

Article

National-Scale Techno-Economic and Environmental Assessment of Used Engine Oil Utilization for Utility-Scale Power Generation in Kuwait

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Abstract

Used engine oil (UEO) is a hazardous waste stream that poses significant environmental risks when improperly managed. However, its high heating value makes it a promising candidate for energy recovery. In Kuwait, rising vehicle ownership has led to increasing quantities of UEO, while the power sector remains heavily dependent on conventional fossil fuels. Although extensive research has examined UEO treatment methods and combustion characteristics, limited attention has been given to its integration into utility-scale power-generation systems. This study presents a national-scale techno-economic and environmental assessment of using UEO as a supplementary fuel for electricity generation in Kuwait. East Doha Power Station was selected as a representative case study to evaluate fuel-substitution potential and the practicality of integrating UEO into existing power-generation infrastructure. Historical vehicle-registration data were used to estimate UEO generation, and future availability was projected through 2035 based on vehicle-growth trends. The corresponding thermal energy potential, equivalent electricity generation, fuel-displacement capacity, economic benefits, and environmental impacts were subsequently evaluated. The results indicate that annual UEO generation is projected to increase from approximately 181,800 tonnes/year in 2024 to 303,300 tonnes/year in 2035. This quantity corresponds to about 12,126 TJ/year of recoverable thermal energy and an equivalent electricity-generation potential of approximately 1.1 TWh/year (4000 TJ/year), assuming a power-plant efficiency of 33%. The recovered UEO could displace approximately 311,000 tonnes/year of heavy oil or 287,000 tonnes/year of crude oil, with estimated net annual fuel-cost savings of approximately 28–30 million KD. Based on literature-reported emission factors, UEO utilization could reduce combustion-related CO₂ emissions by up to 19.0% and NO_x emissions by up to 45.5% compared with heavy oil. Sensitivity analysis further confirmed the robustness of the findings under a range of recovery and operating conditions. To the best of the authors' knowledge, this study represents the first comprehensive national-scale assessment of the potential use of UEO for utility-scale power generation in Kuwait. The findings indicate that UEO has the potential to serve as a strategic secondary energy resource that supports waste reduction, fuel conservation, economic savings, and circular-economy objectives. However, practical implementation will require appropriate collection and treatment infrastructure together with further technical validation, pilot-scale demonstration, and regulatory evaluation.



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1. Introduction

Global energy demand continues to increase due to population growth, urbanization, industrial development, and rising living standards. Despite substantial investments in renewable energy technologies, fossil fuels remain the dominant source of primary energy worldwide, accounting for approximately 80% of global energy consumption, according to the International Energy Agency (IEA) [1,2]. This continued dependence on petroleum-based fuels has intensified concerns regarding greenhouse gas emissions, environmental pollution, fuel-price volatility, and long-term energy security. Consequently, increasing attention has been directed toward improving resource efficiency and identifying alternative energy resources capable of supplementing conventional fuel supplies while reducing environmental impacts. Alongside rising energy demand, the world is also facing increasing challenges associated with the generation and disposal of hazardous waste. One such waste stream is UEO, which is generated from passenger vehicles, heavy-duty transportation systems, industrial machinery, marine engines, and power-generation equipment. UEO contains degraded hydrocarbons, combustion by-products, sulfur compounds, metallic particles, fuel residues, and other contaminants that accumulate during engine operation [3–6]. Improper disposal practices, including uncontrolled burning, illegal dumping, and direct discharge into soil or water bodies, can result in significant environmental pollution and long-term ecological damage [4,5]. Globally, millions of tonnes of UEO are generated each year, yet only a fraction is properly collected, treated, or recovered, particularly in regions where waste-management infrastructure remains underdeveloped [7,8]. Although UEO is commonly regarded as a hazardous waste requiring treatment and disposal, it also represents a valuable secondary energy resource. Previous studies have shown that properly treated UEO possesses a heating value comparable to those of conventional liquid fuels and can therefore be used in combustion-based energy applications [9–11]. As a result, UEO has attracted increasing interest within waste-to-energy and circular-economy frameworks aimed at recovering value from waste streams while reducing dependence on virgin fossil-fuel resources. The use of UEO as a supplementary fuel offers a dual benefit by addressing hazardous-waste management challenges while contributing to energy production. For Kuwait, the management and utilization of UEO are particularly important because substantial quantities of waste lubricating oil are generated annually from the country's transportation sector. Kuwait's extreme climatic conditions, high vehicle ownership rates, and continued reliance on liquid fuels for electricity generation create a distinctive environment in which UEO generation and utilization potential may differ significantly from those reported in moderate-climate regions. At the same time, Kuwait remains heavily dependent on conventional fossil fuels for electricity generation and seawater desalination. The electricity-generation sector relies primarily on large thermal power stations, including East Doha, West Doha, Sabiya, Shuaiba, and Az-Zour, which consume significant quantities of crude oil, heavy oil, gas oil, and natural gas. Consequently, recovering energy from UEO may provide an opportunity to supplement existing fuel resources while simultaneously addressing an important waste-management challenge. Rapid population growth, urban expansion, and increasing cooling requirements have resulted in continuous growth in electricity demand, particularly during the summer season, when air-conditioning loads dominate national power consumption [12,13]. This increasing demand places additional pressure on domestic fuel resources and highlights the importance of exploring supplement-

tary energy sources capable of improving resource utilization efficiency. Several studies have investigated UEO recovery technologies, fuel-treatment methods, combustion characteristics, and emissions performance [9–11,14–17]. However, the majority of the previous research has focused primarily on laboratory-scale experiments, fuel-quality improvement, combustion analysis, or small-scale engine applications. Comparatively limited attention has been directed toward evaluating the large-scale integration of the nation's generated UEO into utility-scale power-generation infrastructure operating under real fuel-demand conditions. For Kuwait specifically, no previous study has comprehensively quantified the relationships among national vehicle growth, UEO generation potential, utility power-station fuel demand, fuel-substitution capability, economic benefits, and environmental implications within a single integrated techno-economic framework. A preliminary assessment of UEO utilization for power generation at East Doha Power Station was previously reported by Alrajhi et al. [18]. That study focused primarily on the feasibility of utilizing UEO as an alternative fuel and provided an initial economic and environmental comparison with conventional fuels. The present work substantially expands the scope of the previous study by incorporating national vehicle-growth analysis, long-term UEO availability forecasting through 2035, utility-scale resource assessment, fuel-displacement modelling, sensitivity analysis, and a comprehensive techno-economic and environmental evaluation framework. Consequently, the present study expands the scope of previous work by evaluating the national-scale potential of UEO utilization for utility-scale power generation in Kuwait.

Accordingly, this study evaluates the national-scale potential of UEO utilization for utility-scale power generation in Kuwait. The analysis quantifies historical and future UEO availability, estimates energy-recovery potential, assesses conventional-fuel displacement capability, and evaluates the associated economic and environmental implications.

2. Literature Review of UEO as a Waste-to-Energy Resource

2.1. Global Energy Demand and Waste-Oil Management Challenges

Growing energy demand and increasing quantities of hazardous waste have intensified interest in resource-recovery strategies that can simultaneously address environmental and energy-security concerns. Among petroleum-derived waste streams, UEO represents a significant environmental challenge because improper disposal can contaminate soil, water, and air resources. At the same time, UEO retains a substantial portion of its original hydrocarbon content and possesses a relatively high heating value, making it a potentially valuable secondary energy resource [3–10]. Within circular-economy and waste-to-energy frameworks, UEO has attracted increasing attention as a waste stream that can be recovered and utilized rather than discarded. Recovering energy from UEO not only reduces hazardous-waste accumulation but can also decrease dependence on conventional fossil fuels. As a result, considerable research has focused on technologies for UEO recovery, treatment, and energy utilization, as discussed in the following sections.

2.2. UEO Recovery and Fuel Conversion Technologies

Several methods have been developed for recovering and utilizing UEO, including physical treatment, chemical purification, thermal conversion, and re-refining processes. Physical-treatment techniques such as filtration, sedimentation, centrifugation, and dewatering are commonly used to remove suspended solids, sludge, and water before fuel utilization [19–21]. These methods are relatively simple and economically attractive for large-scale applications. Chemical-treatment processes, including solvent extraction and adsorption, have also been investigated to improve fuel quality and reduce contaminant concentrations. Katiyar et al. [21] reported that solvent-based treatment can effectively

improve the properties of recovered oil and facilitate its subsequent use as a fuel. More advanced approaches include pyrolysis and catalytic cracking, which convert UEO into lighter hydrocarbon fractions with properties similar to those of commercial petroleum fuels. Lam et al. [22,23] and Abu-Elella et al. [24] reported that these technologies can improve fuel quality and increase resource recovery; however, they generally require higher capital investment and greater process complexity. Although re-refining is often considered the highest-value recovery pathway because it regenerates base lubricating oil for reuse, direct utilization of properly treated UEO remains one of the most practical options because of its high heating value and relatively modest processing requirements. Consequently, many researchers have investigated UEO as an alternative fuel for combustion-based energy applications.

2.3. Previous Studies on UEO as an Alternative Fuel

UEO has attracted considerable interest as an alternative energy source because it retains a substantial fraction of its original hydrocarbon content and possesses energy characteristics comparable to those of conventional liquid fuels. Numerous investigations have shown that properly treated UEO exhibits physical and chemical properties similar to diesel fuel, gas oil, and heavy fuel oil [6,11]. These similarities have led to its evaluation in a variety of combustion systems, including diesel engines, industrial burners, furnaces, marine engines, and other thermal-energy technologies. Naima and Liazid [12] reviewed the use of waste oils in diesel engines and concluded that waste lubricating oil can provide acceptable combustion performance following appropriate treatment and filtration. Likewise, Đorđić et al. [13] reported satisfactory engine performance and manageable emissions when testing a waste-oil-based fuel in a marine diesel engine. Other investigations have shown that blending UEO with diesel fuel can improve fuel stability while reducing operational concerns associated with the direct use of untreated oil [14]. Interest in UEO has also expanded to industrial combustion systems because of its suitability as a replacement for petroleum-derived fuels. Earlier work reported calorific values comparable to those of heavy fuel oil and gas oil, supporting its use in equipment designed for liquid hydrocarbons [6]. Power-plant boilers and industrial furnaces are generally capable of accommodating fuels with different viscosities and compositions through preheating and atomization, making these facilities potential candidates for incorporating recovered oil. In parallel, several treatment approaches have been developed to improve fuel quality before combustion. Chatziaras et al. [15] examined pyrolysis-derived waste engine oil as an alternative diesel fuel and reported promising combustion behavior together with strong energy-recovery performance. Similarly, Lam et al. [23] demonstrated that catalytic cracking can convert waste lubricating oil into lighter hydrocarbon fractions suitable for energy production. These findings highlight the availability of multiple pathways for upgrading recovered oil and improving its suitability for practical use. In addition to its technical advantages, UEO offers environmental benefits when diverted from conventional disposal practices. Recovering waste oil for productive purposes reduces hazardous-waste accumulation while lowering dependence on virgin fossil resources. Directing this material toward controlled combustion systems may also help reduce environmentally harmful practices such as illegal dumping and uncontrolled burning [8,9]. Such benefits align closely with the objectives of resource conservation, waste reduction, and circular-economy implementation. Despite these encouraging results, most published work has focused on laboratory-scale combustion experiments, engine-performance assessments, emissions characterization, or fuel-treatment methods. Far less attention has been given to the incorporation of recovered oil into utility-scale power-generation facilities operating under actual fuel-demand conditions. This limitation is particularly relevant in Gulf countries such as Kuwait, where large

thermal power stations, continued reliance on petroleum fuels, and substantial annual UEO generation present a strong opportunity for waste-to-energy deployment. Although the existing literature generally reports favorable combustion performance and meaningful energy-recovery benefits, most findings are derived from controlled laboratory environments or small-engine applications. Whether these outcomes can be directly translated to utility-scale facilities remains uncertain because treatment requirements, oil-quality variability, long-term equipment reliability, operational constraints, and emissions-control requirements differ considerably from those encountered in laboratory studies. Consequently, additional investigation is required to assess the practical integration of UEO into large-scale power-generation systems under real operating conditions.

2.4. Technical Considerations for Utility-Scale UEO Utilization

Although previous studies have reported favorable fuel characteristics for UEO, several uncertainties remain regarding its use in large electricity-generation facilities. Most published research has focused on combustion performance, treatment technologies, or emissions characterization rather than long-term operation in utility power plants. In addition, the composition of recovered oil can vary considerably depending on engine type, lubricant formulation, contamination levels, operating conditions, and treatment quality. Such variations may influence combustion behavior, equipment durability, ash formation, corrosion, and pollutant emissions. As a result, laboratory-scale findings alone are insufficient to confirm suitability for sustained operation under utility-scale conditions. Successful integration into power-generation facilities depends on several factors, including compatibility with existing equipment, combustion stability, operational reliability, treatment requirements, and regulatory compliance. Unlike small combustion devices or diesel-engine applications, utility plants operate continuously while handling substantial quantities of fuel. Therefore, any evaluation of UEO must consider both its physical and chemical properties as well as the capabilities of existing infrastructure. One factor supporting the use of UEO is its similarity to conventional petroleum-derived fuels. Reported heating values generally range from 38 to 42 MJ/kg, which is comparable to values for heavy fuel oil, crude oil, and gas oil [6,11]. Because lubricating oils originate from petroleum feedstocks, treated UEO retains many of the characteristics required for efficient combustion. Experimental investigations have demonstrated satisfactory performance in industrial burners, furnaces, diesel engines, and thermal-energy systems when appropriate treatment and quality-control measures are applied [12–15]. These results indicate that recovered oil possesses the fundamental attributes necessary for large thermal-power applications. Another important consideration is compatibility with existing generating infrastructure. Modern thermal power stations are typically equipped with fuel-storage systems, transfer equipment, preheating units, atomization devices, combustion controls, and emissions-monitoring technologies capable of handling liquids with different properties. Furthermore, alternative liquid fuels have already been incorporated into several industrial sectors, including cement production and heavy industrial heating [25]. This experience suggests that introducing UEO as a supplementary energy source may require only modest modifications, compared with constructing dedicated waste-to-energy facilities. Consequently, existing generating assets could provide a practical platform for recovering energy from waste lubricating oil. Despite these advantages, several technical challenges must be addressed before widespread deployment becomes feasible. The quality of recovered oil depends heavily on its source and handling practices. Untreated material may contain water, sludge, metallic particles, sulfur compounds, ash-forming substances, degraded additives, and combustion residues [4,21]. If these contaminants are not adequately removed, they can contribute to fouling, injector blockage, corrosion, ash deposition, higher

maintenance requirements, and unstable operation. Therefore, pretreatment remains one of the most important factors influencing successful implementation. Reliable operation generally requires filtration, sediment removal, dewatering, contaminant reduction, and routine quality monitoring. In addition, gradual introduction through controlled blending with conventional fuels may help minimize implementation risks during the early stages of deployment. Similar strategies have been adopted in other alternative-fuel programs to maintain stable combustion while allowing operators to evaluate long-term performance and equipment reliability under actual operating conditions. From a practical perspective, the use of UEO within existing generating facilities offers several advantages over dedicated waste-conversion plants. Utility operators already possess the combustion equipment, fuel-handling systems, storage capacity, operational expertise, and environmental-monitoring frameworks required for large-scale energy production. Utilizing this infrastructure could reduce capital expenditures while accelerating deployment. In countries such as Kuwait, where electricity generation continues to depend heavily on liquid petroleum fuels, recovered oil represents a potentially valuable supplementary resource that supports both energy production and waste-management objectives. Although many investigations have demonstrated the technical viability of treated UEO in combustion systems, most have been limited to laboratory experiments, engine testing, emissions assessments, or treatment technologies [12–15,21–24]. Comparatively few studies have examined its practical application in utility-scale generating facilities operating under actual fuel-demand conditions. This gap is particularly relevant in Gulf countries, where substantial quantities of UEO are produced annually while thermal power stations continue to consume large volumes of conventional fuels. Additional research is therefore needed to evaluate the technical, economic, and environmental implications of integrating UEO into large-scale power-generation systems under region-specific operating conditions.

2.5. Economic and Environmental Implications of UEO Utilization

The use of UEO as a supplementary energy source has attracted considerable interest because of its potential economic and environmental advantages. Unlike conventional petroleum fuels, UEO is generated as a by-product of transportation and industrial activities, making it an existing resource that can be recovered and redirected toward productive applications. This characteristic has encouraged interest in recovering value from waste streams while reducing reliance on conventional energy resources. From an economic standpoint, several investigations have reported that recovering waste lubricating oil can provide a cost-effective alternative to conventional disposal practices while reducing dependence on virgin fossil fuels [6,8,23]. Treated UEO possesses a calorific value comparable to those of crude oil, gas oil, and heavy fuel oil, allowing its use in combustion-based systems with minimal impact on energy output [6,11]. Consequently, it has been evaluated as a supplementary energy source for industrial boilers, furnaces, diesel engines, and thermal-power applications. Earlier studies have indicated that replacing a portion of conventional fuel consumption with recovered oil can lower procurement costs while increasing the value derived from waste materials [8,23]. Additional economic advantages may arise through reduced expenditures associated with waste handling and environmental management. Improper disposal of waste lubricating oil often requires environmental monitoring, remediation measures, and regulatory enforcement, all of which impose financial burdens on governments and industries. Redirecting recovered oil toward productive use can help avoid a portion of these costs while creating value from a material that would otherwise require disposal. Furthermore, in countries that depend heavily on liquid fuels for electricity generation, recovered oil may partially offset domestic fuel demand and increase the availability of conventional petroleum products for higher-value uses or export markets.

Environmental considerations provide another important motivation for recovering UEO. Waste lubricating oil contains degraded hydrocarbons, heavy metals, sulfur-containing compounds, combustion residues, and additive by-products that can contaminate soil and water resources if improperly managed [4–6,21]. Recovering and utilizing this material in controlled combustion systems can reduce the risks associated with illegal dumping, uncontrolled burning, and inappropriate disposal practices. Several authors have emphasized that converting waste-derived resources into useful energy supports more sustainable waste-management strategies while reducing the environmental burden associated with waste accumulation [8–10]. Nevertheless, environmental performance depends strongly on treatment quality, combustion conditions, and emissions-control technologies. Inadequately processed oil may contain contaminants capable of increasing particulate matter, sulfur oxides, nitrogen oxides, or trace-metal emissions during combustion [14,21]. For this reason, filtration, dewatering, contaminant removal, and routine quality monitoring are essential for environmentally responsible operation. These requirements highlight the importance of considering technical, economic, and environmental factors simultaneously when evaluating large-scale deployment strategies. Although numerous studies have examined recovery technologies, combustion performance, and emissions characteristics, relatively little attention has been given to the broader implications of integrating the nation's generated UEO into utility-scale power-generation systems. The existing literature has rarely combined resource availability, fuel-substitution potential, economic performance, and environmental impacts within a single assessment framework. This limitation underscores the need for integrated evaluations that reflect actual operating conditions and large-scale energy demand. In addition, reported benefits vary considerably according to collection efficiency, treatment requirements, local fuel prices, regulatory frameworks, and the emissions factors adopted in the analysis. As a result, conclusions derived from small-scale studies or specific regional settings may not be directly transferable to utility-scale power-generation facilities operating under different economic and regulatory conditions. This research gap provides the foundation for the assessment presented in the following subsection.

2.6. Research Gap and Novel Contribution

Although numerous studies have examined UEO recovery technologies, treatment methods, combustion performance, and emissions characteristics [12–15,20–24], most have focused on laboratory-scale experiments, engine testing, or process optimization. As a result, relatively little attention has been given to long-term resource availability, large-scale fuel substitution, economic viability, and environmental impacts within national electricity-generation systems. Kuwait provides a particularly relevant setting for evaluating the potential role of recovered oil in the energy sector. The country is characterized by high vehicle ownership rates, extreme climatic conditions, elevated ambient temperatures, and continued reliance on liquid fuels for electricity generation. These conditions often result in more frequent lubricant replacement intervals than those observed in moderate climates, contributing to substantial quantities of waste oil. At the same time, Kuwait's electricity sector continues to consume significant volumes of crude oil and heavy fuel oil, creating an opportunity to incorporate a locally generated waste-derived resource into existing generating infrastructure. These factors distinguish Kuwait from many previously studied regions and provide a unique basis for assessing the large-scale energy potential of UEO. No previous study has comprehensively linked national vehicle-growth trends, annual UEO generation, utility power-plant fuel demand, fuel-substitution potential, economic performance, and environmental impacts within a single techno-economic assessment based on operational data from a major Kuwaiti power station. A preliminary

investigation of UEO utilization at East Doha Power Station was previously reported by Alrajhi et al. [18]. That work focused primarily on the feasibility of using recovered oil as an alternative fuel and provided an initial economic and environmental comparison with conventional energy sources. The present study significantly expands upon that earlier assessment by incorporating national vehicle-growth projections, forecasting future UEO availability through 2035, evaluating large-scale energy-recovery potential, quantifying fuel substitution, performing sensitivity analysis, and integrating technical, economic, and environmental considerations within a unified framework. The principal contributions of this study include

- Quantification of national UEO generation and projected resource availability in Kuwait;
- Evaluation of energy-recovery potential, using East Doha Power Station as a representative utility-scale case study;
- Assessment of conventional fuel substitution and the associated economic implications;
- Analysis of environmental impacts based on comparative emissions scenarios;
- Integration of resource availability, energy production, economic performance, and environmental considerations within a comprehensive assessment framework.

To the best of the authors' knowledge, this study represents the first national-scale assessment of the potential contribution of UEO to electricity generation in Kuwait. It simultaneously evaluates future resource availability, equivalent electricity-generation potential, fuel substitution, economic benefits, environmental impacts, and sensitivity to key operating parameters within a single analytical framework. The findings provide a foundation for assessing the role of recovered oil in Kuwait's energy sector and support informed decision-making regarding future waste-to-energy initiatives and resource-recovery strategies.

3. Methodology

3.1. Study Framework and System Boundary

This study employed an integrated techno-economic and environmental framework to evaluate the feasibility of using UEO as a supplementary fuel for electricity generation in Kuwait. East Doha Power Station was selected as the representative case study because the annual quantity of UEO generated in Kuwait is comparable to the station's liquid-fuel consumption, providing a realistic basis for evaluating fuel-substitution opportunities under actual operating conditions. In addition, East Doha is one of Kuwait's major electricity and desalination facilities, making it a suitable case study for examining the practical integration of waste-derived fuels into existing generating infrastructure. The analytical framework consisted of five sequential stages:

1. Estimation of historical UEO generation using national vehicle statistics and lubricant-consumption data;
2. Projection of future UEO availability through 2035 based on vehicle-growth trends;
3. Quantification of recoverable thermal energy and equivalent electricity-generation potential;
4. Evaluation of conventional fuel-substitution potential relative to East Doha Power Station fuel demand;
5. Assessment of the associated economic and environmental impacts.

The system boundary extends from UEO generation within Kuwait's transportation sector to its final use within the electricity-generation system. Accordingly, the analysis includes UEO generation, collection, transportation, treatment, storage, and energy recovery through combustion. Activities associated with crude-oil extraction, lubricant manufacturing, vehicle operation, detailed combustion chemistry, and full life-cycle environmental

assessments were excluded from the scope of this study. The overall methodology is illustrated in Figure 1.

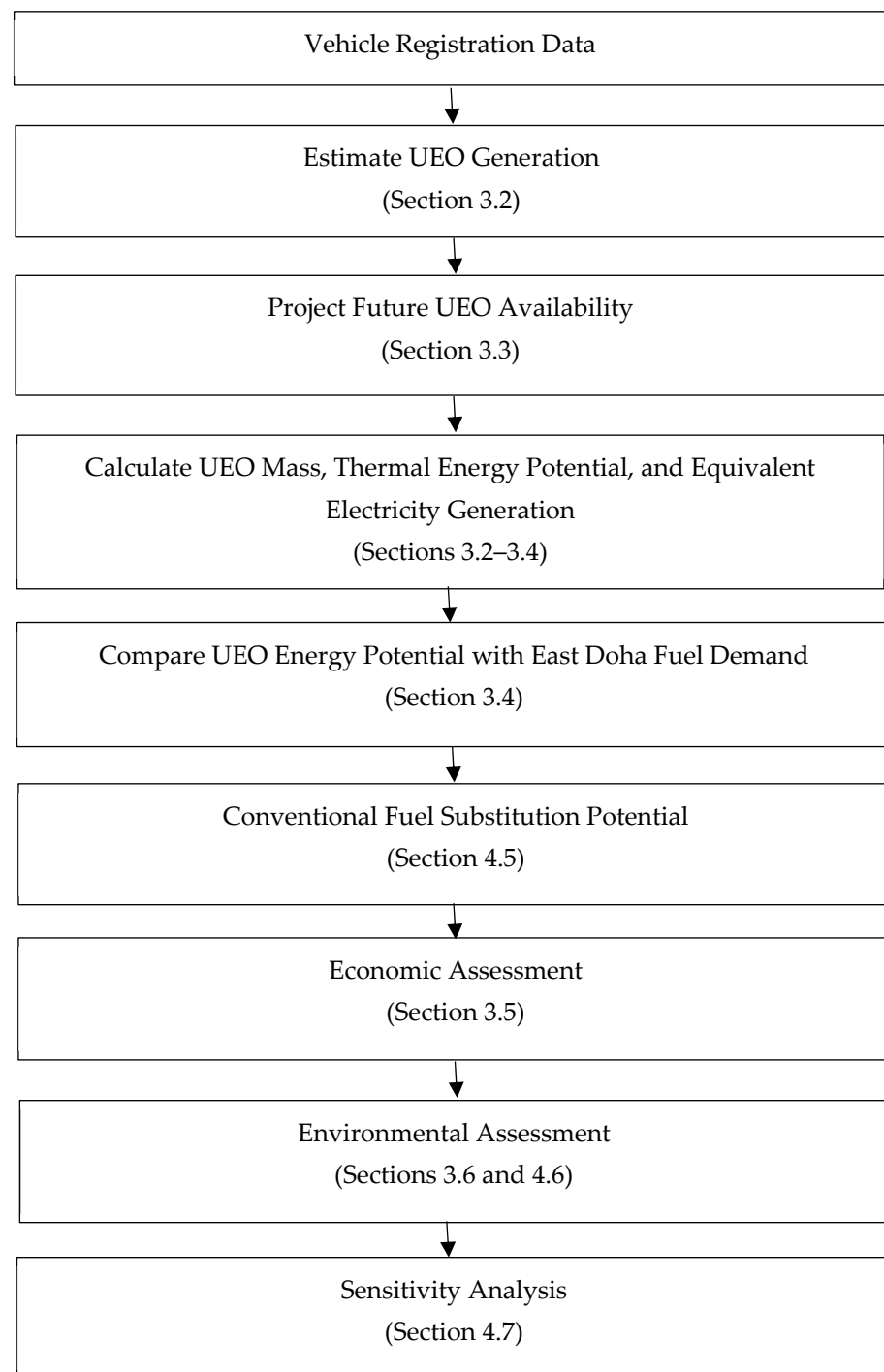


Figure 1. Methodological framework adopted in this study.

The framework outlines the sequence of steps used to estimate future resource availability, quantify energy potential, compare recovered energy with fuel demand at East Doha Power Station, and evaluate the associated economic and environmental implications. This analysis was designed to provide a national-scale assessment of the potential contribution of UEO to Kuwait's electricity sector. Several simplifying assumptions were therefore adopted regarding average oil consumption, oil-replacement frequency, and fuel properties. These assumptions were derived from published literature and were consid-

ered representative of large-scale resource estimation. Nevertheless, actual generation and recovery rates may vary depending on vehicle type, maintenance practices, lubricant formulations, collection efficiency, and future changes in fleet composition. Accordingly, the results should be interpreted as indicative estimates rather than precise predictions of future resource availability.

3.2. Estimation of UEO Generation in Kuwait

The quantity of UEO generated annually in Kuwait was estimated using national vehicle-registration statistics, together with representative engine-oil consumption and replacement-frequency data reported in the literature [16,26–28]. Vehicle-registration data were obtained from official publications of the General Administration of Statistics and the Ministry of Interior of Kuwait [16]. The adopted lubricant-consumption parameters were selected to represent typical vehicle-maintenance practices under Kuwaiti operating conditions. Annual UEO generation was estimated using

$$M_{UEO} = \frac{N_v V_o F_c \rho_{\{UEO\}}}{10^6} \quad (1)$$

where

- M_{UEO} is the annual UEO mass (tonnes/year).
- N_v is the total number of registered vehicles.
- V_o is the average engine-oil volume per vehicle per oil change (L/change).
- F_c is the annual oil-change frequency.
- $\rho_{\{UEO\}}$ is the density of UEO (kg/m³).

Equation (1) is based on a mass-balance approach commonly used to estimate lubricant consumption and waste-oil generation from vehicle fleets. The adopted oil volume represents a fleet-average value intended for national-scale resource assessment rather than individual vehicle categories. Although oil capacities vary among passenger cars, commercial vehicles, and heavy-duty vehicles, the selected value provides a practical approximation for estimating aggregate UEO generation. The influence of this assumption is evaluated through the sensitivity analysis presented in Section 4.7. The quantities estimated using Equation (1) represent the theoretical annual generation of UEO based on vehicle population, lubricant consumption, and oil-replacement frequency. Actual recoverable quantities may be lower because of collection inefficiencies, storage losses, informal disposal practices, and treatment constraints. Accordingly, the calculated values should be interpreted as theoretical generation potential rather than guaranteed recoverable quantities.

3.3. Future Projection of UEO Generation

Future UEO availability was projected using historical vehicle-growth trends in Kuwait. The future number of registered vehicles was estimated using the compound annual growth model:

$$N_f = N_i(1 + r)^n \quad (2)$$

where

- N_f is the projected vehicle population.
- N_i is the initial vehicle population.
- r is the annual growth rate.
- n is the projection period in years.

Equation (2) is a standard compound-growth relationship commonly used for vehicle-population forecasting. Projected vehicle populations were subsequently substituted into

Equation (1) to estimate future UEO generation using the same lubricant-consumption assumptions adopted for the historical analysis. The projections do not explicitly account for future changes in fleet composition resulting from increasing vehicle electrification. Although hybrid vehicles continue to require periodic engine-oil replacement, large-scale adoption of battery-electric vehicles could influence long-term UEO availability and therefore represent a source of uncertainty beyond the scope of the present analysis.

3.4. East Doha Power Station Fuel Consumption Analysis

The fuel-substitution potential of UEO was evaluated relative to the fuel consumption of East Doha Power Station, one of Kuwait's major electricity and desalination facilities. The analysis considered the station's annual fuel consumption and operating characteristics. The thermal energy content of the available UEO was calculated using

$$Q_{UEO} = \frac{M_{UEO} \times HV_{UEO}}{1000} \quad (3)$$

where

- Q_{UEO} is the annual thermal energy available from UEO (TJ/year).
- M_{UEO} is the annual UEO mass (tonnes/year).
- HV_{UEO} is the heating value of UEO (MJ/kg).

The equivalent electrical energy contribution was estimated using

$$E_e = \eta \times \frac{Q_{UEO}}{3600} \quad (4)$$

where

- E_e is the equivalent electrical energy potential (TWh/year).
- η is the thermal-to-electrical conversion efficiency of the power station.

The resulting thermal and electrical energy potentials were subsequently compared with East Doha Power Station fuel-consumption data to evaluate the potential contribution of UEO as a supplementary fuel source.

3.5. Economic Assessment Methodology

The economic assessment was conducted to evaluate the potential fuel-cost savings associated with utilizing UEO as a supplementary fuel for electricity generation. The analysis considered the costs of UEO collection, transportation, treatment, and storage and compared them with the value of the conventional fuels displaced by UEO, namely, crude oil and heavy oil. Annual net savings were estimated using

$$S = (M_{\{eq\}} \times P_f) - C_t \quad (5)$$

where

- S is the annual net savings.
- $M_{\{eq\}}$ is the equivalent displaced conventional fuel mass.
- P_f is the conventional fuel price.
- C_t represents total UEO processing, transportation and storage costs.

The economic assessment was based on average fuel-consumption and fuel-expenditure data for East Doha Power Station during the period 2013–2021. Representative fuel costs were obtained by dividing the average annual fuel expenditure by the corresponding average annual fuel consumption, thereby reducing the influence of short-term fuel-price fluctuations. The collection, transportation, and handling cost of UEO was assumed to be

17 KD/tonne (approximately 55 USD/tonne), based on values reported for waste-lubricating-oil collection systems in Saudi Arabia [29]. Because Saudi Arabia and Kuwait share similar regional logistics, transportation infrastructure, and fuel-distribution conditions, this value was considered representative for Kuwait. The analysis focuses on direct fuel-displacement savings and does not include secondary economic benefits such as avoided environmental remediation costs or reduced waste-disposal expenditures. Crude-oil prices obtained in U.S. dollars were converted to Kuwaiti Dinars (KD) using an average exchange rate of 1 USD = 0.305 KD. All economic results are reported in Kuwaiti Dinars to ensure consistency with local economic conditions.

3.6. Environmental Assessment Methodology

The environmental assessment evaluated the potential impacts of utilizing UEO as a supplementary fuel within Kuwait's power-generation sector. The analysis considered the diversion of UEO from conventional disposal pathways, the reduction of hazardous-waste accumulation, and the displacement of conventional liquid fuels used for electricity generation. Because a full life-cycle assessment (LCA) was beyond the scope of this study, the environmental evaluation was based on a comparative analysis of fuel-substitution potential and literature-reported emission characteristics of UEO, crude oil, and heavy oil. Environmental implications were assessed in terms of waste reduction, resource recovery, and estimated combustion-related emissions. The reported CO₂ and NO_x emission comparisons are based solely on literature-reported combustion emission factors applied to the equivalent electrical energy contribution calculated in this study. Upstream processes, alternative UEO management pathways, avoided disposal impacts, and broader life-cycle effects were not quantified. Therefore, the reported emission differences should be interpreted as comparative combustion-emission estimates rather than net life-cycle environmental benefits or greenhouse-gas reductions.

3.7. Assumptions and Limitations

Several assumptions were adopted to establish a practical framework for evaluating the technical, economic, and environmental feasibility of utilizing UEO for utility-scale power generation in Kuwait. The analysis assumes that collected UEO undergoes adequate filtration, dewatering, and preliminary treatment prior to utilization, thereby producing fuel suitable for combustion applications. The heating value, density, sulfur content, and emission factors adopted in this study were obtained from the published literature and are therefore representative values rather than site-specific measurements of Kuwaiti UEO. These parameters were used for comparative assessment purposes and may vary depending on fuel composition, treatment processes, and operating conditions. The analysis further assumes that existing combustion systems can accommodate partial UEO substitution with limited operational modifications and without major infrastructure replacement. Future projections of UEO availability also assume that vehicle ownership growth and lubricant-consumption trends remain generally consistent with historical patterns observed in Kuwait. The present study is intended as a techno-economic and environmental feasibility assessment and therefore does not include experimental combustion testing, pilot-scale validation, detailed combustion modeling, pollutant-formation analysis, boiler heat-transfer modeling, or long-term equipment-performance evaluation. Similarly, fuel-quality variability, advanced treatment processes, and operational issues such as fouling, corrosion, nozzle clogging, ash deposition, and emission fluctuations were not investigated. Evaluation of these factors requires dedicated experimental studies and pilot-scale demonstrations beyond the scope of the present work. The analysis is based on annualized UEO-generation and fuel-consumption data and therefore does not explicitly account for seasonal varia-

tions in electricity and desalination demand, fuel-storage requirements, or power-station operating schedules. Because UEO can be collected, stored, and utilized throughout the year, the study focuses on annual resource availability and fuel-displacement potential rather than short-term operational behavior. Evaluation of seasonal demand fluctuations, dispatch strategies, storage requirements, and time-dependent integration of UEO within Kuwait's power-generation system was beyond the scope of the present study and should be considered in future investigations. Accordingly, the findings should be interpreted as an assessment of resource availability, fuel-substitution potential, economic feasibility, and environmental implications rather than a comprehensive engineering design or operational validation. Future research should focus on fuel characterization of locally collected UEO, combustion and emissions testing, pilot-scale demonstrations, fuel-treatment optimization, and long-term reliability assessments under utility-scale operating conditions.

4. Results and Discussion

4.1. Kuwait Energy Demand and Long-Term UEO Resource Potential

Kuwait's electricity demand has increased steadily over the past decade as a result of population growth, urban development, industrial activity, and extensive reliance on air-conditioning systems. As shown in Figure 2, annual electricity demand increased from approximately 182,000 TJ/year in 2011 to approximately 290,000 TJ/year in 2024, representing an increase of approximately 59% over the study period.

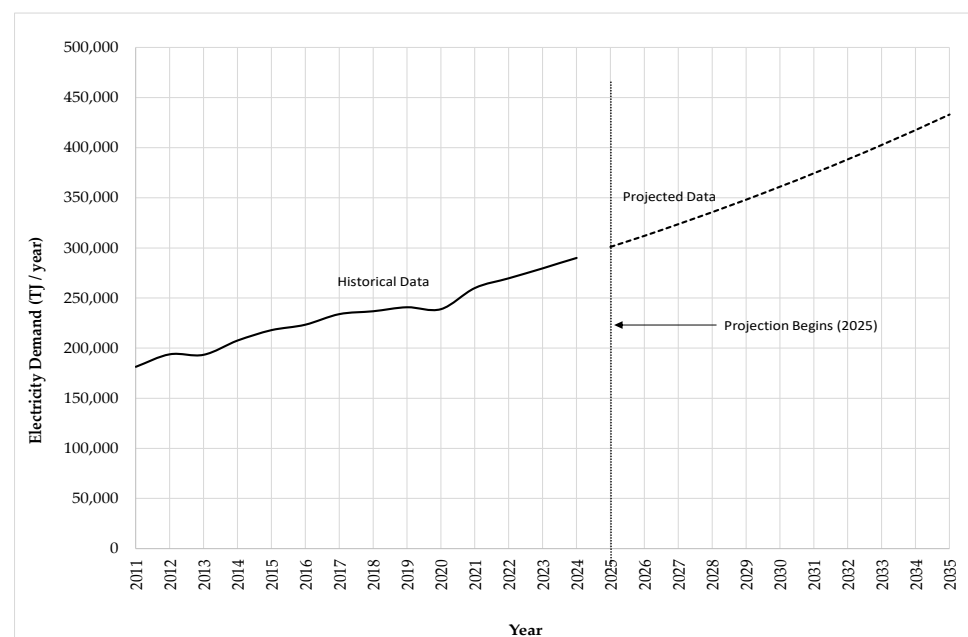


Figure 2. Historical (2011–2024) and projected (2025–2035) electricity demand in Kuwait.

Although a temporary decline was observed in 2020 due to the COVID-19 pandemic and the associated slowdown in economic activity, the overall trend indicates continued growth in electricity demand. Based on the adopted projection model, electricity demand is expected to reach approximately 433,000 TJ/year by 2035, highlighting the need for additional energy resources to support future electricity generation requirements. In parallel with increasing electricity demand, Kuwait's vehicle fleet has expanded substantially, resulting in a corresponding increase in UEO generation. The number of registered vehicles increased from approximately 1.54 million in 2011 to more than 2.81 million in 2024. Using Equation (1), annual UEO generation was estimated to increase from approximately 99,700 tonnes/year in 2011 to approximately 181,800 tonnes/year in 2024. As illustrated in

Figure 3, the growth in vehicle ownership has been accompanied by a sustained increase in the quantity of recoverable UEO available for potential energy-recovery applications.

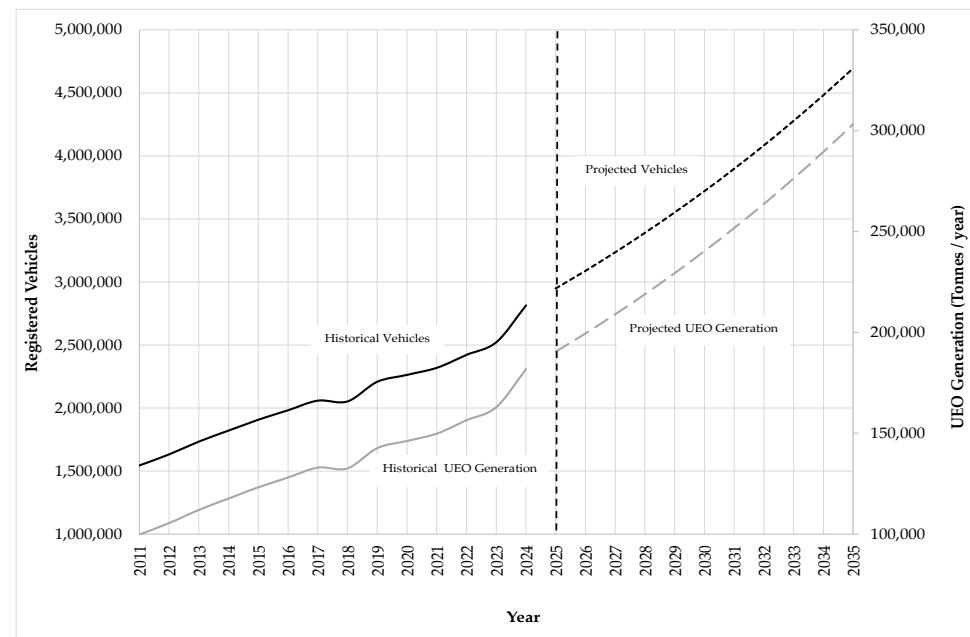


Figure 3. Historical (2011–2024) and projected (2025–2035) registered vehicles and corresponding UEO generation in Kuwait. The vertical dashed line indicates the transition from historical data to projected values (projection begins in 2025).

Based on the vehicle-growth projections obtained using Equation (2), the number of registered vehicles is expected to increase from approximately 2.81 million in 2024 to approximately 4.70 million by 2035. Substituting the projected vehicle population into Equation (1) results in an estimated UEO generation of approximately 303,300 tonnes/year by 2035, compared with approximately 181,800 tonnes/year in 2024. This represents an increase of approximately 66.9% during the forecast period, which is an increase of more than 204% relative to 2011 levels. The results indicate that UEO generation in Kuwait is expected to increase alongside electricity demand, creating an expanding waste-derived energy resource. The projected growth in UEO availability provides the basis for evaluating its potential contribution to utility-scale power generation and its ability to partially offset conventional fuel consumption, as discussed in the following sections.

4.2. Fuel Consumption and Characteristics of East Doha Power Station

East Doha Power Station was selected as the representative case study because of its substantial fuel consumption and its strategic role in Kuwait's electricity and desalinated-water production infrastructure. The station operates primarily on conventional fossil fuels, including heavy oil, crude oil, natural gas, and limited quantities of gas oil. The principal fuel properties relevant to this study are summarized in Table 1.

Among these fuels, heavy oil and crude oil constitute the dominant liquid fuels used for electricity generation, whereas gas oil is primarily utilized for startup and operational support. Historical fuel-consumption data for East Doha during the period 2013–2021 are presented in Figure 4.

The results indicate noticeable year-to-year variations in fuel utilization due to changes in electricity demand, fuel availability, maintenance schedules, and operational strategies. Crude oil was the dominant liquid fuel during most years of the study period, whereas heavy oil became the primary fuel in certain years, particularly 2018 and 2021. In 2021, East Doha consumed approximately 5.08 million barrels of crude oil and 1.15 million barrels of

heavy oil, corresponding to a total liquid-fuel consumption exceeding 6.2 million barrels. Annual electricity-generation data for the period 2019–2023 are summarized in Table 2.

Table 1. Comparison of liquid fuel properties and emission factors of UEO and conventional fuels used in Kuwait’s power-generation sector [6,12–15,21,23].

Parameter	UEO	Crude Oil	Heavy Oil
Heating Value (MJ/kg)	40	42–47	39–42
Density (kg/m ³)	897	<934	934–1000
Sulfur Content (%)	0.2–0.5	0.05–5.0	1–4
CO ₂ Emissions (g/kWh)	750–950	800–1000	900–1200
NO _x Emissions (g/kWh)	40–80	60–120	70–150
Availability in Kuwait	Waste-derived local resource	Primary fossil fuel	Residual petroleum fuel

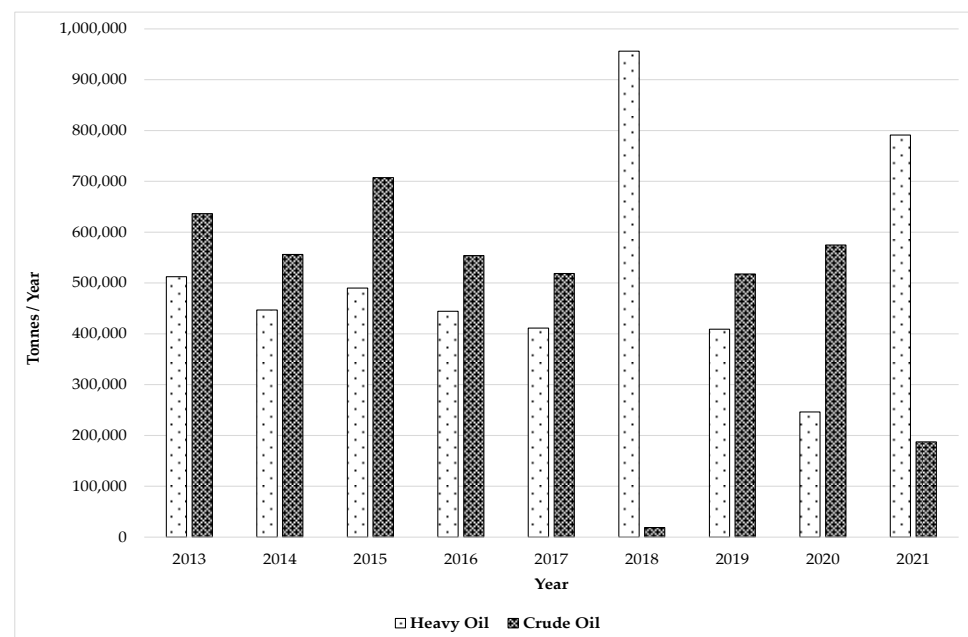


Figure 4. Annual crude oil and heavy oil consumption at East Doha Power Station during 2013–2021.

Table 2. Annual electricity generation of East Doha Power Station during 2019–2023.

Year	Generated (TWh)
2019	3.834
2020	3.669
2021	3.639
2022	3.908
2023	3.575
Average	3.725

The station generated between approximately 3.58 and 3.91 TWh/year, with an average annual electricity generation of approximately 3.73 TWh/year. The combination of high liquid-fuel consumption and stable electricity production provides a suitable basis for evaluating the potential contribution of UEO as a supplementary fuel source within Kuwait’s power-generation sector.

4.3. Technical Feasibility of UEO Fuel Substitution

The feasibility of utilizing UEO within East Doha Power Station was evaluated by comparing annual UEO availability with the station’s crude-oil and heavy-oil consumption.

Table 3 summarizes the annual quantities of heavy oil, crude oil, and estimated UEO availability during the period 2013–2021.

Table 3. Comparison of annual UEO availability with heavy-oil and crude-oil consumption at East Doha Power Station (2013–2021).

Year	Heavy Oil (tonnes/year)	Crude Oil (tonnes/year)	Available UEO (tonnes/year)
2013	512,334	636,566	111,978
2014	446,692	556,134	117,610
2015	490,116	707,144	123,191
2016	444,422	553,998	128,054
2017	411,293	518,577	132,974
2018	956,093	18,555	132,602
2019	408,974	517,900	142,617
2020	246,075	574,765	146,178
2021	791,369	187,118	149,827

The results indicate that the quantity of UEO generated annually in Kuwait is substantial relative to the liquid-fuel consumption of East Doha Power Station. During the study period, annual UEO availability increased from approximately 112,000 tonnes/year in 2013 to approximately 150,000 tonnes/year in 2021, reflecting continued growth in Kuwait's vehicle fleet and lubricant consumption. Over the same period, heavy-oil and crude-oil consumption exhibited noticeable year-to-year variations due to changes in electricity demand, fuel availability, maintenance schedules, and operating strategies. The available UEO corresponded to approximately 14–59% of annual heavy-oil consumption and 17–80% of annual crude-oil consumption. The upper-bound crude-oil percentage occurred in 2018, when crude-oil consumption declined significantly while heavy oil became the dominant liquid fuel. On average, approximately 132,000 tonnes/year of UEO were available during the study period, corresponding to approximately 25% of average annual heavy-oil consumption and 28% of average annual crude-oil consumption at East Doha Power Station. Based on the projections presented in Figure 3, annual UEO availability is expected to increase to approximately 303,300 tonnes/year by 2035. At this level, the available UEO resource would be equivalent to approximately 58% of the average annual heavy-oil consumption and 64% of the average annual crude-oil consumption observed during the 2013–2021 period. These results indicate that UEO could provide a meaningful contribution toward offsetting conventional liquid-fuel demand within Kuwait's power-generation sector. From a technical perspective, the feasibility of UEO utilization is supported by its fuel properties, which are comparable to those of the liquid fuels currently used at East Doha Power Station. As shown in Table 1, the heating value of UEO (approximately 40 MJ/kg) is similar to those of heavy oil and crude oil, while its density falls within the range commonly encountered in utility-scale liquid-fuel applications. Accordingly, properly treated UEO appears technically suitable for use as a supplementary fuel within existing combustion systems. Nevertheless, large-scale implementation would depend on effective collection, treatment, fuel-quality management, and operational validation under actual power-station conditions.

4.4. Energy Recovery Potential and Electrical Energy Contribution

The projected UEO resource in Kuwait represents a potentially significant source of recoverable energy. To quantify this potential, the projected annual UEO generation was converted into its equivalent thermal-energy content using the properties summarized in Table 4.

Table 4. Assumptions and physical properties used in the analysis.

Parameter	Value	Unit
UEO Density	897	kg/m ³
UEO Heating Value	40	MJ/kg
Thermal-to-Electrical Efficiency	33	%

The annual thermal energy available from UEO was calculated using Equation (3). Based on the projected UEO generation of approximately 303,300 tonnes/year in 2035 and an average heating value of 40 MJ/kg, the corresponding thermal-energy potential is estimated at approximately 12,126 TJ/year. The equivalent electrical energy contribution was subsequently estimated using Equation (4). A thermal-to-electrical conversion efficiency of 33% was adopted as a representative value for conventional steam power plants [30,31]. Under this assumption, the projected UEO resource could provide approximately 4000 TJ/year of electricity-equivalent energy, corresponding to approximately 1.1 TWh/year. This electrical-energy contribution is equivalent to an average continuous generating capacity of approximately 126 MW and represents approximately 29.5% of the average annual electricity generation of East Doha Power Station (3.725 TWh/year). These results indicate that recovered UEO can provide a substantial supplementary energy contribution to Kuwait's power-generation sector. Although UEO alone cannot satisfy future electricity demand, the projected energy potential demonstrates that it can partially offset conventional fuel consumption while recovering value from a waste-derived resource. The magnitude of the available thermal and electrical energy highlights the long-term potential of UEO as a supplementary fuel within Kuwait's utility-scale power-generation infrastructure.

4.5. Conventional Fuel Displacement Potential

The equivalent displaced fuel quantities presented in Table 5 were calculated using Equation (6), which relates the annual thermal energy available from UEO to the heating value of the conventional fuel being replaced:

$$M_f = [Q_{UEO}/HV_f]/1000 \quad (6)$$

where

- M_f is equivalent displaced fuel mass (tonnes/year).
- Q_{UEO} is annual thermal energy available from UEO (MJ/year).
- HV_f is heating value of the conventional fuel (MJ/kg).

This equation is based on the conventional energy-balance relationship commonly applied in fuel-substitution and waste-to-energy assessments.

Table 5. Equivalent heavy-oil and crude-oil displacement achievable from the projected UEO energy resource in 2035.

Fuel	Heating Value (MJ/kg)	Equivalent Displaced Fuel (tonnes/year)
Heavy Oil	39	310,923
Crude Oil	42.3	286,667

Based on the projected UEO resource available in 2035, corresponding to approximately 12,126 TJ/year of thermal energy, recovered UEO could displace approximately 310,923 tonnes/year of heavy oil or 286,667 tonnes/year of crude oil. When compared with the historical fuel-consumption data presented in Section 4.3, the projected UEO resource could partially replace approximately 58% of the average annual heavy-oil consumption

and approximately 64% of the average annual crude-oil consumption recorded at East Doha Power Station during the period 2013–2021, as shown in Figure 5.

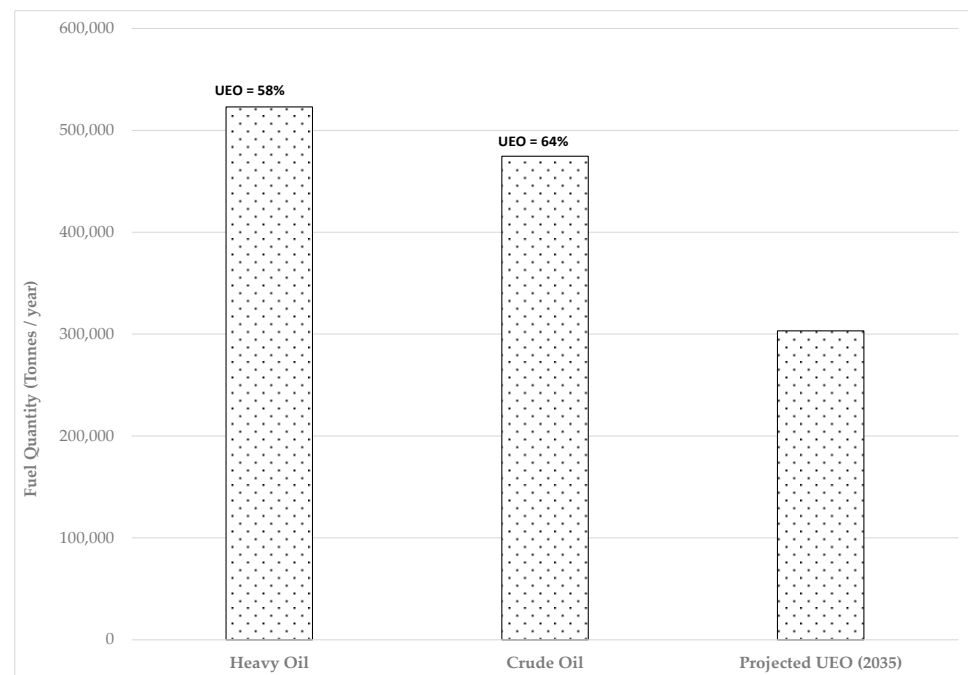


Figure 5. Comparison of projected UEO availability in 2035 with average annual heavy oil and crude oil consumption at East Doha Power Station.

The displacement quantities are comparable to the annual liquid-fuel consumption levels observed at East Doha Power Station, indicating that UEO could provide a substantial supplementary fuel resource. Because the heating values of UEO, heavy oil, and crude oil differ by less than approximately 8%, the displaced fuel quantities remain close to the available UEO mass. This result indicates that UEO can serve as an effective supplementary liquid-fuel substitute from an energy-content perspective. Overall, the projected UEO resource demonstrates considerable potential for reducing conventional liquid-fuel consumption within Kuwait’s power-generation sector. The associated economic and environmental implications of this fuel displacement are discussed in Section 4.6.

4.6. Comparative Economic and Environmental Assessment of UEO Utilization

The economic and environmental implications of UEO utilization were evaluated by comparing the projected UEO resource with the conventional liquid fuels currently used in Kuwait’s power-generation sector. The assessment considered fuel-displacement potential, fuel costs, and literature-reported emission characteristics as shown in Table 6.

Based on the projected UEO resource available in 2035, the gross avoided fuel expenditure was estimated at approximately 33.4 million KD/year when UEO replaces heavy oil and approximately 35.2 million KD/year when UEO replaces crude oil. After accounting for UEO collection, transportation, and handling costs, the corresponding net annual savings were estimated at approximately 28.2 million KD/year and 30.0 million KD/year, respectively. These results indicate that recovered UEO can provide substantial fuel-cost savings while partially offsetting conventional fuel consumption. The environmental performance of UEO was evaluated using the emission factors presented in Table 1, together with the equivalent electrical energy contribution of approximately 1.1 TWh/year estimated in Section 4.4. The resulting annual emissions are summarized in Table 7.

Table 6. Economic assumptions and estimated annual savings associated with projected UEO utilization in 2035.

Parameter	Heavy Oil Case	Crude Oil Case
Equivalent displaced fuel (tonnes/year)	310,923	286,667
Average fuel cost (KD/tonne)	107.3	122.7
Gross avoided fuel expenditure (million KD/year)	33.36	35.18
UEO quantity utilized (tonnes/year)	303,300	303,300
UEO collection, transportation, and treatment cost (KD/tonne)	17.0	17.0
Total UEO handling cost (Million KD/year)	5.16	5.16
Net annual savings (Million KD/year)	28.20	30.02

Table 7. Estimated annual CO₂ and NO_x emissions corresponding to the equivalent electrical energy contribution of approximately 4000 TJ/year (1.1 TWh/year).

Fuel	CO ₂ Emissions (Mt/year)	CO ₂ Reduction Achieved by UEO (%)	NO _x Emissions (Mt/year)	NO _x Reduction Achieved by UEO (%)
UEO	0.94	—	0.067	—
Crude Oil	1.00	5.6	0.100	33.3
Heavy Oil	1.17	19.0	0.122	45.5

The emissions presented in Table 7 were estimated using literature-reported combustion emission factors and should therefore be interpreted as comparative values rather than direct measurements from East Doha Power Station. Based on these emission factors, UEO is associated with lower estimated combustion-related emissions than both crude oil and heavy oil. Relative to crude oil, UEO could reduce estimated CO₂ emissions by approximately 5.6% and NO_x emissions by approximately 33.3%. Relative to heavy oil, the corresponding reductions are approximately 19.0% for CO₂ and 45.5% for NO_x. These results indicate that UEO utilization could provide both economic and environmental benefits while recovering energy from a waste-derived resource. In addition to reducing conventional fuel consumption, the recovery and utilization of UEO supports resource-efficiency and circular-economy objectives by converting a hazardous waste stream into a useful energy source.

Overall, the results demonstrate that UEO has the potential to provide substantial fuel-cost savings together with measurable reductions in estimated combustion-related emissions, supporting its role as a supplementary fuel within Kuwait's power-generation sector.

4.7. Sensitivity Analysis

The projected electrical energy contribution from UEO depends on several key assumptions, including UEO recovery efficiency, vehicle-growth rate, power-station efficiency, and fuel heating value. A sensitivity analysis was therefore performed to evaluate the robustness of the projected energy contribution under low, base, and high scenarios. For each scenario, the equivalent electrical energy contribution was recalculated using Equation (4) after adjusting the projected vehicle population, UEO recovery efficiency, heating value, and power-station efficiency. The adopted assumptions and corresponding results are summarized in Table 8. Because not all generated UEO can be expected to be collected and recovered for energy utilization, recovery efficiency was included as a key sensitivity parameter.

Table 8. Sensitivity analysis assumptions and corresponding equivalent electrical energy contribution.

Scenario	Recovery Efficiency (%)	Vehicle Growth Rate (%)	Power Station Efficiency (%)	UEO Heating Value (MJ/kg)	Equivalent Electrical Energy Contribution (TJ/year)
Low	70	3.0	30	38	2220
Base	90	4.77	33	40	4000
High	100	6.0	40	42	6400

A base-case recovery efficiency of 90% was adopted to represent an effective national collection and recovery system. The compound annual growth rate (CAGR) calculated from 2011–2024 vehicle-registration data was approximately 4.77%, and this value was used for the base-case projection. The selected parameter ranges represent plausible conservative and optimistic scenarios based on reported UEO properties, historical vehicle-growth trends in Kuwait, and typical thermal-to-electrical efficiencies reported for conventional steam power plants. The results indicate that the equivalent electrical energy contribution varies from approximately 2220 TJ/year under the low scenario to approximately 6400 TJ/year under the high scenario, compared with a base-case value of approximately 4000 TJ/year. This corresponds to a variation ranging from approximately 44.5% below to 60.0% above the base-case value. The analysis indicates that UEO recovery efficiency and vehicle-growth rate are among the most influential parameters because they directly affect the quantity of UEO available for energy recovery. In contrast, variations in heating value have a comparatively smaller effect because the reported range for UEO heating value is relatively narrow. Although power-station efficiency influences the equivalent electrical energy contribution, the availability of recoverable UEO remains the primary factor governing long-term energy-recovery potential. Despite these uncertainties, the projected electrical energy contribution remains substantial across all evaluated scenarios. Even under conservative assumptions, the recoverable UEO resource could contribute approximately 2220 TJ/year of electricity-equivalent energy, indicating that the principal conclusions of the study remain robust. It should be noted that the quantities estimated in this study represent the theoretical generation potential of UEO based on vehicle population and lubricant-consumption assumptions. The quantity ultimately available for power generation may be lower because of collection inefficiencies, storage and handling losses, fuel-treatment requirements, fuel-quality constraints, and regulatory or operational limitations associated with utility-scale implementation. Consequently, the results should be interpreted as an assessment of resource potential rather than a prediction of the quantity that can be directly utilized at a power station without further technical validation and regulatory approval.

4.8. Strategic, Environmental, and Policy Implications of UEO Utilization

The results of this study indicate that UEO should be regarded not only as a hazardous waste requiring management but also as a secondary energy resource with the potential to contribute to Kuwait's power-generation sector. The projected increase in UEO availability, driven by continued growth in vehicle ownership, suggests that this resource will remain substantial over the coming decade. Consequently, UEO represents a locally available fuel source that can support both energy-recovery and waste-management objectives. From an energy-security perspective, the utilization of recovered UEO offers an opportunity to partially replace the consumption of conventional liquid fuels currently used in thermal power stations. Although UEO is not intended to replace conventional fuels entirely, the results demonstrate that it could provide a meaningful supplementary energy contribution while improving fuel diversification and resource-utilization efficiency. The findings also support the application of circular-economy principles within Kuwait's energy and environmental sectors. Rather than being treated solely as a waste stream requiring disposal,

UEO can be recovered and utilized as a fuel, thereby extracting additional value from an existing petroleum-derived resource. This approach aligns with broader waste-to-energy strategies that emphasize resource recovery, waste minimization, and sustainable resource management. The environmental assessment indicates that UEO utilization may contribute to reductions in estimated combustion-related CO₂ and NO_x emissions relative to conventional liquid fuels while simultaneously reducing the quantity of waste oil requiring management. Although the present study does not include a full life-cycle assessment, the results suggest that UEO recovery and utilization can provide environmental benefits through both energy recovery and waste reduction. The successful implementation of utility-scale UEO utilization would require the establishment of an efficient national collection, transportation, treatment, and quality-control system. As demonstrated by the sensitivity analysis, recovery efficiency is one of the most influential factors affecting future energy-recovery potential. Consequently, policies aimed at improving collection infrastructure, regulating waste-oil handling practices, and encouraging participation by vehicle-service centers and industrial facilities could significantly enhance the benefits associated with UEO utilization. Potential measures may include licensed collection systems, mandatory waste-oil reporting requirements, centralized treatment facilities, and regulatory oversight of waste-oil handling and transportation practices. However, the development and evaluation of such policy frameworks were beyond the scope of the present study. From a practical perspective, integrating UEO into existing thermal power stations may offer advantages over constructing dedicated waste-to-energy facilities because fuel-storage, handling, combustion, and emissions-control infrastructure already exists. This approach could reduce implementation costs and facilitate deployment within existing operational frameworks. Overall, the results indicate that UEO utilization has the potential to support Kuwait's energy, environmental, and sustainability objectives through fuel conservation, resource recovery, and improved waste-management practices. These findings highlight the strategic value of UEO as a supplementary fuel within Kuwait's future energy portfolio.

5. Conclusions

This study evaluated the national-scale technical, economic, and environmental feasibility of utilizing UEO as a supplementary fuel source for utility-scale power generation in Kuwait, with East Doha Power Station serving as a representative case study. The assessment integrated national vehicle-growth trends, UEO generation potential, fuel-substitution capability, economic implications, environmental impacts, and future resource availability within a unified techno-economic framework. The results demonstrated that Kuwait generates substantial quantities of UEO as a consequence of its large and continuously expanding vehicle fleet. Based on projected vehicle-growth trends, annual UEO generation is expected to increase from approximately 181,800 tonnes/year in 2024 to approximately 303,300 tonnes/year by 2035. This quantity corresponds to approximately 12,126 TJ/year of recoverable thermal energy. Assuming a thermal-to-electrical conversion efficiency of 33%, the projected UEO resource could provide approximately 4000 TJ/year (1.1 TWh/year) of electricity-equivalent energy, corresponding to an average continuous generating capacity of approximately 126 MW and approximately 29.5% of the average annual electricity generation of East Doha Power Station. The projected UEO resource could displace approximately 310,923 tonnes/year of heavy oil or 286,667 tonnes/year of crude oil, which is equivalent to approximately 58% and 64% of their respective average annual consumption at East Doha Power Station during the period 2013–2021. Economic assessment indicated potential annual net fuel-cost savings of approximately KD 28.2 million relative to heavy oil and KD 30.0 million relative to crude oil. Based on literature-reported combustion

emission factors, UEO utilization was associated with estimated reductions of up to 19.0% in CO₂ emissions and 45.5% in NO_x emissions, relative to heavy oil. Sensitivity analysis confirmed the robustness of the findings, with projected electrical energy contributions ranging from approximately 2220 TJ/year under conservative assumptions to approximately 6400 TJ/year under favorable conditions. Although the results demonstrate substantial UEO resource availability and promising techno-economic potential, they do not constitute proof of long-term technical, environmental, or regulatory suitability for utility-scale deployment. The quantities reported in this study represent theoretical generation potential rather than guaranteed operational utilization, and practical implementation will depend on collection efficiency, fuel-treatment requirements, combustion compatibility, operational performance, and regulatory approval. Accordingly, the findings should be interpreted as an assessment of resource potential rather than a prediction of direct utility-scale utilization.

Overall, the results indicate that UEO represents a potentially valuable secondary energy resource capable of supporting fuel conservation, economic savings, resource recovery, and improved waste management within Kuwait's power-generation sector. To the best of the authors' knowledge, this study represents the first comprehensive national-scale assessment of the utility-scale utilization potential of the nation's generated UEO within Kuwait. Future research should focus on fuel characterization of locally collected UEO, pilot-scale demonstrations, combustion and emissions validation, fuel-quality standardization, life-cycle environmental assessment, and optimization of national UEO collection and recovery infrastructure to support large-scale deployment.

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