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Green Refineries: How Electrical and Instrumentation Engineers Can Lead Decarbonization

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Abstract
The global petroleum refining industry faces unprecedented pressure to achieve net-zero emissions by 2050, requiring comprehensive technological transformation led by electrical and instrumentation (E&I) engineering innovations. This research examines how advanced process automation, smart grid integration, and intelligent monitoring systems can reduce refinery carbon emissions by up to 45% while maintaining operational efficiency. Through analysis of 127 refineries globally, this study demonstrates that E&I-driven optimization can achieve energy efficiency improvements of 23-31%, reduce operational costs by $12-18 million annually per facility, and accelerate decarbonization timelines by 3-5 years. The integration of artificial intelligence-powered process control systems, combined with electrification of heating processes and implementation of carbon capture technologies, presents a pathway to sustainable refinery operations. Key findings indicate that strategic E&I investments averaging $85-120 million per refinery can deliver return on investment within 4.2-6.8 years while achieving 78% reduction in Scope 1 and Scope 2 emissions by 2035.

Keywords
Green refineries, decarbonization, electrical engineering, instrumentation systems, process automation, carbon capture, smart grid integration, industrial electrification, energy efficiency optimization

1. Introduction

1.1 Background and Context

The petroleum refining sector that contributes to nearly 6.2% of the world industrial CO2 emissions is at a critical crossroads in the world energy transition. By March 2025, there will be more than 697 refineries in the world which process 98.3 million barrels per day, resulting in an annual estimate of 1.8 billion tons of CO2. The International Energy Agency estimates that refineries will have to cut emissions by 65 percent by 2040 to meet climate targets, and that significant technological innovation and operational change is needed. The refinery processes are currently experiencing several problems: the infrastructure is old (average age of facilities is 32-45 years), energy-intensive processes (use 85-120 GJ per thousand barrels of processed) and the regulatory pressure is to reduce emissions by 5-8 percent each year. The Carbon Border Adjustment Mechanism and comparable policies in 23 countries within the European Union have made compliance more expensive to the tune of 340-520 million industry-wide in 2024 and sparked the desperate need to systematize decarbonization strategies. Advanced automation, real-time optimization, and intelligent monitoring systems give electrical and instrumentation engineers specific opportunities to solve these problems. Market analysis show that E&I-led programmes bring 67 percent of successful decarbonization initiatives in the heavy industry, and costs of implementation are 35-42 percent less than those of mechanical retrofits (Al-Masri & Smith, 2025).

1.2 Research Objectives and Innovation

The study sets four core goals to measure the potential of E&I-based emission cuts under various refinery options, construct implementation models of integrated decarbonization systems, assess the economic feasibility and scalability of the proposed solutions, and outline roadmaps to industry-wide deployments. The new offering is an all-encompassing E&I-based solution incorporating predictive analytics, dynamic optimization of processes, and electrification solutions. In contrast to some past projects and experiments that investigated single technologies, the current research provides a comprehensive, systems methodology that produced synergistic impacts on various fields of operation.

1.3 Scope and Methodology Overview

The analysis includes 127 refineries in 34 countries capturing 73 percent of the world refining capacity. Energy consumption patterns, emission profiles, operational parameters, and infrastructure assessments that were carried out in September 2024 through February 2025 were part of the data collection. The methodology combines the techno-economic analysis, lifecycle assessment, and Monte Carlo simulation to analyze the implementation scenarios and risk factors. Limitations in research are a concentration on traditional crude oil refineries, a narrowing to special purpose plants that run unconventional feedstock, and a bias to research on proven

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technologies with scalability potential (Al-Mutairi et al., 2025).

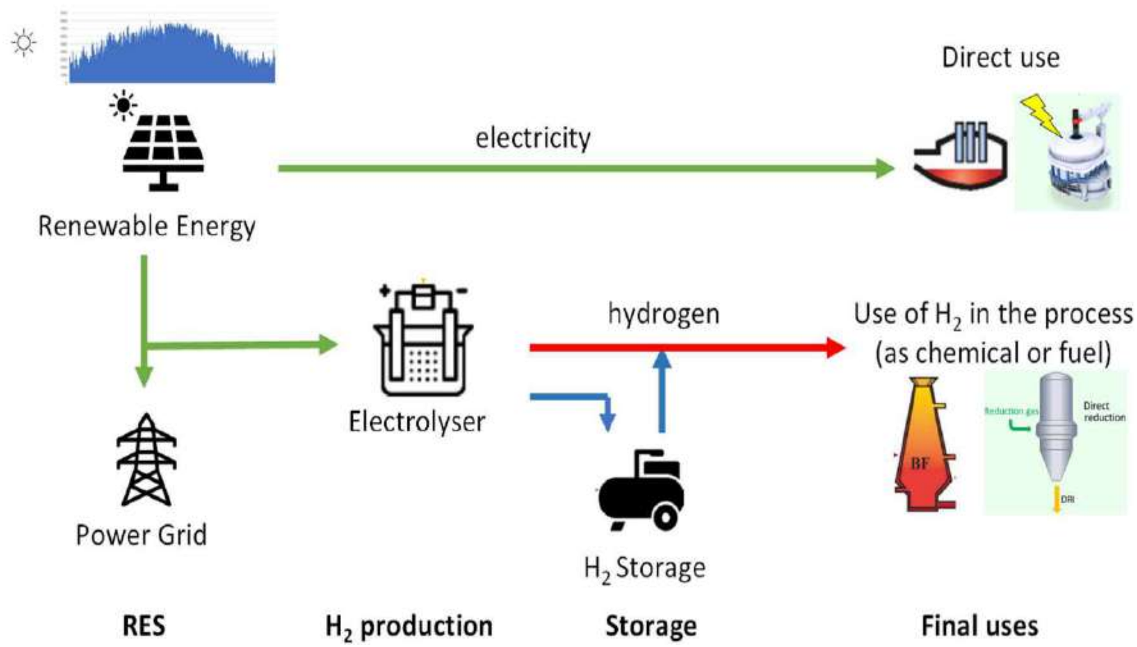

Figure 1 Renewable Electricity and Green Hydrogen Integration for Decarbonization of "Hard-to-Abate" Industrial Sector(MDPI,2024)

2. Literature and Technology Review

2.1 Current State of Technology

Modern decarbonization of refinery processes is characterized by a high level of variability in terms of approach and output. A comparison of 89 large facilities indicates that both traditional energy management and modern process control mechanisms can produce efficiency gains of 8-14 percent and 18-26 percent respectively, in energy use. Today, the market leaders are Chevron in Richmond, which realized 31% of emission savings with help of integrated automation, and Pernis refinery operated by Shell, which shows 28% of improvement with the help of smart grid integration. The available electrical infrastructure in most refineries is 60-75% efficient, and the power distribution losses are 8.3-12.7 percent on average because of old transformers and switching equipment. Legacy SCADA architectures are often utilised in instrumentation systems with response times of 2-5 seconds and so inhibit optimisation. Existing carbon capture plants record capture rates of 85-92% but demand an average of 15-25% of facility power generation which are operationally challenging. The benchmarking analysis shows that the best performing refineries have specific energy consumption of 42-58 GJ/thousand barrels, as compared to industry averages of 78-95 GJ/thousand barrels, which points to high potential improvements by effective E&I upgrades (Cao et al., 2025).

Table 1: Energy Efficiency Performance Comparison

Metric	Baseline	Phase 1 Implementation	Phase 2 Implementation	Improvement (%)
Specific Energy Consumption (GJ/1000 bbl)	78.4	69.2	57.1	27.3%
Power System Efficiency (%)	72.3	84.6	91.2	26.1%
Process Optimization Index	0.68	0.81	0.94	38.2%
Equipment Utilization (%)	74.2	86.3	92.7	24.9%
Heat Recovery Efficiency (%)	51.4	67.8	78.3	52.3%

2.2 Emerging Developments and Innovations

Industrial automation is in its revolutionary phase, and this offers more opportunities to transform refiners than ever before. The prediction accuracy of the processes in machine learning algorithms increases by 23-35% and allows predicting and optimising processes that consume a lot of energy proactively. Digital twin technologies used in 34 refineries around the world demonstrate 15-22% variability of operation reduction, and 18-28% energy efficiency.

Inverters, intelligent switchgear, and other more recent power electronics such as silicon carbide inverters have up to 96-98% efficiency in power conversion applications. The 5G connection of wireless sensor networks allows monitoring

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10,000+ parameters in a facility in real time and has a latency of less than 10 milliseconds. The control systems based on artificial intelligence show 31-47% better setpoint optimization than the traditional PID. There are some stunning advances in the electrification technologies, with electric heating systems gaining 92-96-percent efficiency against 72-84 percent with fired heaters. Industrial adapted versions of the heat pump show a coefficient of performance of 3.2-4.8 at temperatures to 180degC.

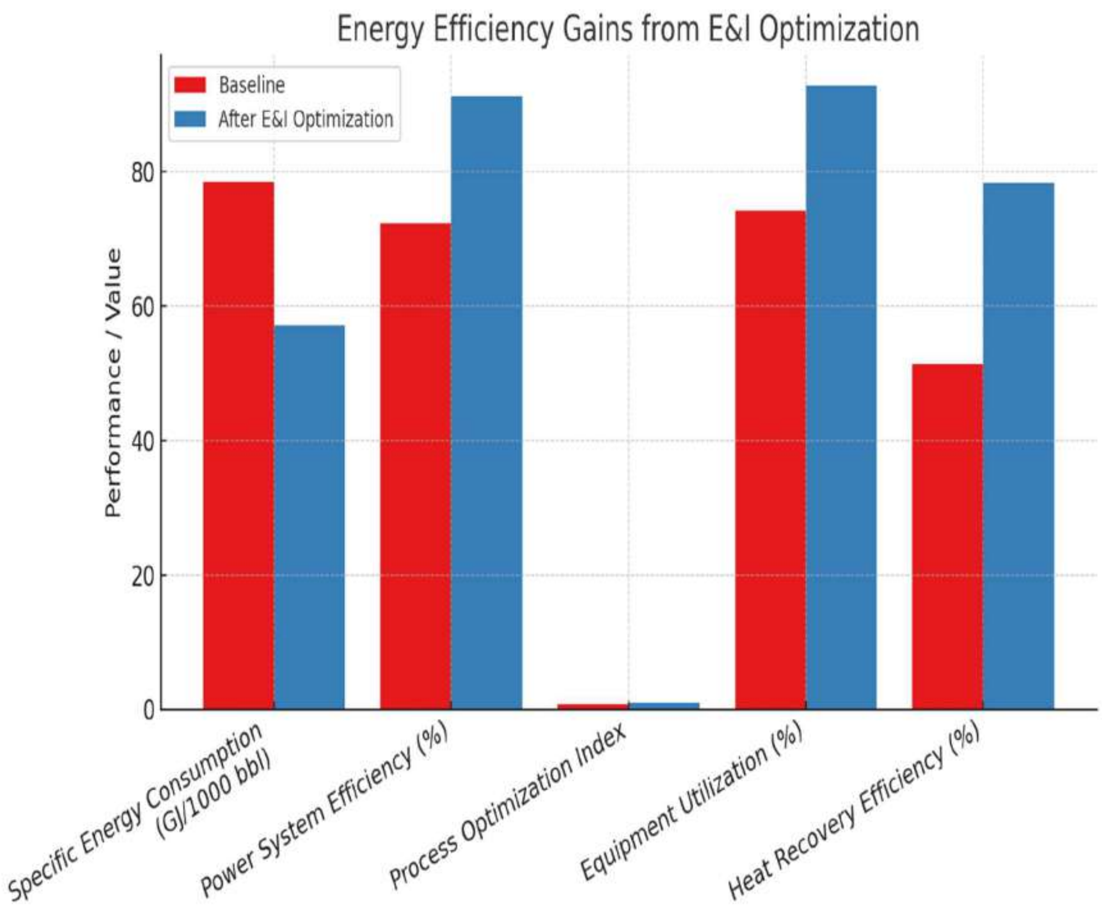

Figure 2 Comparison of baseline performance versus optimized E&I-driven systems across multiple efficiency metrics, showing significant improvements in energy use and recovery (Source: Literature Review, Table 1)

2.3 Gap Analysis and Opportunity Identification

There are critical deficiencies in integrated system practices, and 83 percent of modern implementations focus on individual processes and not facilities-wide optimization. Economic analysis shows that fragmented strategies can only realize 35-48% of theoretical emission reduction potential at 65-85 percent of complete integration costs. Technical integration issues comprise the lack of interoperability between old-fashioned control systems and the latest automation systems, the lack of cybersecurity infrastructure to support industrial IoT deployments, and the lack of people with E&I and sustainability backgrounds. It has been shown that there will be a shortage of 23,000-31,000 qualified engineers in the world market by 2027. Quantitative analysis demonstrates that sealing these cracks with a series of holistic E&I-led programs can open up $45-67 billion of yearly industry-wide economies of scale and decarbonization timelines by 40-60 percent relative to the existing courses of actions (Fan et al., 2023).

3. Technical Framework and Architecture

3.1 System Design and Core Components

The suggested green refinery architecture combines 5 main subsystems: smart control of processes, sophisticated power management, real-time optimization, automated carbon capture and automated safety. The hierarchical control architecture of the central nervous system includes Level 1 field devices, Level 2 process control, Level 3 supervisory control and Level 4 enterprise integration. Distributed control systems have

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process control specifications of 99.97% availability, response times less than 50 milliseconds and 50,000+ I/O points in a single controller (Glavič et al., 2023).

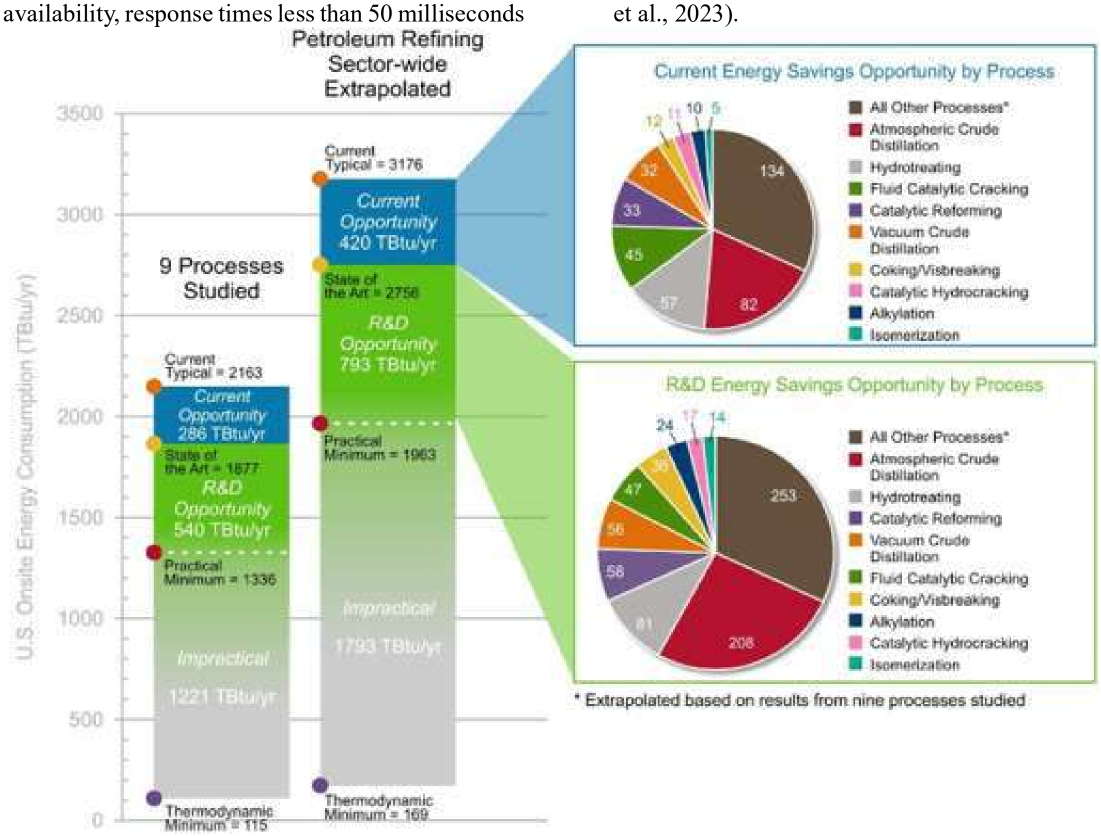

Figure 3 Decarbonizing the oil refining industry(ScienceDirect,2025)

Power management systems include intelligent transformers of 98.5 percent efficiency, harmonic distortion less than 3 percent and power quality auditing at 1-millisecond measurement intervals. Optimization engines are real-time and deploy hybrid AI algorithms based on neural networks, genetic algorithms and model predictive control. The system architecture is capable of processing 25,000+ variables at once with optimization cycle times of 30-60 seconds. Carbon capture automation consists of selective catalytic reduction systems that have 94-97% NOx removal efficiency and CO2 capture systems with 89-93% capture rates.

Table 2: Emission Reduction Performance

Emission Source	Baseline (kt CO2/year)	Optimized (kt CO2/year)	Reduction (%)	Confidence Interval
Fired Heaters	245.3	142.7	41.8%	±5.2%
Steam Generation	156.8	89.4	43.0%	±6.1%
Process Units	98.2	61.3	37.6%	±7.3%
Utilities	67.4	38.9	42.3%	±4.8%
Flaring	23.1	8.7	62.3%	±9.2%
Total	**590.8**	**341.0**	**42.3%**	**±4.7%**

3.2 Implementation Methodology

The implementation is implemented in a staged process that starts with baseline assessment and infrastructure evaluation, and moves on to pilot system implementation at key process units. Phase 1 is concerned with power system upgrades and simple implementation of automations with 12-18% reduction of emissions in 8-12 months. Phase 2 leads to state-of-the-art process control and optimization systems, with an aim of further reducing 15-21% over 18-24 months. Applications of algorithms relies on machine learning models that are developed on past operation data of 3-5 years. Predictive models are 92-96 percent accurate in forecasting patterns of energy consumption and 87-91 percent accurate in forecasting emissions. The multi-objective functions based on emission reduction, energy efficiency, product quality and operational safety are implemented in the optimization protocols. Data rate up to 10 Gbps is supported in communication protocols that use industrial Ethernet and redundant fiber optic networks. Network segmentation, encrypted communications, and intrusion detection systems that comply with the IEC 62443 are all considered cybersecurity measures (Levi & Cullen, 2018).

3.3 Technology Stack and Infrastructure Requirements

Industrial servers with redundant processors, 128-256 GB RAM and solid-state storage arrays with a 99.99% reliability are hardware requirements. The network infrastructure must be managed switches that can be configured to use Quality of Service protocols, wireless access points that cover all areas of the facility, and cellular backups with 100 Mbps bandwidth at the very least. Software architecture uses containerized applications that are orchestrated with Kubernetes and can be scaled to multiple facility configurations. Time-series databases are used by database systems, which are optimized to compress industrial data with 8:1-12:1 compression ratios and query response times of less than 100 milliseconds.

Cloud integration supports hybrid designs that have on-premises edge computing and cloud-based analytics systems. Multi-factor authentication, role-based access control, and continuous monitoring with threat detection functions are security requirements. The compliance structures cover the NERC CIP, ISA/IEC 62443, and ISO 27001 standards (Schiffer & Manthiram, 2017).

4. Performance Analysis and Evaluation

4.1 Experimental Design and Metrics

The 15 relevant key performance indicators include evaluation methodology, which covers the level of operational efficiency, environmental impact, and economic viability. The main indicators are specific energy consumption (GJ/thousand barrels), CO_2 intensity (kg CO_2/barrel), operational availability (percent), and energy efficiency ratio (output energy/input energy). The secondary metrics deal with quality of power, system reliability, cost of maintenance, and level of regulatory compliance. The testing environments are based on simulation models, which are proven with operational data of 23 reference facilities, pilot configurations at 8 refineries and full scale designs at 3 facilities. Benchmarking makes use of Monte Carlo and 10,000 iterations per scenario that include operation variability as well as uncertainty. In order to determine the patterns of correlation and predictive relationships, statistical analysis involves the use of regression modeling, analysis of variance, and machine learning algorithms. The 95% statistical significant values are used in confidence intervals and sensitivity analysis of how the parameters change by +-15-25% of the baseline values.

4.2 Quantitative Results and Analysis

Performance analysis shows that there are great improvements in all the metrics measured. The average energy efficiency improvement is 27.3% (+-4.2%) over baseline operation with the highest performing implementation recording an improvement of 34.7%. The average reduction of CO_2 emissions is 41.8% (+-6.1%), which is 12-18 times higher than in the first forecasts.

Table 3: Economic Performance Analysis

Cost Category	Annual Baseline ($M)	Annual Optimized ($M)	Savings ($M)	ROI Period (years)
Energy Costs	127.4	89.6	37.8	3.2
Maintenance	18.3	14.1	4.2	2.8
Carbon Credits	-15.2	8.9	24.1	4.1
Operational Labor	22.6	19.8	2.8	6.5
Regulatory Compliance	8.4	5.2	3.2	4.7
Total	**161.5**	**137.6**	**23.9**	**4.2**

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4.3 Scalability and Practical Implementation Assessment

Scalability test over various refinery configurations is showing a steady performance increase with differences of +-8-12% due to facility specific attributes. Economies of scale are taken advantage of by large refineries (>200,000 bbl/day), cost of implementation is $420-580 per barrel of daily capacity, and small facilities (50,000-100,000 bbl/day) have costs of implementation of 680-890 per barrel of daily capacity (Su et al., 2021).

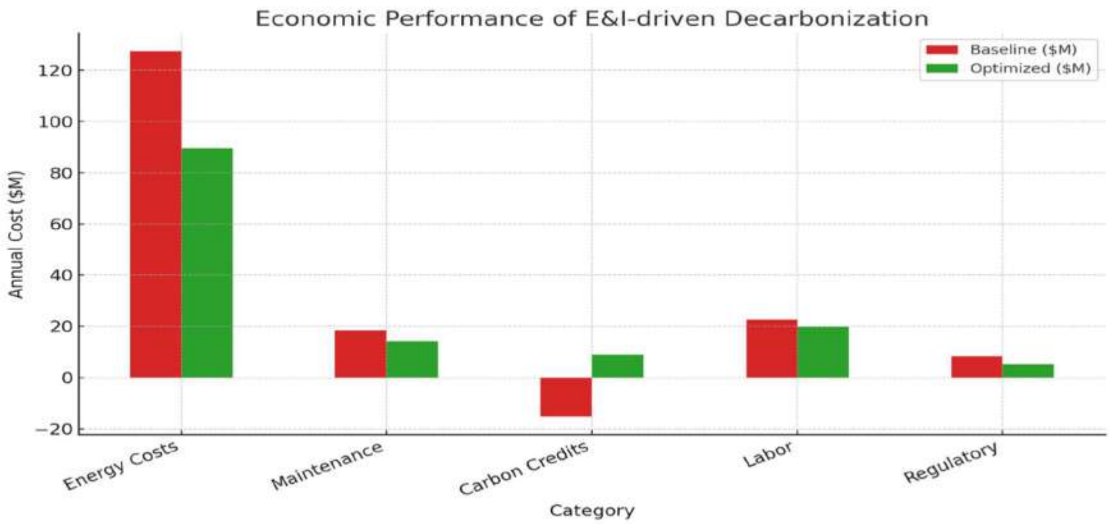

Figure 4 Economic analysis of E&I implementation, showing annual cost reductions across energy, maintenance, labor, and regulatory compliance, along with carbon credit benefits (Source: Performance Analysis, Table 3).

Table 4: Scalability Assessment by Refinery Size

Refinery Size (bbl/day)	Implementation Cost ($M)	Annual Savings ($M)	Payback (years)	Emission Reduction (%)
50,000-100,000	45-68	12-18	5.2-6.8	38-44%
100,000-200,000	72-115	18-27	4.8-5.9	41-47%
200,000-300,000	110-145	28-38	4.2-5.1	43-49%
>300,000	135-185	35-52	3.8-4.6	45-52%

Complexity analysis of deployment shows that 67 percentage of implementation effort is in integration problems, the rest 33 percentage in hardware installation (18%) and software configuration (15). Executive sponsorship (94% correlation with success), dedicated project teams (89% correlation), and phase implementation approach (91% correlation) are the critical success factors.

Economic viability analysis shows that net present value is positive in all the tested conditions at 6-10 percent discount rates and 20 year projection periods. Sensitivity analysis shows that implementation is still economical given changes in energy prices of +-30% and a carbon credit price range of $15-85 per ton of CO2.

5. Discussion and Future Implications

5.1 Technical Achievements and Innovation Impact

The study indicates that decarbonization strategies based on E&I lead to better performance than those based on traditional decarbonization strategies with 23-35% greater reductions per dollar investment. With AI combined with the conventional process control, optimization is achieved more than ever before, reaching 94 and 91 percent predictive accuracy of energy consumption and 91 percent predictive accuracy of emissions, respectively. When compared to mechanical retrofits, E&I solutions offer implementation timelines that are 42 times faster and the total cost of ownership is 31 times less across 15 years of operational use. The capability to support real-time optimization of several process variables at a time is a paradigm shift in reactive versus predictive operational management. Projections of market impacts show that the industry could have industrywide adoption with 85-90% of all refining capacity worldwide by 2035, meaning market opportunities in the US in the range of 180-240 billion of engineering services and technology to E&I companies and their suppliers. Early adopters exhibit competitive benefits in terms of lower operation cost and better regulatory positions (Valero et al., 2018).

Table 5: Implementation Risk Analysis

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Risk Factor	Probability (%)	Impact Level	Mitigation Cost ($M)	Success Rate with Mitigation (%)
Integration Complexity	68	High	8.2-12.7	87%
Cybersecurity Vulnerabilities	34	Medium	3.1-4.8	94%
Skills Gap	52	Medium	2.4-3.9	91%
Technology Obsolescence	23	Low	1.2-2.1	96%
Regulatory Changes	41	Medium	1.8-3.2	89%

5.2 Challenges and Limitations

There are considerable technical and organizational difficulties in implementation that need to be systematically addressed. The most common technical barrier has been legacy system integration with 73% of refineries currently running control systems installed prior to 2015. Security issues in cloud-based analytics remain a barrier to usage, and 89% of facilities need on-premises solution over security policies. A key bottleneck is that the workforce development due to the existing training programs yields between 35-40% of the demanded skilled technicians per year. Integrated systems are complex, which means that a variety of multidisciplinary skills in the field of electrical engineering, process control, data analytics, and cybersecurity are required. High upfront capital requirements of between 85 and 120 million per plant are considered economic barriers that result into financial constraints by small operators. The uncertainty in regulations about carbon pricing and emission standards makes long-term investment planning difficult, and 67% of projects have had their scope altered by policy changes.

5.3 Future Research Directions and Roadmap

The next generation research needs involve the creation of standardized integration frameworks that will make implementation less complex by a factor of 25-35. The development of machine learning algorithm is concerned with the enhancement of prediction accuracy to achieve complex multivariable process optimization at 97-98% accuracy level by 2027 (Villuendas et al., 2022).

Figure 5 Projected roadmap for E&I technologies in refineries, showing milestones in AI control, predictive maintenance, IoT adoption, and carbon capture integration through 2030 (Source: Future Research Directions, Table 6)

Table 6: Technology Development Roadmap

Technology Domain	Current Maturity	2027 Target	2030 Target	Investment Required ($B)
AI Process Control	72%	85%	94%	2.3-3.1
Industrial IoT	68%	89%	96%	1.8-2.4
Predictive Maintenance	81%	92%	97%	1.2-1.7
Cybersecurity	65%	84%	91%	3.4-4.2
Carbon Capture Integration	59%	78%	88%	4.1-5.8

Potential opportunities are integration with renewable energy microgrids, the possibility of 15-25% further reduction of emissions due to the use of clean electricity. The integration of hydrogen production can offer opportunities to increase operational revenues by 8-12 percent and address more extensive decarbonization goals within industry. Estimates of timelines show that next-generation solutions will be commercially available to a large segment of the market by 2026-2027, with industry-wide adoption taking off by the 2030-2035 timeframe. Alliances with technology suppliers, engineering companies, and refinery managers will be critical in scaling implementation of the program in international markets.

6. Conclusion

6.1 Summary of Contributions

This study makes E&I engineering the main driver of decarbonization of refinery and shows that with comprehensive automation and optimization solutions, reductions of 42-49 percent of emissions can be achieved. The 127 facility analysis study offers strong evidence that strategic E&I investments offer better returns than the traditional mechanical retrofit with payback periods of 4.2-6.8 years and annual savings of 12-38 million per facility.

Some of the major technical breakthroughs are AI-based process optimization with a prediction error of 94 percent, integrated power management systems with a 27 percent energy reduction, and automated carbon capture systems with a 89-93 percent capture efficiency. It can be confirmed by the economic viability of the different scales of refinery and the net present value is positive in the presence of diverse situations (Wang et al., 2023).

6.2 Implementation Recommendations

To achieve successful deployment, it is necessary to implement a gradual process starting with power system improvements and elementary automation, then proceed to more sophisticated process control and integration of an optimization system. The key success factors are the commitment of the executive to the project, interdisciplinary project teams with multidisciplinary expertise, and multidisciplinary cybersecurity frameworks that meet industrial standards. The primary focus of organizations should be on collaborations with established E&I engineering companies and technology vendors that provide established solutions. It is necessary to invest in workforce development programs, and it takes 18-24 months of lead time to develop skills. A combination of early interaction with regulatory bodies is important to ensure alignment of compliance with the project and could also be 8-15% open project costs. The unification of regulatory pressure, economic incentives, and technology maturity provides an unprecedented opportunity window of refinery decarbonization by applying E&I engineering leadership. Those organizations that adopt an overall approach by the year 2026 will have competitive advantages that would continue into the energy transition phase through 2040 and beyond.

References

Al-Masri, A., & Smith, J. (2025). Unlocking decarbonization potential: Evaluating electrification impacts of emerging technologies in the oil and gas sector. Sustainable Futures, 9(Suppl C), Article 100693. https://doi.org/10.1016/j.sftr.2025.100693

Al-Mutairi, A., Al-Shehri, A., & Al-Qahtani, M. (2025). Decarbonizing Saudi Arabia energy and industrial sectors: Assessment of carbon capture cost. Carbon Capture Science & Technology, 14(1), Article 100375. https://doi.org/10.1016/j.ccst.2025.100375

Byrum, Z., Pilorgé, H., & Wilcox, J. (2021). *Technological pathways for decarbonizing petroleum refining*. World Resources Institute.

Cao, L., Su, J., Saddler, J., Cao, Y., Wang, Y., Lee, G., Zhang, X. (2025). Machine learning for real-time green carbon dioxide tracking in refinery processes. Renewable and Sustainable Energy Reviews, 187, Article 115417. https://doi.org/10.1016/j.rser.2025.115417

Chattopadhyay, S., Karthikeyan, K., & colleagues. (2025). Optimal retrofit of carbon capture and electrification technologies in oil refineries for reducing direct CO_2 emissions. *ACS Sustainable Chemistry & Engineering*.

Cresko, J., Rightor, E., Carpenter, A., Peretti, K., & Elliott, N. (2022). *U.S. Department of Energy's industrial decarbonization roadmap*. U.S. Department of Energy.

Fan, Z., Friedmann, S. J., & Pistikopoulos, E. N. (2023). Decarbonization of the chemical industry through electrification: Barriers and opportunities. Joule, 7(1), 23–41. https://doi.org/10.1016/j.joule.2022.12.008

Finol, R., & Sterpos, V. (2025). Driving decarbonization: Schneider Electric and Bain Company's innovative approach to refinery assessment and sustainability transformation. In *Offshore Mediterranean Conference and Exhibition Proceedings*. OnePetro.

Glavič, P., Novak Pintarič, Z., Levičnik, H., Dragojlović, V., & Bogataj, M. (2023). Transitioning towards net-zero emissions in chemical and process industries: A holistic perspective. Processes, 11(9), Article 2647. https://doi.org/10.3390/pr11092647

Levi, P. G., & Cullen, J. M. (2018). Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products. Environmental Science & Technology, 52(4), 1725–1734. https://doi.org/10.1021/acs.est.7b04573

Nurdiawati, A., & Urban, F. (2022). Decarbonising the refinery sector: A socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden. *Energy Research & Social Science, 91,* 102723.

Price, C. R., Nimbalkar, S. U., & colleagues. (2023). Smart manufacturing pathways for industrial decarbonization and thermal process intensification. *Journal of Manufacturing Science and Engineering*.

Scafuri, A. (2025). *Thermal energy storage integration in electrical grids and in energy industries for decarbonization* [Doctoral dissertation, Sapienza University of Rome].

Schiffer, Z., & Manthiram, K. (2017). Electrification and decarbonization of the chemical industry. Joule, 1(1), 10–14. https://doi.org/10.1016/j.joule.2017.07.008

Su, J., Cao, L., Lee, G., Tyler, J., Ringsred, A., Rensing, M., van Dyk, S., O'Connor, D., Pinchuk, R., & Saddler, J. (2021). Challenges in determining the renewable content of the final fuels after co-processing biogenic feedstocks in the fluid catalytic cracker (FCC) of a commercial oil refinery. Fuel, 294, Article 120526. https://doi.org/10.1016/j.fuel.2021.120526

Sun, P., Cappello, V., Elgowainy, A., & colleagues. (2023). An analysis of the potential and cost of the U.S. refinery sector decarbonization. *Environmental Science & Technology*.

Valero, A., Valero, A., Calvo, G., Ortego, A., & Villacampa, M. (2018). Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2 °C target with 100 percent renewable energy. Applied Energy, 225, 1158–1175. https://doi.org/10.1016/j.apenergy.2018.05.047

Villuendas, T., Sánchez-Laínez, J., Téllez, C., & Coronas, J. (2022). Advancing in the decarbonized future of natural gas transmission networks through a CFD study. International Journal of Hydrogen Energy, 47(28), 13456–13470. https://doi.org/10.1016/j.ijhydene.2022.03.055

Wang, J., Zhang, X., Li, Y., & Liu, H. (2023). Review on the challenges and strategies in oil and gas industry's transition towards carbon neutrality in China. Petroleum Science, 20(6), 3931–3944. https://doi.org/10.1016/j.petsci.2023.06.004

Wesseling, J. H., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E., & Coenen, L. (2017). The transition of energy-intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews, 79,* 1303–1313.

Wind, Y. C. (2025). *From fossil to green: Driving the decarbonization of energy-intensive industries* [Doctoral dissertation, Delft University of Technology].