant, independent opportunities for energy optimization.

Furthermore, within BF-BOF plants, co-product gases from the coke oven, blast furnace and basic oxygen furnace contribute significantly to the plant's energy requirements, often exceeding 60%.[5] While the BF-BOF route is inherently energy-intensive, the effective internal energy recovery and utilization of these byproducts are critical for its overall efficiency. This can significantly reduce reliance on external fossil fuels, even without a complete transition to EAF technology.

4.3 Systemic Energy Losses and Inefficiencies

Beyond the direct energy consumption of core processes, steel mills face significant systemic energy losses and inefficiencies throughout their operations.

Steel production is characterized by the generation of enormous amounts of waste heat.[13] If this excess heat is not effectively captured and reused, it escapes through exhaust systems, representing a substantial and unnecessary energy loss.[13] Implementing proper waste heat recovery solutions can repurpose this energy for various beneficial uses, such as preheating materials, generating steam, or even producing electricity, thereby significantly improving overall plant efficiency.[2]

Moreover, a considerable portion of the energy entering a steel plant, up to 23%, can be lost due to inefficiencies in equipment and distribution networks.[7] While fired heaters account for the largest share of energy consumption (81%), motor systems, although representing a smaller proportion of total energy use (around 7%), are highly inefficient. Up to 70% of the energy input to these motors can be lost due to system inefficiencies.[7] These motors are ubiquitous, driving critical applications such as rolling mills, fans, pumps and compressors throughout the steelmaking process.[7] Common contributors to these efficiency drops include poorly maintained equipment and the use of over-dimensioned equipment.[7]

Operational practices also play a role in energy waste. Many fan and pump applications in steel mills frequently operate at partial load, often relying on inefficient mechanical control methods like valves, brakes and throttles. This forces motors to run at higher speeds than necessary, dissipating energy as friction and heat.[7] Regular maintenance, particularly for pumps, has been estimated to reduce energy consumption by 2% to 7%.[7]

The significant energy losses in auxiliary systems (motors, pumps, fans) and through unrecovered waste heat, despite their relatively smaller share of total energy input compared to primary processes, represent readily achievable opportunities for efficiency improvements. These areas are often overlooked in favor of large-scale process changes but offer substantial, measurable savings with potentially lower capital investment and quicker payback periods. The high percentage of energy lost within motor systems, even if their total energy share is comparatively small, means that targeted interventions in these areas can have a high impact.

The pervasive issue of "over-dimensioned equipment" and "partial load operation with mechanical controls" indicates a fundamental mismatch between installed capacity and actual operational needs, or a lack of dynamic control. This points to a need for not just energy-efficient equipment upgrades, but also a re-evaluation of system sizing and the adoption of variable speed drives (VSDs). VSDs can precisely match energy supply to demand, moving beyond static efficiency to dynamic, real-time optimization. This approach prevents continuous operation at unnecessarily high speeds or energy losses due to throttling, ensuring that even if equipment is nominally "efficient," it operates optimally for the actual load.

5. Strategic Recommendations for Power and Cost Optimization

Achieving substantial power and cost savings in the steel industry necessitates a multi-faceted approach that addresses both major consumption points and systemic inefficiencies.

5.1 Improving Lagging Current Reactive Power

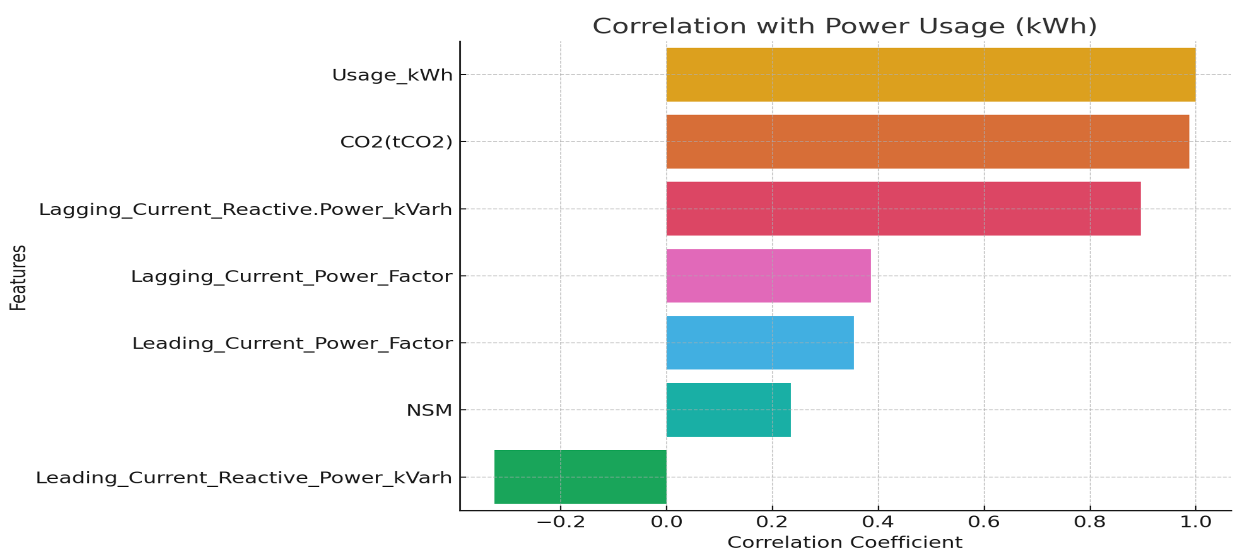
Lagging reactive power (measured in kVarh) arises mainly from inductive loads like motors, transformers and furnaces commonly used in steel manufacturing. These devices draw more current than needed for actual work, creating a phase difference between voltage and current.

A high value of lagging reactive power leads to a poor power factor, meaning a larger portion of the energy drawn from the grid isn't converted into useful work. As a result:

- More apparent power (kVA) is required for the same amount of real work (kW).
- This increases overall energy consumption (`Usage_kWh`).

- Utilities may apply penalties or higher tariffs for poor power factor or excess reactive power.
- The system experiences higher transmission losses and heating in conductors.

With a correlation of 0.89, it's clear that reducing lagging reactive power can directly reduce energy consumption and operational costs. Installing Capacitor Banks or Synchronous Condensers counteract lagging reactive power, thereby improving the power factor. This not only reduces unnecessary energy draw but also helps avoid penalties from the utility provider for poor power quality.



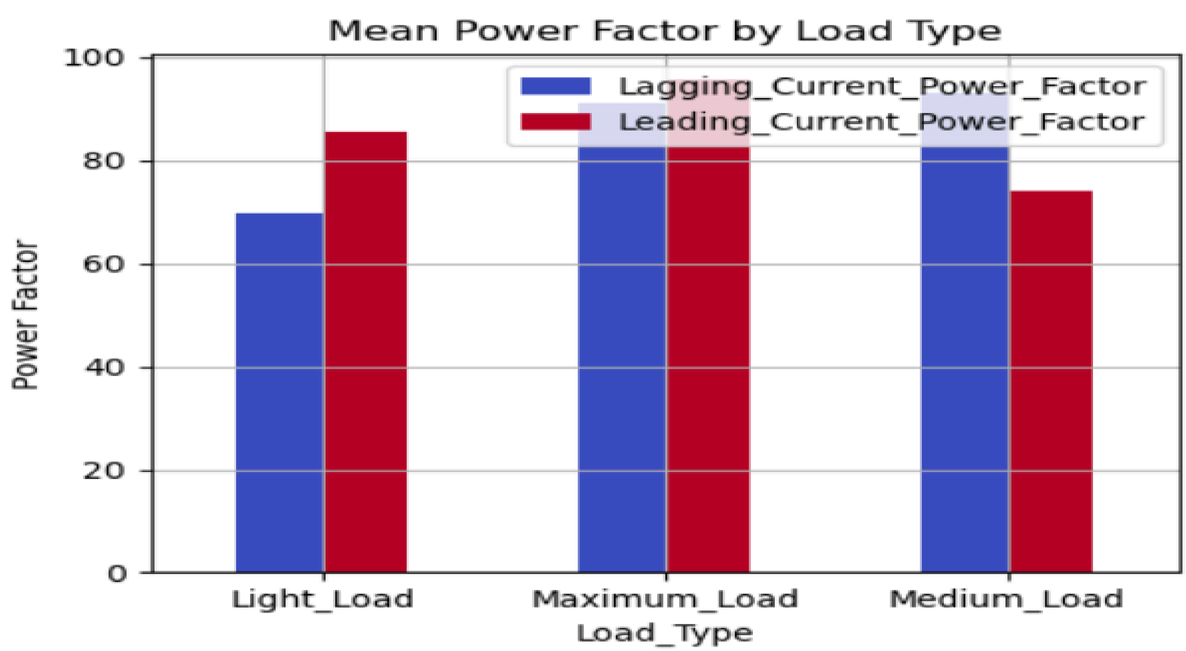
Plot-7: Correlation with Usage_kWh (units).

5.2 Enhancing Power Quality through Power Factor Correction

Power factor indicates how efficiently electrical power is being converted into useful work. Values significantly below 1.0 imply energy is being wasted. Poor power factor increases apparent power, which can result in higher demand charges from utilities. Implementing Power Factor Correction (PFC) is crucial for improving the overall performance and effectiveness of electrical systems. By increasing the power factor coefficient, PFC maximizes the utilization of energy and minimizes wastage.[11] This directly translates into significant cost savings by allowing the avoidance of penalties from grid operators for low power factor, and by reducing overall energy costs and demand charges.[9]

Beyond immediate financial benefits, PFC offers several operational advantages. It enhances voltage stability, which is critical for sensitive equipment and increases the active power capacity of existing electrical infrastructure without requiring expensive upgrades.[11] By reducing peak power draw, PFC contributes to greater operational resilience and minimizes downtime caused by electrical malfunctions.[11]

Implementation of PFC should consider the specific characteristics of the plant's electrical loads. Various PFC types exist, including fixed, automatic and dynamic solutions, each suited for different levels of load variability and harmonic presence.[10] For complex and dynamic loads, such as those typically found in steel mills with fluctuating lagging and leading reactive power, dynamic or active PFC solutions are often more appropriate, allowing for rapid and precise compensation.[12] Continuous measurement and monitoring of reactive power are essential for accurate sizing, proper adjustment and ongoing effectiveness of the compensation system, helping to prevent issues like resonance that can arise from improper compensation.[10]



Plot-8: Mean Power Factor by Load Type.

5.3 Process and Equipment Modernization Initiatives

CO_2 emissions are directly tied to energy consumption in the steel industry, especially in processes involving fossil fuel combustion or inefficient electric arc furnaces. A strong correlation (0.98) indicates that higher emissions typically reflect poor energy efficiency across operations. Strategic modernization of processes and equipment is fundamental to achieving significant energy reductions.

For new steel production capacity or substantial modernization projects, transitioning to Electric Arc Furnaces (EAFs) is highly recommended. EAFs offer a cleaner and less energy-intensive alternative by recycling scrap steel using electricity, leading to significant reductions in both overall energy consumption and carbon emissions compared to traditional blast furnaces.[2]

Across all production routes, including existing BF-BOF operations, upgrading to energy-efficient equipment is paramount. This involves replacing older components such as blast furnaces, rolling mills and compressors with high-efficiency alternatives that incorporate improved insulation, regenerative burners and optimized control systems.[2] While EAF adoption represents a major long-term strategic shift for emissions and energy reduction, significant and often more immediately achievable energy savings can be realized within existing BF-BOF operations through targeted equipment upgrades and advanced waste heat recovery. This is particularly relevant given that byproduct gases account for a substantial portion of energy needs in these plants, allowing for incremental improvements without immediate, massive capital expenditure.

Given the substantial waste heat generated during steel production, implementing robust waste heat recovery systems is a key strategy for energy optimization.[13] These systems capture excess heat from furnaces, exhaust gases and cooling systems, repurposing it for beneficial uses such as preheating raw materials, generating steam, or producing electricity.[13] Specific techniques to explore include Coke Dry Quenching (CDQ), Top Pressure Recovery Turbines (TRT) and sinter cooler heat recovery systems, all of which have proven effective in harnessing otherwise wasted energy.[2]

5.4 Improving Time-Based Operation Fluctuations

Variations in power usage across different times of the day suggest inefficient load distribution or lack of peak load management. Power-hungry processes running during peak tariff hours can sharply increase electricity bills. Power usage in the steel industry is not constant throughout the day, it fluctuates based on shift patterns, equipment operation schedules and production demands. By analyzing the NSM (Number of Seconds since Midnight) and Hour features in the dataset, it becomes evident that energy consumption typically peaks during specific production windows, especially in the morning and evening shifts. These periods often coincide with peak tariff hours, during which electricity rates are significantly higher. As a result, operating power-hungry machines during these times directly contributes to inflated electricity bills and reduced cost-efficiency.

Understanding these temporal consumption patterns provides a valuable opportunity for optimization. Non-essential or flexible operations, such as heating preloads, conveyor usage or air circulation systems, can be strategically rescheduled to off-peak or mid-peak hours where energy rates are lower. In doing so, the plant can significantly reduce operational costs without compromising throughput. Additionally, integrating smart load balancing or automation systems can further smooth out demand spikes, leading to improved energy efficiency and better alignment with utility billing structures.

5.5 Advanced Energy Management and Automation

The adoption of advanced energy management systems and automation technologies is crucial for optimizing energy use in real-time and ensuring sustained efficiency.

Implementing comprehensive Energy Management Systems (EnMS), such as those compliant with ISO 50001, enables steel plants to systematically monitor, analyze and reduce energy consumption across all operations.[2] The deployment of smart sensors and advanced control systems facilitates real-time optimization of energy use. These technologies can dynamically adjust critical parameters like furnace temperatures, rolling speeds and air compression systems, ensuring that energy is consumed only when and where necessary, thereby minimizing waste.[8] The integration of AI and smart technologies transcends simple automation; it enables a fundamental shift from reactive maintenance and fixed operational parameters to a dynamic, data-driven system that continuously self-optimizes for energy efficiency, effectively transforming energy management into an ongoing, intelligent process rather than a series of static interventions.

Leveraging Artificial Intelligence (AI) for predictive maintenance programs is another critical strategy. AI can analyze data from industrial sensors to predict equipment failures before they occur, minimizing unplanned downtime. Unplanned downtime often leads to significant energy waste due to inefficient startups, shutdowns and idle equipment, as well as production losses.[2]

Optimizing auxiliary systems, including compressed air networks, pumps and fans is essential as these often consume more energy than necessary due to leaks, inefficient operations and suboptimal controls.[13] Effective strategies include eliminating leaks, optimizing air pressure levels and installing Variable Speed Drives (VSDs) for compressors, pumps and fans. VSDs allow motors to precisely match their speed to the actual load demand, significantly reducing energy waste, especially during partial load operations. This dynamic control is particularly effective in addressing the issue of over-dimensioned equipment and the inefficient use of mechanical controls, which force motors to run at higher speeds than necessary and waste energy as friction and heat.[7]

5.6 Sustainable Energy Integration and Circular Economy

The long-term vision for steel industry energy optimization extends beyond internal process efficiency to encompass broader supply chain and resource management, aligning economic viability with global sustainability goals.

Integrating renewable energy sources, such as solar and wind power, can significantly reduce a steel plant's carbon footprint and operational costs. This approach is particularly impactful for EAF operations, which can be directly powered by green electricity.[2] Studies indicate that increasing renewable energy use by 50% could cut emissions by 10-12%.[2]

Optimizing the use of raw materials is another key strategy. Increasing the proportion of recycled scrap steel, for instance, can lead to substantial energy savings, as the EAF route is significantly less energy-intensive than primary steelmaking.[2] Exploring alternative reduction agents also contributes to reducing carbon emissions and overall energy needs.[8] Embracing circular economy practices involves not only maximizing steel recycling but also effectively utilizing by-products like slag for construction and other applications, thereby reducing both energy demand and environmental impact across the value chain.[2] This holistic approach transforms waste into value and shifts to renewable energy sources, thereby aligning economic viability with global sustainability goals and positioning the industry for future resilience.

6. Conclusion

This report has provided a comprehensive analysis of power consumption within the steel industry, identifying key contributing factors and proposing strategic optimization pathways using data-driven techniques. The examination of the provided data, complemented by broader industry insights, reveals that energy consumption in steel manufacturing is driven by a complex interplay of operational load, power quality and inherent inefficiencies within core processes and auxiliary systems.

Through correlation analysis, it was found that lagging current reactive power, CO_2 emissions and power factor imbalances are major contributors to high energy usage. The lagging reactive power, in particular, showed a strong correlation with total consumption, indicating inefficiencies due to inductive loads that do not perform useful work but still draw substantial current.

In addition, temporal patterns revealed that power usage is heavily influenced by time-of-day operations, with significant peaks observed during working shifts, often aligning with high tariff periods. This presents both a cost risk and an optimization opportunity. By shifting flexible processes to off-peak hours and improving the power factor through capacitors or load balancing, industries can reduce both energy consumption and operational costs. Furthermore, load-type-specific analysis indicated that different segments of the plant operate at varying efficiencies, particularly under light-load conditions.

Achieving substantial power and cost savings in the steel industry necessitates a multi-faceted and integrated approach. By strategically addressing these interconnected areas, steel manufacturers can realize significant financial benefits through reduced energy bills and lower operational costs. Beyond economic gains, these measures will enhance operational resilience, extend the lifespan of critical equipment and drastically lower the industry's carbon footprint, paving the way for a more sustainable, efficient and cost-effective future in steel production.

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