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**Comparative Analysis of Railway Interoperability Standards for Energy
Subsystem for East African Railway Network**

A Thesis for MSc. Railway Engineering (Traction and Train Control)

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A Thesis

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Master of Science**

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UNDERTAKING

I confirm the originality of the thesis, "**Comparative Analysis of Railway Interoperability Standards for Energy Subsystem for East African Railway Network,**" and its non-submission for evaluation to any other institution. Materials obtained from other sources have been rightfully referenced and credited.

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ABSTRACT

Railway system fragmentation is described by non-standardized and distributed networks, which remain a global challenge. Achieving railway interoperability is important for improving regional connectivity and operational efficiency. East Africa's expanding railway network also faces challenges in having a well-organized interoperability framework across the region, and this thesis focuses on the lack of standardized energy subsystem practices in East Africa.

This thesis examines and compares energy subsystem standards, technical and non-technical parameters, including power supply, environmental considerations, and cost-efficiency, across the railway networks of Ethiopia, Kenya, Tanzania, Uganda, Rwanda, Burundi, and South Sudan. The findings include differences in railway electrification systems, gauge incompatibilities, and old infrastructure that impede cross-border operations. The thesis focuses on adopting and comparing international standard frameworks, including IEC, EN, Chinese Class I & II, and AREMA for East Africa.

The thesis employed qualitative approaches, defined through descriptive analysis, focusing on the current and future networks and standards, as well as their technological, operational, and environmental consequences. Then, the comparative analysis examined the compatibility of these standards by defining technical criteria and non-technical parameters. The analysis result outlined that the standards were technically aligned partially, and there was a big difference in non-technical areas.

Based on the evaluation of technical and non-technical alignment, this thesis recommends adopting the Chinese standard in the region and establishing a long-term harmonized alignment for an international energy subsystem standardization framework. This framework is recommended to integrate Chinese standards with IEC standards, with modifications tailored to the East African region.

Keywords: *East Africa Region, Energy Subsystem, Interoperability, Standards, Railway*

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List of Acronyms

Table 0-1 Acronyms and Abbreviations

Abbreviation	Name
A	Ampere
AAR	Association of American Railroads
AC	Alternative Current
AIHSRN	African Integrated High-Speed Railway Network
APTA	The American Public Transportation Association
AREMA	American Railway Engineering and Maintenance of Way Association
AS	Australia Standards
BRI	Belt and Road Initiative
CCCC	China Communications Construction Corporation
CCECC	China Civil Engineering Construction Corporation
CEN	The European Committee for Standardization
CENELEC	The European Committee for Electrotechnical Standardization
CHSTP	The California High-Speed Train Project
CPUC	California Public United Commission
CRS	China Railway Society
DC	Direct Current
DRC	Democratic Republic of Congo
EAC	East African Community
EC	European Commission
EDR	Ethio-Djibouti Railway
EN	European Norms
EMS	On Board Energy Measuring System
ERA	European Union Agency for Railway
ERC	Ethiopian Railway Cooperation
EU	European Union
FDIS	Final Draft International Standard
FRA	Federal Railroad Administration Regulation
HSR	High-Speed Railways
Hz	Hertz

IAR	Interoperability Assessment Report
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRIS	International Railway Industry Standard
ISO	International Organization for Standardization
Km	Kilometre
kV	Kilo Volt
LRT	Light Rail Transit
MCA	Multi-Criteria Analysis
mm	Millimeter
Mph	Miles Per Hour
NRA	National Railway Administration
OCL	Overhead Contact Line
PIDA	Program For Infrastructural Development in Africa
RAMS	Reliability, Availability, Maintainability, and Safety
SRG	Standard Gauge Railway
TAZARA	Tanzania-Zambia Railway Authority
TSE	Turkish Standards Institution
TSI	Technical Specification for Interoperability
UIC	International Union of Railway
U.S.	United State
USD	United States Dollar
V	Volt

CHAPTER ONE

1. Introduction

1.1. Background

The railway network is one of the modes of transport. It has been critical to economic progress and social integration[1]. Integration became increasingly essential as technology shifted from steam to diesel to electric. Railways expanded rapidly in the nineteenth century for transporting people and commodities required for the Industrial Revolution[2].

For a long time, railway enterprises were limited to their markets and created individual assets and cultures[2]. Globalization had a substantial impact on the commercial environment by the mid-1900s[3]. Integration was necessary, which included physically linking rails and synchronizing cross-border activities[4]. This necessitated the passage of new legislation, joint investments in technologically suitable transportation infrastructure, and the removal of international trade obstacles. Common standards for collaboration had to be developed and agreed upon, which is how the railway industry adopted the concept of interoperability[2], [5].

Railway interoperability refers to “the ability of multiple railway systems to operate together smoothly and safely, which is crucial in a globalized society where trains frequently cross borders.”[6]. “Interoperability necessitates standardized technical and operational components such as traction power supply, rolling stock design, train control systems, track gauge, and loading gauge.”[7]. These standards enable trains to travel across different networks without encountering compatibility concerns, resulting in a more integrated global railway system.

Historically, railways operated independently and to varied standards, resulting in inefficiencies. The necessity for uniform standards became obvious over time[5]. Developed nations, including the European Union, Japan, the United States, and China, have set standards to ensure compatibility[8]. However, many countries, especially in Africa, lack their own standards and frequently adopt standards from developed countries[9]. This makes it difficult to achieve local and international railway interoperability.

The African Union's vision, the second aspiration of Agenda 2063, is to develop an integrated high-speed rail network across the continent[9], [10]. Africa's rail systems were established during European colonization in the early 20th century, primarily to support military movements and transport goods, such as raw materials from large mining or farming operations[11]. Technical standardization, harmonization, and issues like effective border crossings were not prioritized.

As a result, Africa's railway network today is fragmented and discontinuous. While some interconnected sections are within the Eastern and Southern African rail systems, most national railway networks in sub-Saharan Africa remain largely independent. Integrated rail networks in Africa between Burkina Faso and Côte d'Ivoire, Senegal and Mali, Ethiopia and Djibouti[12].

The majority of African railways rely on diesel power and limited electrification. The modern standard of 25 kV AC and some outdated lines still operate on the older 3 kV DC system. Additionally, 750 V DC is commonly used for city trams[13]. This lack of uniformity across the continent's rail systems underscores the ongoing challenges of achieving comprehensive railway integration and standardization in Africa[10].

The East African Railway Network (EARN) is an organization in the East African region that oversees the development and expansion of the region's railway network. It proposed a master plan to upgrade and expand railways serving Burundi, the Democratic Republic of Congo (DRC), Djibouti, Ethiopia, Kenya, Rwanda, South Sudan, Tanzania, and Uganda[13]. Its main objectives include infrastructure development, interoperability, regulatory harmonization, capacity building, and fostering trade and economic integration[13]. However, achieving interoperability across the region requires a common standard, with existing challenges including funding, technical incompatibilities, border crossing bottlenecks, and road and air transport.

This thesis analyses railway interoperability standards for energy subsystems within the East African railway network. It highlights technical standards harmonization of opportunities, challenges, and improvements, as well as comparison of standards with non-technical parameters. The findings enhance connectivity and economic growth in the East African region.

1.2. Statement of the Problem

The East African Railway Network is a proposed railway network to integrate the region[13]. However, attaining rail interoperability faces technical, political, and economic problems due to the diverse and varied conditions across the region's railway systems. The lack of established energy subsystem interoperability standards is a challenge to achieving rail interoperability in the East African Railway Network. Common standards enable trains to move freely and efficiently[10]

Consequently, to overcome these challenges and achieve rail interoperability in the East African region, it needs to adopt common interoperability standards.

1.3. Research Questions

The following are research questions for the thesis:

1. What are the existing standards and practices for railway energy subsystem interoperability that have been adopted by East African countries and aligned with international best practices?

2. How do the existing standards for railway energy subsystems in East Africa compare to the international best practice?
3. What are the recommended standards for improving the railway energy subsystem interoperability in East Africa?

1.4. Objectives

1.4.1. General Objective

This thesis aims to identify and evaluate the suitable railway interoperability standards for energy subsystems that effectively align with the East African Railway Network.

1.4.2. Specific Objectives

1. Collect the existing, under-construction, and planned railway network with standards related to the interoperability standards for the energy subsystem in East Africa.
2. Conduct a descriptive and comparative analysis of the collected standards for the energy subsystem to find alignment with international best practices.
3. Based on the analysis, the result recommends a suitable interoperability standard for the energy subsystem of the East African railway network.

1.5. Scopes and Limitations of the Study

1.5.1. Scopes of the Study

This thesis compares, evaluates, and recommends appropriate interoperability standards for the East African Railway Network only for energy subsystems. The comparative analysis focuses on the significance of harmonizing energy subsystem standards only for electrified lines.

1.5.2. Limitations of the Study

This thesis admits constraints while assessing railway energy subsystem interoperability standards for the East African Railway Network. These include issues with data availability, stakeholder involvement, and different regional standards. The results' application may be limited by a variety of political, economic, and infrastructure issues that impact their generalizability and long-term importance.

1.6. Methodology

The comparative analysis of energy subsystems in the East African railway network intends to assess interoperability standards for energy subsystems in East African countries. The study aimed to discover gaps and inconsistencies in energy subsystem standards for the region and standardize solutions to integration.

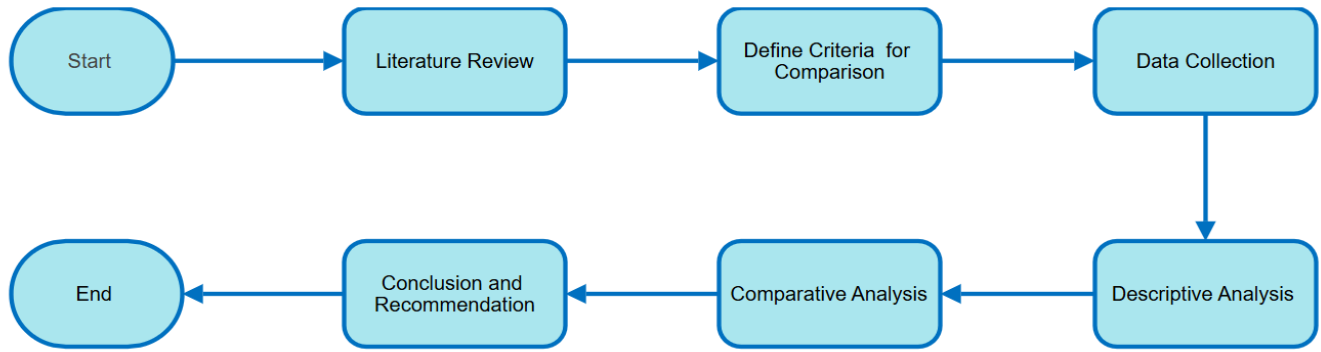


Figure 1-1 Flowchart of the Thesis

Figure 1-1 outlines a structured research methodology for the Comparative Analysis of Railway Interoperability Standards for Energy Subsystems for the East African Railway Network. Below is a step-by-step explanation of the flowchart:

- **Start:** The study method begins by defining the objectives, scope, and structure for research.
- **Comprehensive Literature Review:** Provides valuable insights from international and regional standards, best practices, and existing studies, establishing a theoretical and practical foundation for understanding regional challenges and opportunities.
- **Define Evaluating Criteria for Comparative Analysis:** Identify evaluation criteria for comparison of energy subsystem standards in East Africa, considering technical specifications, cost, environmental impact, and railway network compatibility.
- **Data Collection:** Accurate data on railway infrastructure, energy subsystem standards, and operational plans should be sourced from reliable sources like government reports, industry publications, and technical documents.
- **Descriptive Analysis:** Examines East Africa's railway lines, concentrating on technical configurations, gauge type, electrification status, and energy subsystem standards, emphasizing the need for interoperable standards.
- **Comparative Analysis:** Compares different energy subsystem standards based on given evaluation criteria for their technical adequacy, operational feasibility, economic efficiency, and compatibility with East African railway networks to find feasible alternatives.
- **Conclusion and Recommendation:** Summarize the findings by highlighting insights and providing actionable recommendations for harmonizing energy subsystem standards. Suggestions may include adopting hybrid standards.
- **End:** Concluded by creating a structured report that presents the findings, recommendations, and future research opportunities clearly and comprehensively.

1.7. Research Design

This thesis uses a qualitative, descriptive, comparative multi-criteria analysis research design to examine railway interoperability standards for energy subsystems within the East African railway network. It uses secondary data sources, including documents, reports, and case studies, to evaluate energy systems and cross-border railway integration. The study analysed documents from organizations like the African Union, the International Union of Railways, and governmental bodies, as well as case studies from railway projects. The research also identified gaps in existing interoperability frameworks and proposed improvements.

1.8. Significance of the Study

The thesis examines railway interoperability standards for energy subsystems in the East African Railway Network, aiming to improve regional integration and safety. It advocates for a common energy subsystem standard, promoting operational efficiency, safety, and economic integration. A common energy subsystem standard reduces delays and operational costs, minimizes accidents, and encourages technological innovation. It also positions railways as a more competitive and sustainable mode of transportation, boosting regional cooperation and reducing dependency on other modes of transportation.

1.9. Structural Organization of the Thesis

Chapter One (Introduction)

This chapter describes railway interoperability in the East African Railway Network, energy subsystem interoperability concerns, and a lack of unified standards.

Chapter Two (Literature Review)

This chapter explores railway interoperability literature and theoretical background, focusing on global and regional contexts, reviews different literature related to the thesis, and then identifies gaps and opportunities.

Chapter Three (Analysis and Discussion)

This chapter collects and conducts a comparative and descriptive analysis to evaluate the different standards and practices in use across the East African Railway Network, highlighting best practices and areas for improvement.

Chapter Four (Conclusion, Recommendation, and Future Work)

This chapter summarizes the outcomes of a comparative study on energy subsystem interoperability in East Africa's railway network, emphasizing its limitations and suggesting future research.

CHAPTER TWO

2. Literature Review

2.1. Introduction

This chapter explores the literature on railway interoperability standards for energy subsystems within the East African Railway Network, providing a theoretical framework for comparative analysis to identify research opportunities related to regional railway standardization in East Africa.

2.2. Interoperability

Railway interoperability facilitates integration of systems, networks, and technologies through technological standards, rolling stock interchangeability, and standardized procedures, enabling seamless travel across borders or regions. This includes standardizing components such as track gauges, signalling systems, power supplies, and communication protocols.

According to the Interoperability Directive 2008/57/EC, interoperability is "the ability of the rail system to allow the safe and uninterrupted movement of trains that accomplish the required levels of performance"[14].

According to Section 3 of AS 7450:2013, interoperability is "the ability of a process, system, or product to work with other processes, systems, or products." This implies that a train can practically cross boundaries without stopping at internal or external borders, switching locomotives, or stopping to perform any special activities unique to the current infrastructure[15]. The primary technological differences between the states are evident in the rail system, power supply system, control system, and legislation governing train traffic.[16].

The three components of railway interoperability[1].

1. **Legal interoperability:** Standardized contractual responsibilities.
2. **Technical interoperability:** Standardized technical requirements.
3. **Operational interoperability:** Standardized operating procedures.

2.2.1. Technical Specification for Railway Interoperability

The Technical Specifications for Interoperability (TSI) are a set of standards defined by the European Union to ensure the technical and operational compatibility of the railway system across member states[17]. EU Directive 2016/797, the TSI outlines essential requirements for safety, reliability, environmental protection, and accessibility, among others[18]. It also dictates when infrastructure and rolling stock should be upgraded or renewed, and establishes conditions for obtaining new authorizations[19]. These standards are designed to promote the railway network, ensuring interoperability between different subsystems within the EU.

2.2.2. Interoperability Subsystems

Railway interoperability involves the interconnected components of structural and operational subsystems.[20]. Structural subsystems include infrastructure, energy, control, rolling stock, and operational subsystems like rail traffic management, maintenance, and telecommunications applications.[14]. Energy subsystems manage power generation, transmission, and distribution, while control systems manage train operations. Rolling stock includes trains, locomotives, and wagons[21]. Operational subsystems include maintenance, scheduling, and safety protocols[14]. Interoperability between these subsystems is essential for the smooth functioning of the railway network.

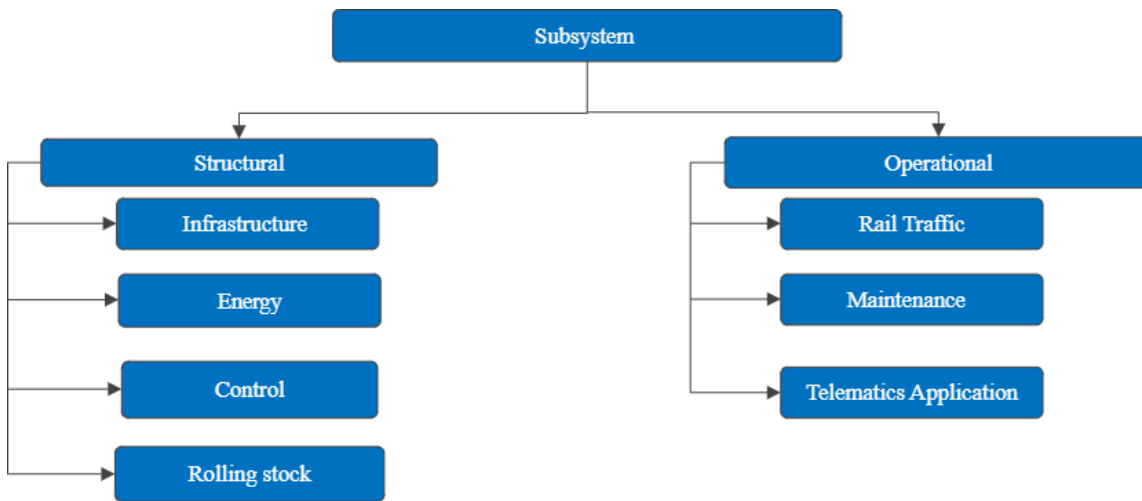


Figure 2-1 Railway Interoperability Subsystems

Energy Subsystem

The energy subsystem encompasses all necessary permanent infrastructure for delivering traction energy to trains, ensuring operational interoperability across the Union's rail networks. This subsystem includes high-speed and conventional rail lines and vehicles, while explicitly excluding metros, trams, light rail systems, private infrastructure, and vehicles designated for local or non-interoperable uses.[22], [23].

The energy subsystem includes the contact line system, a return circuit, substations, sectioning places, and separation sections. The energy subsystem of the rail system interacts with other subsystems to achieve the desired performance. These subsystems include Rolling stock, Infrastructure, Trackside control command and signaling, On-board control command and signaling, and Operation and traffic management[21], [22], [23].

1. **Contact Line System:** The contact line system is a network of wires and structures that supply electrical power to electric trains[23].
2. **Return Circuit:** The return circuit that allows current to flow back to the source[23].

3. **Substations:** Railway substations are used to transform voltage from high voltage to low and vice versa[23].
4. **Sectioning Places:** Sectioning places divide the overhead contact line system along the railway line, allowing for efficient power management and control across different segments without affecting the entire system[23].
5. **Separation Sections:** Separation sections, also known as neutral or dead sections, are gaps in the overhead contact line system where there is no electrical power, used to separate different electrical systems or phases.[23].

2.3. Standards

Standards are guidelines, requirements, or specifications that ensure products, services, or systems meet quality, safety, and compatibility benchmarks[24]. Created by industry groups, regulatory bodies, or technical organizations like ISO or IEEE, they facilitate interoperability, maintain quality control, and support innovation across various sectors.

2.3.1. Railway Networks Standards

Railway standards are a set of specifications, guidelines, and requirements developed by regulatory bodies, industry organizations, and standardization bodies[5].

2.3.2. Types of Railway Networks Standards

2.3.2.1. Voluntary and Optional Standards

Voluntary Standards are guidelines that organizations can adopt to maintain industry quality and performance. Such as the International Union of Railways (UIC), the American Public Transportation Association (APTA), and the European Committee for Standardization (CEN) guidelines[5], [24]. Compliance is not mandatory. The voluntary standards for the railways:

1. International Standards
2. National Standards
3. Regional Standards
4. Group Standards

2.3.2.2. Mandatory and Legally Binding Standards

Mandatory Standards are regulations that must be followed to ensure legal compliance with guidelines and are critical for getting operating certification and avoiding legal consequences. Governments enforce them to guarantee rail safety and infrastructure upkeep, such as the Technical Specifications for Interoperability (TSIs) in the EU, which must be met to ensure railway system safety and interoperability[5], [24].

2.3.3. Railway Networks Standards Developing Institution

Railway networks rely on standardized systems to ensure efficient, safe, and interoperable operations. These standards are created and maintained by specialized institutions that collaborate globally to establish and update norms for infrastructure, rolling stock, and energy subsystems. These institutions encourage safe integration and technical innovation.

The following institutions are engaged in defining railway network standards.

- International Organization for Standardization (ISO)
- International Union of Railways (UIC)
- International Electrotechnical Commission (IEC)
- European Committee for Standardization (CEN)
- American Railway Engineering and Maintenance-of-Way Association (AREMA)
- China Railway Society (CRS)
- European Union Agency for Railways (ERA)
- Association of American Railroads (AAR)
- American Public Transportation Association (APTA)
- National Railway Authorities

2.4. Related Studies

2.4.1. Studies Related to Interoperability

The paper in [14] examined a comprehensive analysis of railway safety and interoperability in the European Union, focused on the implementation of the Railway Safety Directive and the Interoperability Amendment Directive in six member states: Austria, the Czech Republic, France, Germany, the Slovak Republic, and the United Kingdom. The study assesses national transposition measures, progress toward interoperability, and the roles of National Safety Authorities (NSA) and National Investigation Bodies (NIB). However, this paper has gaps like variations in implementation, legal and administrative concerns, certification costs, and the impact of Technical Specifications for Interoperability on the railway industry.

The paper in [25] examined Serbia's efforts to achieve railway interoperability on Corridor X, a critical European transport route, in line with EU Technical Specifications for Interoperability (TSIs). Despite Serbia's non-EU status, the country has enacted the Law on Interoperability to harmonize its rail network with EU standards. The challenges include divergent infrastructure and operational inefficiencies that disrupt cross-border traffic. Serbia has made significant progress along Corridor X, aligning with the Infrastructure Subsystem (INF TSI) through track geometry, structural gauge

upgrades, and bridge safety compliance. Implementing the European Rail Traffic Management System (ERTMS) under Control-Command and Signalling (CCS TSI) is underway, supporting greater interoperability. The study was a benchmark for non-EU nations transitioning toward EU rail interoperability.

The paper in [5] presented the technical standards for railway operations and construction in Metro Manila, specifically the Philippine National Railways lines and LRT Lines 1 and 3. The study aimed to develop comprehensive technical standards for the successful operation and construction of railway systems in the Philippines. Drawing inspiration from Japanese railway technical standards and considering the unique context of the Philippines. The study highlights gaps in technological integration and the lack of a unified national rail law. Future research should focus on quantitative assessments of compliance costs versus safety benefits, digital transformation pathways for legacy systems, and harmonization of policy.

The paper in [22] studied energy and infrastructure subsystems in conventional rail systems emphasizes the need for optimized energy management and modernized electrification technologies. The study also highlights the importance of aligning infrastructure components with energy requirements to maintain operational reliability. The study proposes a functional decomposition and safety analysis method to capture, analyse, and validate system requirements. The study highlights gaps in renewable energy integration and digital transformation, regional disparities, and the need for cost-benefit frameworks, recommending future research on climate resilience and smart grid integration.

The paper in [26] aimed to operate trains at speeds exceeding 220 mph. It compares regulations and technical frameworks from international bodies, including the Federal Railroad Administration (FRA), the European Technical Specifications for Interoperability (TSI), and Japan's railway standards. The memorandum emphasized the need for specific safety and operational standards for high-speed rail systems, especially for trains operating at speeds over 220 mph. The project's regulatory challenges include the 25kV AC system and the need for variances from existing local rules. The memorandum offers insights into the necessary adjustments and collaboration requirements to align California's rail system with global standards while ensuring safety, efficiency, and compatibility.

2.4.2. Studies Related to African Railway Network

The paper in [10] proposed the African Integrated High-Speed Railway Network (AIHSRN) as an infrastructure project under Agenda 2063. It aimed to enhance continental connectivity and economic growth through sustainable transport. The AU's methodology involves public-private partnerships, policy harmonization, and foreign investment. The network could reduce transport costs, boost intra-African trade, and support the African Continental Free Trade Area. However, gaps in financing,

technical capacity, and political coordination remain, and the lack of detailed feasibility studies raises concerns about long-term sustainability and equitable benefits. Addressing these gaps requires stronger institutional frameworks and targeted investments.

The paper in [27] aimed at enhancing regional integration, trade connectivity, and economic potential in Kenya, Ethiopia, and South Sudan. The project focused on developing a modern Interregional Standard Gauge Railway (SGR) network linking Lamu Port to key economic hubs. The railway component is expected to facilitate the efficient movement of goods and people, reduce transportation costs, and promote industrialization. In Ethiopia, the LAPSET railway is integrated with the country's railway development strategy, enhancing access to regional and international markets. The railway component includes constructing Standard Gauge Railway (SGR) lines linking Lamu, Isiolo, Nakodok, Moyale, Addis Ababa, and Juba. The project has progressed through bilateral agreements between Kenya and Ethiopia, completion of design studies, and collaboration with China Civil Engineering Construction Corporation. However, challenges persist, including high construction costs, funding gaps, and cross-border coordination.

The paper in [9] addressed the obstacles of creating an interoperable railway network in Africa and underlined the necessity for standardized technical standards and operational norms to support cross-border railway operations. The report shows that while various African nations are establishing national and regional railway networks, there is no shared legislative framework or agreed-upon technological standards to guide the construction of an integrated and interoperable continental railway system. The paper suggested that the African Union should establish binding technical standards and operational rules to ensure compatibility between high-speed and conventional railway lines, drawing lessons from the European Rail Traffic Management System. This includes standardizing technical components such as track gauges, electrification systems, signaling, and communication. Without a harmonized regulatory framework, the African Integrated High-Speed Railway Network will face operational and technical barriers.

The paper in [13] was a strategic framework developed by the East African Community (EAC) to modernize and expand railway infrastructure in East Africa. The plan aimed to replace outdated meter-gauge networks with a more efficient Standard Gauge Railway (SGR) system across Kenya, Uganda, Tanzania, Rwanda, Burundi, South Sudan, and Ethiopia. Despite progress, financial constraints, technical differences, and institutional challenges remain. The paper emphasizes infrastructure development, regional policy harmonization, and integrated railway management to overcome operational inefficiencies and support trade competitiveness.

The paper in [28] introduced a structured, multi-criteria analysis framework for prioritizing high-speed rail (HSR) projects, particularly in emerging and resource-constrained regions. The methodology evaluates potential HSR links based on economic, technical, environmental, and social criteria, using tools like Geographic Information Systems (GIS) and expert judgment. This transparent, data-driven approach helps policymakers identify high-impact corridors aligned with broader development goals like Africa's Agenda 2063. This transparent, data-driven approach was a practical guide for selecting and sequencing HSR investments with the greatest potential for regional integration and sustainable development. The report aimed to improve evidence-based decision-making for policymakers in resource-constrained settings, particularly in Africa's integrated high-speed railway network. However, gaps persist, such as a lack of empirical case studies, inconsistent data, and limited stakeholder engagement.

2.4.3. Studies Related to China's Role in the East African Railway Network

The paper in [29] was focused on Ethiopia's railway development, with a particular emphasis on the Ethiopia-Djibouti Standard Gauge Railway, highlighting the political economy of the country's railway sector. The study reveals that Ethiopia's railway infrastructure aimed to drive industrialization and regional integration, but technology transfer was limited due to weak institutional capacity, poor coordination, and language barriers. The paper suggested that effective technology transfer requires strong local institutions, strategic planning, and active state involvement for long-term development impact.

The paper in [30] examined China's infrastructure investments in Africa, with a focus on Kenya's Standard Gauge Railway (SGR). The authors argue that while Chinese financing and construction capabilities facilitate rapid development, long-term success depends on host-country governance and institutional frameworks. They suggested recommendations for enhanced transparency, stronger mechanisms for local participation, more rigorous economic and environmental assessments, and improved host-country institutional capacity to manage these investments. The research also highlights the need for economic viability assessments, improved governance, and stakeholder engagement for sustainable and inclusive development.

The paper in [31] presented China's infrastructure development in Africa, particularly Kenya's Standard Gauge Railway (SGR). The project, driven by resource requirements, market development, and geopolitical influence, presents challenges such as non-competitive procurement, weak environmental regulations, and labour disputes. The procurement process was criticized for a lack of transparency, and local enforcement was weak, leading to protests. The SGR created jobs and facilitated skills transfer, but its economic viability remains uncertain due to underutilization and rising operational

losses. The long-term success of China's projects in Africa depends on stronger local governance, better enforcement of regulations, and more transparent procurement practices.

2.4.4. Studies Related to Standard Comparison

The paper in [32] conducted a thorough comparison of US Federal Railroad Administration (FRA) rules to foreign high-speed rail (HSR) standards, finding significant disparities in safety philosophy and regulatory frameworks. While the FRA utilizes a prescriptive paradigm, stressing crashworthiness and heavier train construction. Other standards, such as Europe's TSIs and Japan's Shinkansen, use performance-based approaches to preventative safety systems and lightweight designs. The report highlights problems in the United States, such as the lack of a specialized HSR regulatory framework, incompatibility with global standards, and impediments to interoperability for foreign rolling stock. It also highlights greater differences in noise control, aerodynamics, vehicle-track interaction, and emergency evacuation procedures. The authors emphasized that worldwide harmonization attempts are hampered by local regulatory frameworks, restricted accessibility owing to language barriers, and the absence of a standardized certification system. They advocated for a hybrid regulatory strategy and more research into HSR standards in countries such as Korea, India, Central Asia, and Australia to promote internationally synchronized, safe, and efficient high-speed rail networks.

The paper in [33] provided a thorough appraisal of China's railway electrification system component of the Belt and Road Initiative (BRI). They emphasized the system's conformity with international standards, allowing for effective adoption in nations such as Laos, Ethiopia, Turkey, and Iran. China's electrification model is recognized for being energy-efficient, cost-effective, and ideal for high-speed and heavy-traction operations, and demonstrated adaptability to a wide range of climates and terrains. However, the authors highlight problems, such as the lack of an internationally recognized certification mechanism similar to Europe's IRIS framework and the necessity for consistent macro-level design and administration across BRI projects. They proposed that bridging these gaps through standardized design methodologies and strong certification procedures is critical to improving worldwide interoperability and cementing China's leadership in international railway electrification. The report finished by underlining electrification's critical significance in boosting economic growth along BRI corridors, also encouraging sustained trust in China's standards and practical competence.

The paper in [34] analysed the technological impediments to interoperability between European and Chinese railway systems, with an emphasis on differences in rail technology, standards, and infrastructure. They highlight obstacles such as discrepancies in signalling systems, electrification standards, track gauges, and safety measures that impede smooth cross-border train transportation. While Europe has attempted to standardize standards via the Technical Specifications for

Interoperability (TSI), China's fast railway expansion has been led by national goals, resulting in misalignment with European norms. The authors contend that a lack of global standards for electrification, signalling, and safety systems, as well as variances in track gauge and technical specifications, hamper the integration of the two areas' railways. They push for more international engagement, technical standard alignment, and collaborative research activities to address these impediments and improve global railway interoperability.

The paper in [15] proposed the Rail Systems Interoperability Guideline using an organized and scientific approach to improve interoperability in the Australian rail industry. This framework is focused on the AS 7450:2013 standard, which introduces the Interoperability Assessment Report (IAR) methodology. This approach systematically reviews the requirement for interoperability, assesses current system capabilities, does cost-benefit evaluations, and develops phased implementation plans. The findings demonstrate the IAR's usefulness as a decision-support tool for flexible and risk-managed interoperability planning. However, the guideline highlights several limitations, including a dearth of empirical case studies and a restricted use of iterative, real-world assessments, which limit its practical applicability. The literature asked for further applied study and documentation of real-world implementations to promote comprehension, flexibility, and long-term effectiveness in rail system interoperability initiatives.

2.5. Summary of Literature Review

The related studies on railway interoperability for the energy subsystem present a challenge in achieving a cross-border compatible system with solutions. Papers related to interoperability, including the EU Railway Safety and Interoperability Directives, highlight the impact of different national standards on harmonization and barriers in infrastructure discrepancies and administrative problems. Similarly, studies from Serbia and the Philippines emphasize the importance of harmonizing national standards with international norms, addressing gaps in technological integration, and improving governance frameworks for sustainable railway development. In Africa, the African Union plans to integrate Africa with a high-speed railway network by 2060, the LAPPSET corridor project aims to integrate East Africa, and the East African Master Plan also plans to harmonize the railway network in the region. And the Chinese role in East African railway development projects, including ongoing and planned standard-gauge railways and the existing Ethio-Djibouti line. Lastly, research on standard comparisons for high-speed rail systems finds differences in safety, track designs, and certification mechanisms, which suggests the need for international cooperation and harmonization of standards. The literature presents the importance of adopting consistent, regionally and globally aligned standards to support the development of interoperable and sustainable railway systems.

CHAPTER THREE

3. Data Collection and Analysis

3.1. Data Collection

The data collection process for this research primarily utilizes secondary data sources, complemented by the selective inclusion of primary data. In parallel, secondary data is extensively sourced from a thorough literature review of the current and planned East African railway networks, including regulatory documents, railway standards, country-specific specifications, and technical interoperability guidelines.

3.2. East Africa Railway Network

The African railway network covers around 85,000 kilometres and uses different gauge standards[12]. The tracks are predominantly Cape gauge (1,067 mm) and some standard gauge (1,435 mm) lines[35]. Most African railways are diesel-operated and Electrified, with lines utilizing 3 kV direct current (DC) and 25 kV alternating current (AC)[10].

The East African Railway Network, originally constructed by British colonial authorities in the early 20th century, stretches over 2,800 kilometres, linking Kenya, Tanzania, and Uganda. Later expanded into Uganda, Rwanda, and Burundi. Despite its significance, the network faced numerous challenges, including budget constraints, political upheavals, and geographic barriers. Post-colonial modernization efforts were hindered by the dissolution of the East African Community (EAC) in 1977, which disrupted coordinated railway development[10], [13], [27].

However, in recent years, a renewed focus has been on rebuilding and expanding the network to promote regional economic integration. Modernization activities include updating railroad lines, improving track conditions, and increasing signaling and communication systems. In 2009, the East African Community (EAC) developed the East Africa Railways Master Plan, which proposed several infrastructure projects, including new railway lines in southern and western Tanzania, links to Rwanda and Burundi, and extensions into the Democratic Republic of Congo, Sudan, and Ethiopia. The master plan focuses on standardizing and electrifying the region's rail systems[13].

The Eastern African railway network is undergoing modernization, particularly with the introduction of Standard Gauge Railways (SGR) to enhance regional connectivity and boost cross-border trade. Projects, Kenya's SGR, aim to strengthen trade links with neighbouring countries, including Uganda, Rwanda, and South Sudan. Despite advances, difficulties in political instability, budgetary constraints, and mismatched rail gauges remain. The total railway network in East Africa now spans approximately

9,341 kilometres across countries, including Tanzania, Kenya, Uganda, Ethiopia, Djibouti, Sudan, and Eritrea, with ongoing efforts to extend and standardize the network further.

3.2.1. Existing Railway Networks in East Africa

3.2.1.1. Ethiopia

The Ethiopian railway, originally constructed by the French in 1897, played a pivotal role in the country's economic and social development[36]. The diesel-powered narrow-gauge railway, spanning 781 km and jointly owned by Ethiopia and Djibouti from 1981, was a vital provider of passenger and freight services, particularly in eastern Ethiopia. Operated by Chemin de Fer Djibouto-Éthiopien[36] railway gradually fell into disrepair and became nearly obsolete due to its aging infrastructure and inadequate maintenance. To modernize its transport infrastructure and boost economic growth, Ethiopia shifted towards electrified railways with the help of Chinese contractors and financing. This partnership strengthened diplomatic and economic ties between Ethiopia and China, resulting in the construction of railway projects, including the Addis-Djibouti line, the Awash-Weldiya line, and the Addis Ababa Light Rail[37], [38].

1. Ethio-Djibouti Standard Gauge Railway (EDR)

The Ethio-Djibouti Railway (EDR) is a transport corridor linking Ethiopia to Djibouti, spanning 756 km with a standard gauge track. It is double-tracked between Addis Ababa and Adama and single-tracked from Adama to Nagad, Djibouti. The railway consists of three sections, two sections in Ethiopia and one in Djibouti: Sebeta to Mieso (329.15 km), Mieso to Dewele (344.85 km), and Dewele to Nagad (82 km)[37]. Chinese contractors introduced a modern railway system using standard-gauge tracks, built with Chinese technology and designed for Chinese locomotives. It's Africa's first cross-border electrified railway, with financing from China's Eximbank. The project, part of China's Belt and Road Initiative, replaced an old 1-meter gauge line and connected Addis Ababa to Djibouti. The project, estimated at USD 4.04 billion, opened for freight in 2015 and became commercially operational in 2018. It is expected to break even in eight years[37].

2. Awash-Kombolcha-Hara Gebeya (Weldiya) Railway (AKH)

The Awash-Weldiya/Hara Gebeya Railway Project is the extension of the Addis-Djibouti railway, connecting northern Ethiopia to the central region. The project, led by the Ethiopian Railway Corporation (ERC), spans 447 km, including 389 km of new rail line and additional maintenance and station lines. The first section, built by Yapi Merkezi with \$300 million in Turkish financing, follows European standards, and the second segment is contracted to the Chinese Communications Construction Company (CCCC). Differences in signaling systems between the Turkish and Chinese segments have posed integration challenges, requiring further technical and financial adjustments.[38].

This project is crucial for strengthening Ethiopia's national transportation network and linking it with the Addis-Djibouti railway.[39].



Figure 3-1 Ethio-Djibouti and Awash-Woldiya-Mekele Railway Line[39]

3.2.1.2. Kenya

The Kenya Railways Corporation has a long and pivotal history dating back to the construction of the Uganda Railway in 1896. Built by the British colonial authorities, the railway was intended to link the Indian Ocean port of Mombasa to Lake Victoria at Kisumu, primarily to facilitate British trade and control in East Africa[40], [41]. The railway reached Nairobi in 1899, transforming the area into Kenya's capital. By 1901, the line extended to Kisumu. Dubbed the Lunatic Line due to its high costs and challenging construction. By the early 20th century, extensions were made to connect towns such as Nakuru, Magadi, Taveta, and Eldoret, and further expansions into Uganda.[41]. Following Kenya's independence, the railway was managed by the East African Railways Corporation until its dissolution in 1977, after which the Kenya Railways Corporation took over. A significant modern development has been the construction of the Standard Gauge Railway (SGR), which began operations in 2017, linking Nairobi to Mombasa and enhancing freight and passenger services. The SGR continues to expand, with plans for broader integration into Kenya's transport network, aiming to support the country's economic growth and regional trade.[40], [42].

3.2.1.3. Tanzania

Tanzania's railway system dates back to the early 20th century, initially developed by German colonial authorities[43]. The first line was constructed from Dar es Salaam to Kigoma (the Central Line) between 1905 and 1914. Following World War I, the British expanded the system, integrating it into the Tanganyika Railways. The Tanga-Moshi line, initially built in 1893, was also part of this expansion.[44]. The Tanzania-Zambia Railway (TAZARA), built in 1975 with Chinese support, connected Dar es Salaam to Zambia and remains a significant transport route. In recent years, Tanzania has embarked on ambitious projects, including constructing a Standard Gauge Railway (SGR), which began in 2017 to modernize the country's rail infrastructure. Phases of the SGR from Dar es Salaam to Dodoma were completed in 2022, with ongoing plans to extend it further to Isaka, Rwanda, and

Burundi. However, efforts to upgrade lines, including the Central Line and TAZARA, are positioning the country for increased regional trade and economic integration.[45]

Below in Table 3-1, the existing operational railway lines in East Africa are described by coverage area, electrification status, and the standards.

Table 3-1 Existing Operational Railway Lines

Railway Line	Country	Length (km)	Gauge (mm)	Electrification	Standard
Addis Ababa-Djibouti	Ethiopia	756	1435	25 kV AC / 50 Hz	Chinese National Railway Class II
Mombasa-Nairobi	Kenya	605	1435	Not Electrified	Chinese National Railway Class I
Nakuru – Kisumu	Kenya	216.7	1000	Not Electrified	British colonial
Thika – Nanyuki	Kenya	177	1000	Not Electrified	British colonial
Konza – Magadi	Kenya	146.3	1000	Not Electrified	British colonial
Leseru – Kitale	Kenya	64.9	1000	Not Electrified	British colonial
Gilgil – Nyahururu	Kenya	76.8	1000	Not Electrified	British colonial
Kisumu – Butere	Kenya	69	1000	Not Electrified	British colonial
Massawa-Asmara	Eritrea	Total 337, 118 actives,	950	Not Electrified	Italian standards
Dar es Salaam -Morogoro	Tanzania	300	1435	25 kV AC / 50 Hz	Chinese National Railway Class I
Central line, (Dar es Salaam to Kigoma)	Tanzania	1254	1000	Not Electrified	British colonial
Kidatu Line (Kilosa to Kidatu)	Tanzania	107	1000	Not Electrified	British colonial
Mpanda Line, (Tabora to Mpanda)	Tanzania	210	1000	Not Electrified	British colonial
Singida Line, (Manyoni to Singida)	Tanzania	115	1000	Not Electrified	British colonial
Mwanza Line, (Tabora to Mwanza)	Tanzania	378	1000	Not Electrified	British colonial
Malaba-Tororo- Kampala	Uganda	251	1000	Not Electrified	British colonial

Tororo-Mbale	Uganda	55	1000	Not Electrified	British colonial
Kampala-Port Bell	Uganda	9	1000	Not Electrified	British colonial
Kampala-Nalukolongo	Uganda	5	1000	Not Electrified	British colonial
Jinja-Jinja Pier	Uganda	4	1000	Not Electrified	British colonial

Below in Table 3-2, the existing partial operational railway lines in East Africa are described by coverage area, electrification status, and the standards

Table 3-2 Existing Partial Operational Railway Lines

Railway Line	Country	Length (km)	Gauge (mm)	Electrification	Standard
Mombasa-Nairobi	Kenya	2778	1000	Not Electrified	British colonial
Babanusa-Wau	South Sudan	248	1067	Not Electrified	British colonial
Link Line, (Morogoro- Korogwe)	Tanzania	188	1000	Not Electrified	British colonial
Tanga Line, (Tanga-Arusha)	Tanzania	437	1000	Not Electrified	British colonial
Dar es Salaam - Kapiri Mposhi	Tanzania	1860	1067	Not Electrified	Chinese

Below in Table 3-3, the existing non-functional railway lines in East Africa are described by coverage area, electrification status, and the standards. There are no existing railway lines in Burundi and Rwanda.

Table 3-3 Existing Non-Operational Railway Lines

Railway Line	Country	Length (km)	Gauge (mm)	Electrification	Standard
Mogadishu-Villabruzzi	Somalia	114	950	Not Electrified	Italian
-	Burundi	-	-	-	-
-	Rwanda	-	-	-	-
Voi – Taveta	Kenya	118.6	1000	Not Electrified	British
Ethio-Djibouti	Ethiopia	784	1000	Not Electrified	French
Tororo-Gulu	Uganda	382	1000	Not Electrified	British
Gulu- Pakwach	Uganda	134	1000	Not Electrified	British
Nalukolongo-Kasese	Uganda	330	1000	Not Electrified	British

3.2.2. Under-Construction, Planned, and Proposed Railway Lines in East Africa

East Africa's transportation infrastructure is undergoing substantial transformations, including the development and upgrading of railway networks to enhance economic integration and connectivity. Kenya, Tanzania, Uganda, Ethiopia, Sudan, South Sudan, Rwanda, and Burundi are among the countries involved. These projects align with strategic frameworks, such as the East African Railways

Master Plan and the African Union's Agenda 2063, which aim to build efficient, linked, and sustainable transportation networks across the continent.[10], [13].

The East African Railways Master Plan establishes a framework for expanding railway infrastructure in the region. It focuses on upgrading and standardizing rail systems to build a cohesive network by migrating from obsolete narrow-gauge systems to standard-gauge railroads (SGR)[13]. This change is intended to minimize inefficiencies and enhance trade routes along major corridors such as the Northern Corridor (Kenya-Uganda-Rwanda) and the Central Corridor (Tanzania-Burundi-Rwanda).

The African Union's Agenda 2063 on railway initiatives prioritizes infrastructure development for economic transformation across Africa. The vision includes the African Integrated High-Speed Railway Network, designed to connect major cities through modern and efficient rail systems.[10]

The planned railway corridors include[11]

- North-East Corridor: Connecting Sudan, Ethiopia, Kenya, Tanzania, and Uganda.
- North–East–West Corridor: Extending from Sudan through Chad to Nigeria.
- East–South Corridor: Linking Tanzania with Rwanda, the DRC, and Uganda.
- East–Centre Corridor: Running from Sudan through the Central African Republic to Cameroon.
- South-East Corridor: Extending from Tanzania through Zambia, Zimbabwe, Mozambique, and South Africa.
- Extended East–South Corridor: Spanning Kenya, Tanzania, Uganda, Rwanda, Burundi, and the DRC, with possible extensions to Ethiopia and Sudan, covering approximately 5,600 km.

The projects in East Africa face funding, political instability, road transport competition, and standardization issues. Despite these obstacles, a well-integrated railway network offers cost-effective bulk goods transport, environmental sustainability, and regional integration. It will drive trade, support industrialization, and enhance regional integration.

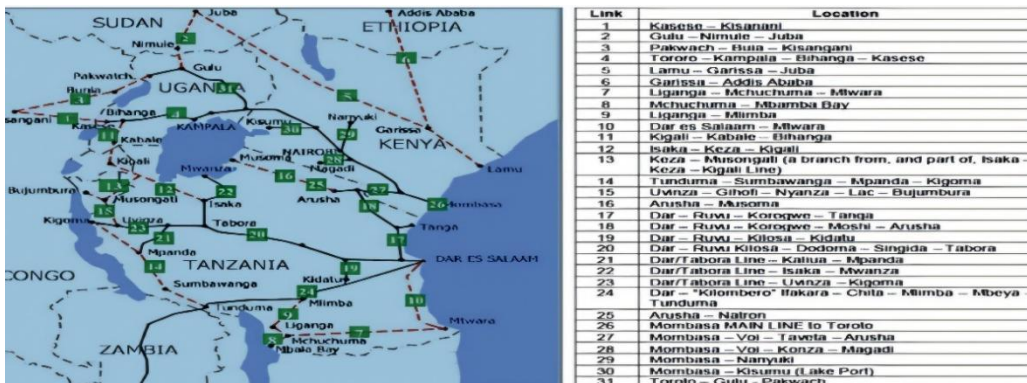


Figure 3-2 Planned Railway Corridors[46]

3.2.2.1. Kenya

Kenya's Standard Gauge Railway (SGR) project is a part of East Africa's railway expansion, linking the strategic port of Mombasa to Nairobi. The project aims to reduce transportation costs and improve efficiency in transporting goods. Phase II will extend the railway to Naivasha, an industrial hub, and future expansions to Kisumu and Malaba on the Ugandan border. This will boost intra-African trade and improve urban mobility.[40].

3.2.2.2. Tanzania

Tanzania's Standard Gauge Railway (SGR) is a crucial part of its infrastructure strategy to improve regional connectivity and economic ties in East Africa. The project is currently under construction, connecting Dar es Salaam's port to Mwanza on Lake Victoria. The line will eventually integrate with the wider East African rail network, linking Tanzania to Rwanda, Burundi, and Uganda. A segment of the project is the development of a line from Isaka to Kigali and Gitega, providing direct access to the Indian Ocean. Tanzania is also working on revitalizing the Tanzania-Zambia Railway (TAZARA), a vital trade route linking Dar es Salaam to Zambia, to enhance the movement of goods between Southern and East Africa.[45]

3.2.2.3. Uganda

Uganda aims to expand its railway network to strengthen trade and economic integration with East Africa. The Malaba-Kampala SGR project, which will connect Uganda to Kenya's transport network and the port of Mombasa, will provide a faster and more efficient route for freight and passenger movement. The Northern Uganda Railway, which will extend from Kampala to Gulu and potentially reach South Sudan, is expected to be a game-changer for regional trade.

3.2.2.4. Sudan and South Sudan

Sudan plans to expand its railway network to enhance regional connectivity with Ethiopia and South Sudan. The Juba-Port Sudan Railway aims to provide South Sudan access to Port Sudan on the Red Sea, enabling it to export oil and other goods more directly to international markets. South Sudan is also exploring the Juba-Malaba-Kampala Railway, which would connect to Kenya's transport network at Malaba, reducing its reliance on road transport and improving trade efficiency.

3.2.2.5. Rwanda and Burundi

Rwanda and Burundi are advancing railway projects to enhance their connectivity and access to trade routes. The Isaka-Kigali Standard Gauge Railway (SGR) will extend from Tanzania's Isaka to Kigali, significantly reducing transportation costs by providing direct access to the Dar es Salaam port. Similarly, the Isaka-Gitega SGR will connect Isaka to Gitega, improving Burundi's access to this port

and integrating it into the East African trade network. The proposed Bujumbura-Kigali railway also aims to strengthen trade relations between the two countries by linking Bujumbura with Kigali.

3.2.2.6. Ethiopia

Ethiopia has made significant progress in its railway infrastructure, particularly with the Addis Ababa-Djibouti Railway, which connects the capital to Djibouti's port, handling 95% of Ethiopia's international trade[29]. This electrified 752 km line has improved trade efficiency and reduced reliance on road transport. Ethiopia is expanding its rail network to connect with other regional partners, including Sudan via the Addis Ababa-Sudan Railway and the Awash-Weldiya-Hara Gebeya Railway. The LAPSET Corridor project aims to connect Ethiopia to Kenya's Lamu Port through a standard-gauge railway, providing an alternative maritime route and expanding to international markets[27].

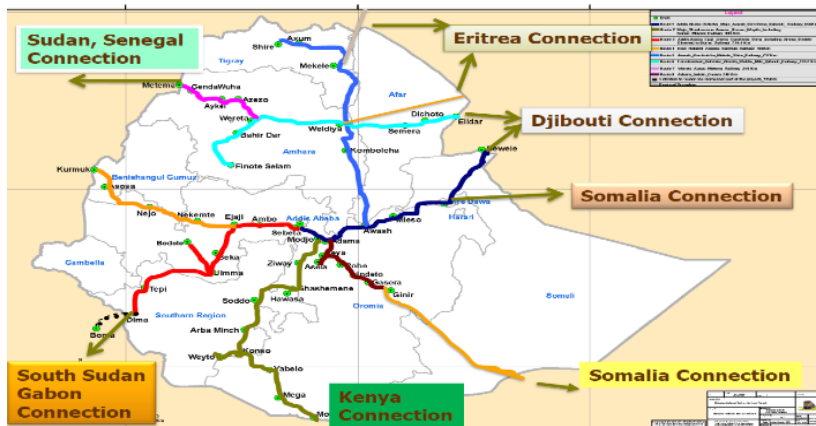


Figure 3-3 Planned Cross-Border Railway Lines of Ethiopia[35]

Below in Table 3-4, the under-construction, planned, and proposed railway lines in East Africa are described by coverage area, electrification status,

Table 3-4 Planned, Under Construction, and Proposed Railway Lines

Railway Line	Country	Length (km)	Gauge (mm)	Electrification	Standard	Status
Awash-Weldiya	Ethiopia	392	1435	27.5 kV AC / 50 Hz	EN, UIC, TSE	Under Construction
Weldiya - Mekelle	Ethiopia	216	1435	27.5 kV AC / 50 Hz	Chinese Class II	Under Construction
Modjo-Hawassa (extension to Kenya)	Ethiopia	Unknown	Unknown	Unknown	Unknown	Planned

Sebeta-Ambo (extension to Sudan)	Ethiopia	Unknown	Unknown	Unknown	Unknown	Planned
Nairobi – Malaba	Kenya	3800	1435	25 kV AC / 50 Hz	Chinese Class I	Under Construction
DaresSalaam-Mwanza	Tanzania	1500	1435	25 kV AC / 50 Hz	Chinese Class I	Under Construction (phases II, III, and V)
Iisaka – Kigali	Tanzania-Rwanda	571	1435	25 kV AC / 50 Hz	UIC (EU) or AREMA	Commencement phase
Keza - Musongati	Tanzania-Burundi	197	1435	25 kV AC / 50 Hz	UIC (EU) or AREMA	Planned
Uganda SRG	Uganda	1724	1435	25 kV AC / 50 Hz	Chinese Class I	Proposed
Kigali-Kampala	Uganda-Rwanda	1100	1435	25 kV AC / 50 Hz	Chinese Class I	Planned
Kampala-Kisangani	Uganda-DR Congo	Unknown	1435	Unknown	Unknown	Planned
Malaba-Juba	Uganda-South Sudan	Unknown	1435	Unknown	Unknown	Planned
Nairobi-Addis Ababa	Ethiopia-Kenya	3000	1435	25 kV AC / 50 Hz	Chinese Class I	Planned
Lamu-Juba, Kisumu-Juba	Kenya-South Sudan	Unknown	1435	Unknown	Unknown	Planned

3.3. Descriptive Analysis

The railway network in East Africa has a variety of electrification methods and rail gauges, which have a considerable impact on interoperability. Ensuring interoperability is critical to regional economic integration and progress. The region's railway network includes operating, partially operational, non-operational, and proposed routes. Operational lines like Addis Ababa-Djibouti and Mombasa-Nairobi include modern infrastructure, whilst non-operational lines represent continuing restoration works. The planned projects show the problems and prospects for extending, upgrading, and adding new routes to the network. A thorough understanding of these variables is critical for improving the growth and integration of East Africa's railway network.

The operational railway lines in East Africa provide a diversified and challenging topography, with significant differences in length, track gauge, electrification, and adherence to various operating rules.

- **Distribution of the Operational East Africa Railway**

The distribution of operational railway lengths across East Africa reflects significant disparities among the countries. Tanzania holds the largest share, accounting for 46% of the total network, which spans 2,525 km. Kenya follows with 26%, equating to 1,284 km, while Ethiopia contributes 15%, totalling 756 km. In comparison, Uganda and Eritrea maintain relatively smaller railway networks, comprising 6% (251 km) and 7% (337 km), respectively. These variations underline the uneven development of railway infrastructure, influenced by historical, economic, and geographical factors. The data highlights Tanzania's dominant position in railway connectivity, while the networks in Uganda and Eritrea remain limited in scope.

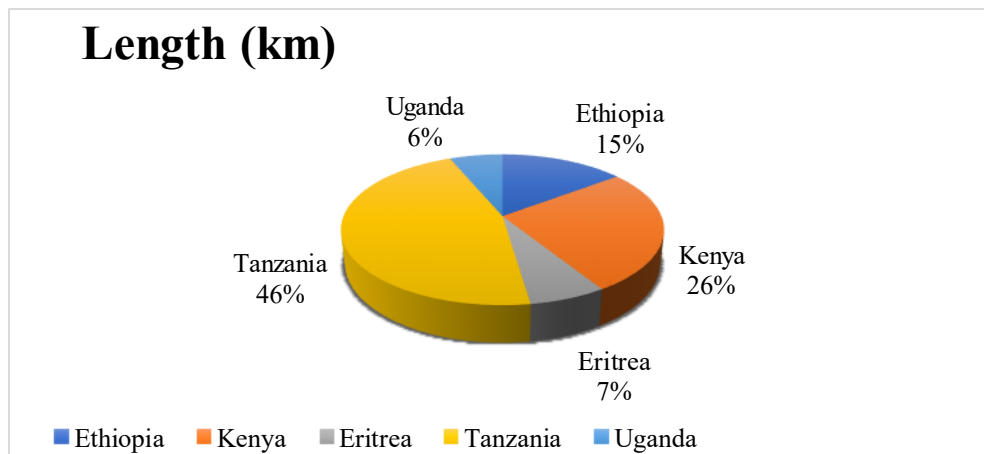


Figure 3-4 Distribution of Operational Railway Lines

- **Gauge Sizes Analysis in East African Railways**

East Africa's railway network features three primary gauge sizes: standard gauge (1,435 mm), meter gauge (1,000 mm), and narrow gauge (950 mm). The standard gauge, symbolizing modern

advancements, is employed in Ethiopia's Addis Ababa-Djibouti line, Kenya's Mombasa-Nairobi line, and Tanzania's Dar es Salaam-Morogoro SGR segment. The meter gauge, a legacy of colonial infrastructure, remains predominant, comprising 16 of the 20 operational lines across the region, the narrow gauge is exclusive to Eritrea, reflecting its Italian colonial heritage. This lack of gauge uniformity creates significant challenges for interoperability, particularly for cross-border freight and passenger operations, resulting in inefficiencies, delays, and increased costs. Addressing these issues requires prioritizing the standard gauge for new projects, gradually converting existing networks, and using dual-gauge tracks as a transitional measure.

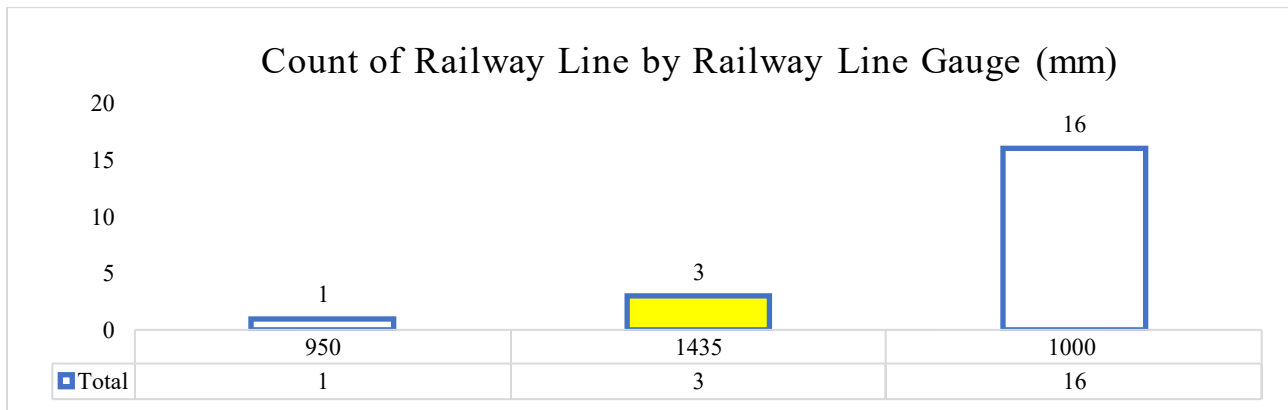


Figure 3-5 Count of Railway Lines by Railway Line Gauge (mm)

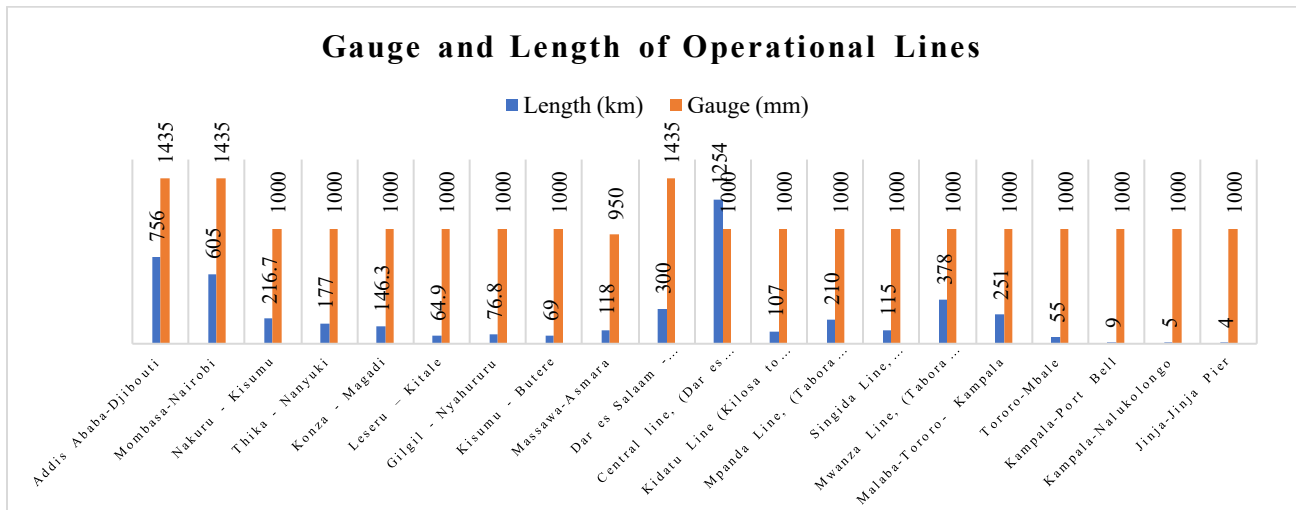


Figure 3-6 Gauge and Length of Operational Lines

• **Electrification Status**

East Africa's railway network is currently limited, with only two lines, Addis Ababa-Djibouti and Dar es Salaam-Morogoro, running on a 25 kV AC / 50 Hz standard. These non-electrified routes use diesel locomotives, which are inefficient and environmentally unsustainable. Implementing a regional electrification strategy that includes high-density corridors and renewable energy sources is critical.

Investing in infrastructure, substations, and transmission systems will modernize the network, reduce costs, increase operational efficiency, and encourage sustainable transportation.

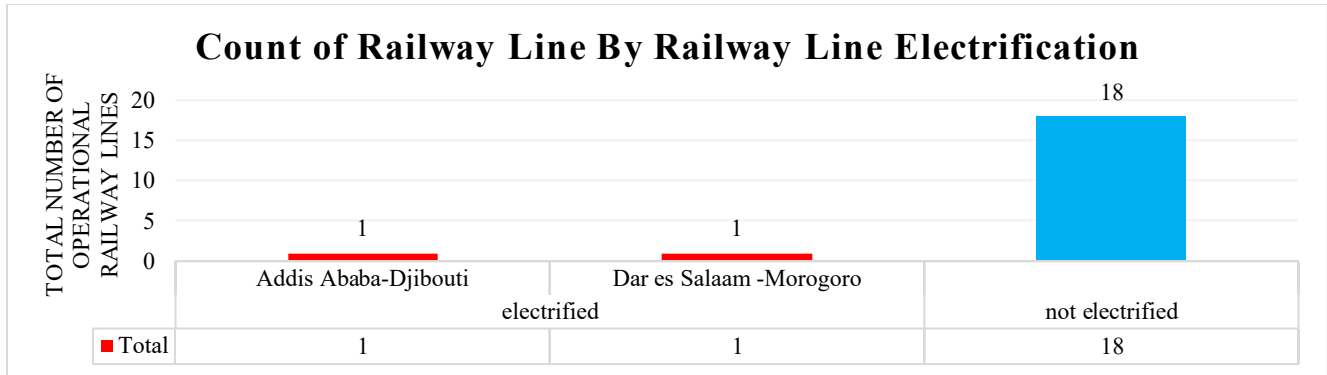


Figure 3-7 Count of Railway Line by Railway Line Electrification

- **Standards**

East Africa's railway network is a mix of modern and legacy infrastructure, with British colonial standards dominating 16 lines and a few adopting Chinese National Railway standards for electrified lines in Ethiopia, Kenya, and Tanzania. Eritrea's Massawa-Asmara line operates under Italian standards, complicating standardization efforts. This diversity of standards presents challenges in interoperability, operational efficiency, and infrastructure modernization. The Chinese National Railway standards offer a contemporary approach, while the narrow-gauge network is often outdated. This creates inefficiencies, bottlenecks, and limits scalability. Recommendations include retrofitting legacy lines with modern technologies and infrastructure, promoting regional agreements on standardization, and promoting interoperable standards for better connectivity and economic growth.

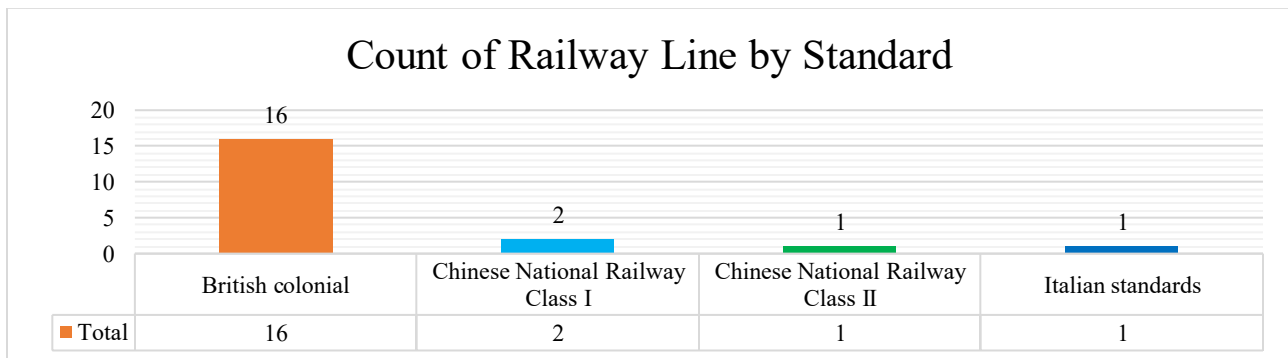


Figure 3-8 Count of Railway Lines by Standards

- **Distribution of the Under Construction East Africa Railway**

The total length of planned and under-construction railway lines across East Africa is approximately 11,892 km. Kenya holds the largest share, accounting for 31.97% of the total network with 3,800 km under construction, followed by the planned Ethiopia-Kenya project at 25.26% (3,000 km). Uganda contributes 14.50% (1,724 km), and Tanzania accounts for 12.61% (1,500 km). Cross-border projects,

including Tanzania-Rwanda (4.80%), Uganda-Rwanda (9.26%), and Tanzania-Burundi (1.66%), make up the remaining 17% of the total. Of the total length, 41% is planned, while 59% is under construction. This distribution highlights Kenya’s dominance in ongoing and Planned projects, with Ethiopia-Kenya emerging as the largest project. The findings underscore the uneven progress in railway infrastructure development across the region, with Kenya, Uganda, and Tanzania playing roles in shaping future connectivity.

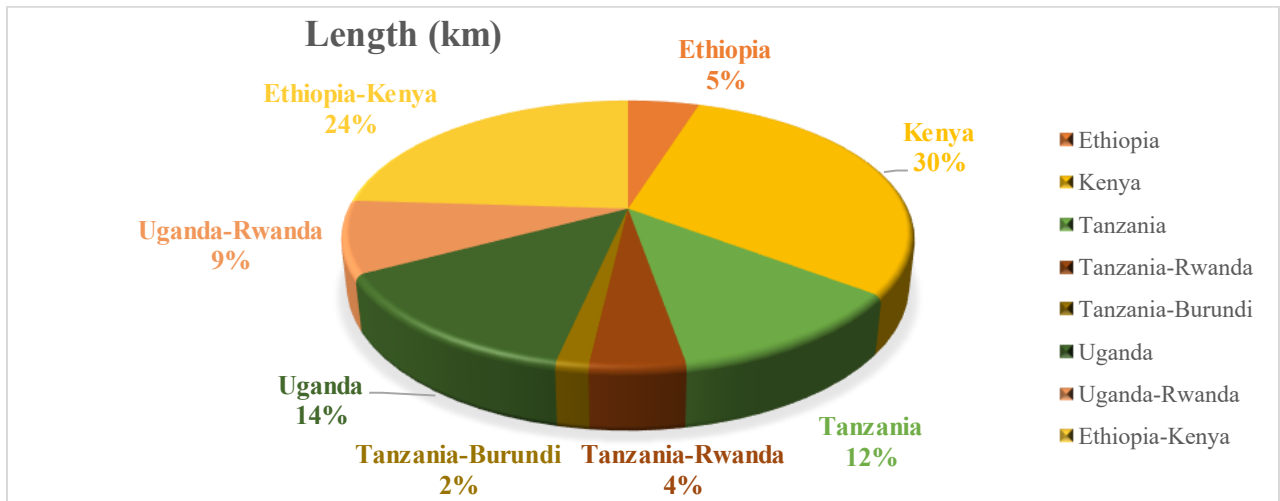


Figure 3-9 Distribution of Planned and Under-Construction Railway Lines

• Gauge

East Africa is implementing the 1435 mm standard gauge in its railway projects, a step towards regional integration and modernization. This gauge ensures interoperability with modern rolling stock and aligns with global railway systems, facilitating cross-border operations. The consistent use of this gauge in Ethiopia, Kenya, Tanzania, Uganda, and Rwanda strengthens the region's efforts to create a unified railway network.

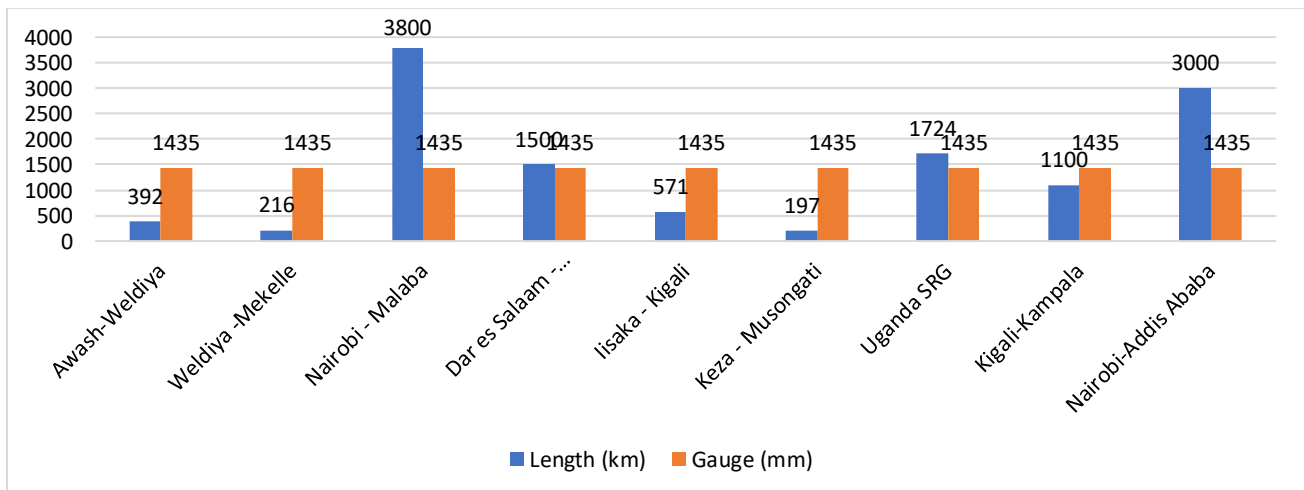


Figure 3-10 Gauge and Length of Planned and Under-Construction Lines

• Electrification

Railways in East Africa are being electrified to increase energy efficiency, sustainability, and operational compatibility. Under-construction railways employ the 25 kV AC / 50 Hz standard, a global benchmark for modern railway systems, ensuring high energy efficiency and reliability. However, Ethiopia's Awash-Weldiya and Weldiya-Mekelle lines adopt a slightly different 27.5 kV AC / 50 Hz standard. Planned lines predominantly propose the 25 kV AC / 50 Hz system, aligning with regional efforts toward standardization. However, some planned projects, such as Kampala-Kisangani, Malaba-Juba, and Lamu-Juba, lack defined electrification plans, which could create future compatibility challenges if inconsistent systems are adopted.

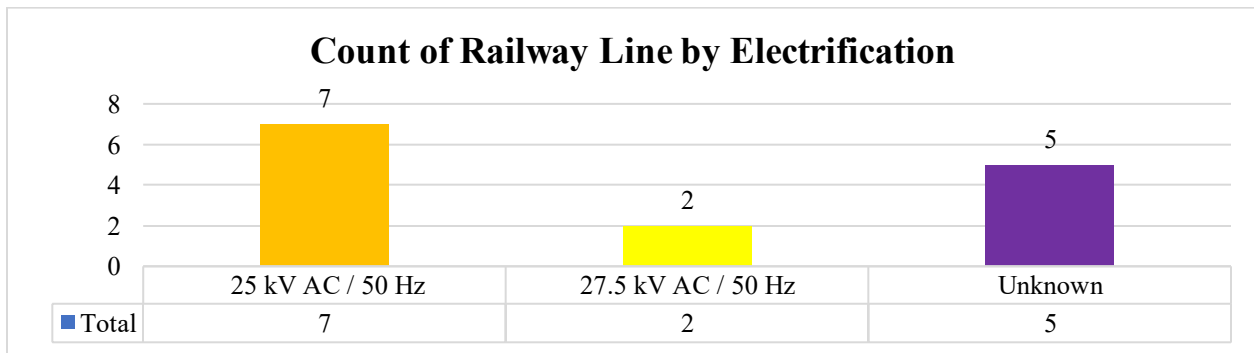


Figure 3-11 Number of Electrified Lines for Planned and Under-Construction Lines

• Standards

The analysis of East Africa's planned and under-construction railway lines reveals a dominant use of Chinese Class I standards in Kenya, Tanzania, and Uganda, reflecting China's significant role in the region's infrastructure development. These lines support high-speed, heavy-duty operations essential for regional connectivity. However, the adoption of Chinese Class II (Ethiopia's Weldiya-Mekelle), AREMA (Isaka-Kigali, Keza-Musongati), and European Norms (EN) (Awash-Weldiya) standards introduces technical diversity that could complicate regional interoperability. This variation highlights the need for a harmonized approach to align standards and ensure seamless cross-border operations, facilitating an integrated East African railway network.

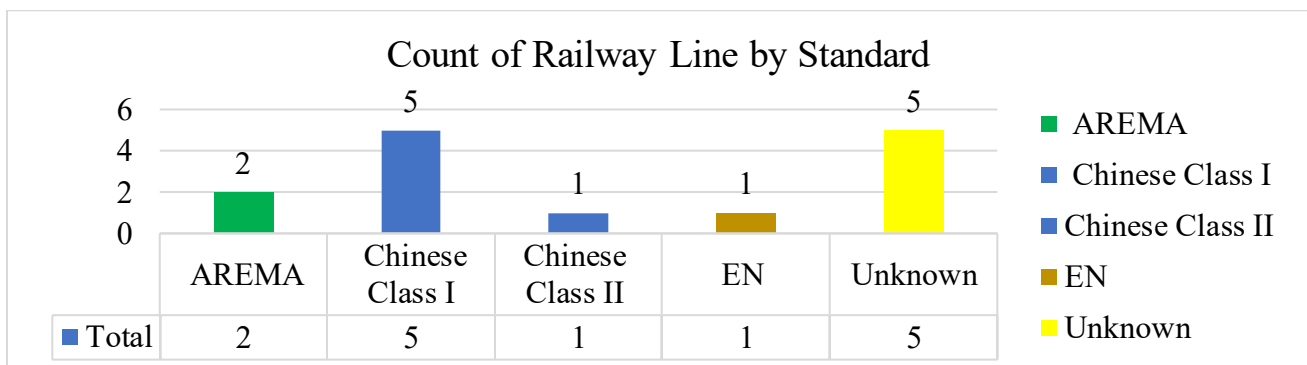


Figure 3-12 Standard will be used for Planned and Under-Construction Lines

3.4. Electrification Standards and Codes

3.4.1. European Standards for Railway Energy Subsystem

The European railway standardization framework ensures interoperability through Technical Specifications for Interoperability (TSIs), European Norms (ENs), and UIC codes. TSIs define mandatory functional requirements to enable seamless cross-border operations across trans-European rail systems, aligning with EU directives. ENs, which offer detailed technical solutions, complement TSIs and, although partially voluntary, are widely adopted due to their practical utility. UIC codes, derived from international research and collaboration, provide non-binding recommendations that often influence ENs and national standards. These elements create a harmonized framework covering infrastructure, rolling stock, and energy systems.

The TSI [19] The "energy" subsystem regulates new, upgraded, or renewed energy systems under Directive 2008/57/EC. It applies to conventional and high-speed trans-European rail networks and other EU rail systems with nominal track gauges of 1,435 mm, 1,520 mm, 1,524 mm, 1,600 mm, and 1,668 mm, excluding metric gauges. Effective for new lines from January 1, 2015, it exempts pre-existing infrastructure unless it is undergoing renewal or upgrading. This approach ensures system-wide harmonization while accommodating the specific conditions of existing networks.

Here are the standards used in railway energy subsystem interoperability:

1. EN 50163:2004-Railway Applications-Supply Voltages of Traction Systems

EN 50163:2004 is a European standard that defines the supply voltages used in railway traction systems. For AC systems, common voltages include 15 kV or 25 kV at frequencies of either 50 Hz or 60 Hz, depending on regional practices. For DC systems, voltages such as 1.5 kV, 3 kV, and 750 V are used. The standard also establishes permissible tolerance levels, allowing for minor voltage fluctuations without impacting the performance or safety of the trains.

Table 3-5 Describes the operating voltage and working frequency below.

Table 3-5 Operating Frequency and Voltage Levels[47]

Electrification System	Minimum Voltage		Nominal Voltage	Maximum Voltage	
	(U_{min2})	(U_{min1})	(U_n)	$(U_{max 1})$	$(U_{max 2})$
DC	400	400	600	720	800
	500	500	750	900	1000
	1000	1000	1500	1800	1950
	2000	2000	3000	3600	3900
AC	11000	12000	15000	17250	18000
	17500	19000	25000	27500	29000

2. EN 50388:2012-Railway Applications-Power Supply and Rolling Stock-Technical Criteria for the Coordination Between Power Supply (Substations) and Rolling Stock to Achieve Interoperability

EN 50388:2012 provides the compatibility of electric trains (rolling stock) with the power supply system, promoting interoperability and efficient operation. It covers:

- **Power Coordination:** Aligns the power demand of trains with the capacity of the power supply, ensuring no overloads.
- **Regenerative Braking:** Ensures trains’ braking systems are compatible with the power grid to return energy efficiently.
- **Protection Coordination:** Defines how protection systems between the train and infrastructure should respond to faults, ensuring quick fault detection and minimal disruptions.
- **Quality of Power Supply:** This section specifies standards for voltage stability and other power characteristics to ensure reliable train operation.
- **Harmonics and Dynamic Effects:** This section addresses how train-related electrical fluctuations should be managed to avoid disturbances in the grid.

3. EN 50367:2012-Railway Applications -Current Collection Systems-Technical Criteria for the Interaction Between Pantograph and Overhead Line (To Achieve Free Access)

EN 50367:2012 is a technical standard that specifies the interaction between pantographs and overhead contact wires, ensuring interoperability across European railway networks. It includes AC and DC systems, including high-speed lines, and emphasizes train speed, pantograph amount, location, and spacing. Infrastructure managers maintain correct geometric properties and test pantograph performance.

Below, in Table 3-6, the maximum current capacity at standstill is described.

Table 3-6 Maximum Current Carrying Capacity at standstill[48]

Maximum current at standstill							
Type	AC				DC		
Speed (km/hr.)	$v \leq 160$ (AC1)	$160 < v \leq 220$ (AC2)	$220 < v < 250$ (AC3)	$v \geq 250$ (AC4)	$v \leq 160$ (DC1)	$160 < v \leq 220$ (DC2)	$220 < v < 250$ (DC3)
Value	80A				300A for 1.5kV 200A for 3kV		

Table 3-7 Describes the maximum current capacity aligned with power and minimum voltage.

Table 3-7 Knee Point Factor (a) and Minimum Voltage[49]

Power supply system	Knee Point Factor (a)	Minimum voltage ($U_{min}=a*U_n$)	Maximum power	Maximum current ($I_{max}=P_{max}/U_{min}$)
25kV, 50Hz	0.9	22,500V	5-12MW	≈600A
15kV, 16.7Hz	0.95	14,250V	4-10MW	≈700A
DC 3000V	0.9	2700V	3-8MW	≈3000A
DC 1500V	0.9	1350V	2-6MW	≈4000A
DC 750V	0.8	600V	1-3MW	≈5000A

4. EN 50119:2009+A1:2013, -Railway Applications-Fixed Installations-Electric Traction Overhead Contact Lines

The EN 50119:2009+A1:2013 standard specifies the design, installation, and maintenance of overhead contact lines for electric traction systems in railway operations. It addresses electrical, structural, and geotechnical issues to assure safety, efficiency, and lifespan. The standard includes thorough documentation for installation and maintenance, such as periodic tests and processes. The standard prioritizes material integrity, continuous maintenance, and adherence to safety norms.

Table 3-8 Describes the height of the overhead contact line along the speed.

Table 3-8 Height of Overhead Contact Line[48], [50]

Overhead Contact Line						
Voltage	AC1	AC2, AC3	AC4	DC1	DC2	DC3
Nominal height (m)	5 – 5.75	5 – 5.5	5.08 – 5.3	5 – 5.6	5 – 5.5	5 – 5.3
Minimum height (m)	4.95	4.95	-	4.9	4.9	4.9
Maximum height (m)	6.2	6	-	6.2	6.2	5.3
Maximum lateral deviation of the contact wire from the track center line under the action of crosswind (m)	0.4	0.4	0.4	0.4	0.4	0.4

5. EN 50122-1:2011+A4:2017- Railway Applications- Fixed Installations- Electrical Safety, Earthing and The Return Circuit- Part 1: Protective Provisions Against Electric Shock

EN 50122-1:2011+A4:2017 focuses on electrical safety provisions in fixed installations associated with AC and DC traction systems and those exposed to hazards from the traction power supply system. It emphasizes the importance of proper earthing, low-impedance earth connections, and stringent earthing standards for railway substations, switchgear, power supply equipment, and trackside equipment. The

revised version also outlines requirements for maintaining electrical safety during maintenance work on electric traction systems and protection.

Table 3-9 Describes the protection stage and reaction time of relays.

Table 3-9 Protection of the Railway[51]

Protection Stage	Time Delay
Primary Protection	No
Backup Protection	≈300ms
For a short Circuit	
AC15000V,16.7Hz	≈100ms
AC 25000V, 50Hz	≈80ms
DC 750V,1500V,3000V	≈20-60ms
Peak load current	≈ 1-5s
Thermal short-term average current	≈ 1min
Thermal overload average current	≈30s

6. EN 50122-2:2010 Railway Applications-Fixed Installations-Electrical Safety, Earthing, and the Return Circuit -Part 3 Mutual Interaction of A.C. And D.C. Traction Systems

EN 50122-3:2010 is a standard that addresses the interaction between AC and DC railway traction systems, focusing on mitigating electrical hazards and interference caused by inductive, capacitive, or conductive coupling. It applies to parallel AC and DC railway systems, shared infrastructure, level crossings, transitions, and system separation sections.

7. EN 50149:2012- Railway Applications- Fixed Installations- Electric Traction and Copper Alloy Grooved Contact Wires

The EN 50149:2012 standard outlines specifications for copper and copper alloy wires used in overhead electric traction systems, specifically railway contact lines. It defines wire characteristics, material specifications, cross sections, electrical properties, testing, quality assurance, jointing, installation, and special considerations. The standard ensures consistent mechanical, electrical, and environmental properties, making them suitable for long-term performance.

8. EN 50126-1:1999 The Specification & Demonstration of Reliability, Availability, Maintainability, and Safety (RAMS) Part 2: Guide to The Application of EN 50126 -1 for Safety

Part 2 of EN 50126-1 provides guidance on applying the principles of Reliability, Availability, Maintainability, and Safety (RAMS) within railway systems. The primary objectives of the guide are to clarify the application of EN 50126-1 for safety. The guide covers developing and documenting

safety cases for system components, managing safety throughout the system lifecycle, identifying hazards and mitigating risks, and continuously ensuring the system's safety through evolving processes.

9. EN 50125-2:2002 Railway Applications- Environmental Conditions for Equipment Part 2: Fixed Electrical Installations

EN 50125-2:2002 is a standard that defines environmental conditions for railway fixed installations, ensuring reliable operation and safety. It addresses temperature, humidity, wind, pollution, vibration, and dynamic forces. It serves as a technical reference, guiding material selection and collaboration between stakeholders.

Table 3-10 Describes the environmental conditions for fixed electrical installations for railway.

Table 3-10 Environmental Condition[50], [52]

Altitude	Solar Radiation	Ice load	Wind
A1(~1400m)	R1 - low - (700W/m ²)	I0 - no ice - (0N/m)	W1- low - (24m/s)
A2(~1000m)		I1 - low - (3.5N/m)	W2 - normal - (27.5m/s)
AX (above 1400m)	R2 - high - (1120W/m ²)	I2 - medium - (7N/m)	W3 - heavy - (32m/s)
		I3 - heavy - (15N/m)	W4 - special - (36m/s)

10. BS EN 50121-5:2015: Railway Applications Electromagnetic Compatibility Part 5: Emission and Immunity of Fixed

The BS EN 50121-5:2015 standard outlines electromagnetic compatibility requirements for railway systems, specifically substations. It covers emissions and immunity from electrical devices within substations, focusing on their interaction with radio frequency fields. The standard provides methods for measuring radio frequency emissions, testing different types of emissions, and providing data on typical emission levels. Its primary purpose is to ensure compatibility, prevent interference, and support compliance with EU EMC directives.

11. EN 50124-1 Railway Applications- Insulation Coordination Part 1: Basic Requirements- Clearances and Creepage Distances for All Electrical and Electronic Equipment

The EN 50124-1 standard outlines requirements for clearances and creepage distances in railway systems, ensuring proper insulation to prevent electrical breakdowns and minimize shock risks. It defines insulation types (functional, basic, supplementary, reinforced) and classifies overvoltage into four categories. The standard also considers environmental factors, pollution degrees, and safety contingencies, providing detailed tables for insulation requirements, clearances, and testing procedures in indoor and outdoor installations.

Tables 3-11 & 3-12 Describes the recommended electrical clearance for dynamic and static conditions.

Table 3-11 Electrical Clearance[50]

Voltage	Recommended values	
	Dynamic (mm)	Static (mm)
DC 750V	100	50
DC 1500kV	100	50
DC 3000kV	150	50
AC 15kV	150	100
AC 25kV	270	150

Table 3-12 Clearance between different Phases[50]

Nominal voltage	Phase difference	Relative voltage	Recommended values	
kV	Degree	kV	Dynamic (mm)	Static (mm)
15	120	26	260	175
15	180	30	300	200
25	120	43.3	400	230
25	180	50	540	300

3.4.2. IEC Standards for Railway Energy Subsystem

The International Electrotechnical Commission (IEC) is a global standards organization that develops and publishes international standards for electrical, electronic, and related technologies. It provides a framework for designing, operating, and maintaining electrical systems in railways, ensuring a safe, reliable, and interoperable energy supply across networks. IEC standards address overhead contact lines, substations, transformers, energy management systems, and electrical safety measures. Here are the standards used in railway energy subsystem interoperability:

1. IEC 60850: Railway Applications- Supply Voltages of Traction Systems

IEC 60850 specifies the main characteristics of supply voltages and frequencies for railway traction systems, including DC and AC electrification systems, to ensure safe, reliable, and interoperable operation. It defines nominal voltage ranges, permissible deviations, and testing methodologies for rolling stock and fixed installations under normal and abnormal conditions. The standard covers applications such as railways, trams, metro systems, and specialized transport, but excludes systems like mines and cable cars. It also addresses unique operational challenges, such as long tunnels or heavy energy demands, and promotes global interoperability by standardizing voltage and frequency requirements.

Table 3-13 Describes the operation voltage and frequency below.

Table 3-13 Operating Voltage and Frequency[53]

	Voltage			Nominal Frequency
	Lowest (V)	Nominal (V)	Highest(V)	
DC	400	600	720	
	500	700	900	
	1000	1500	1800	
	2000	3000	3600	
AC	4750	6250	6900	50 or 60 Hz
	12000	15000	17250	16 ^{2/3} Hz
	19000	25000	27500	50 or 60 Hz

2. IEC 60913:2013: Railway Applications- Fixed Installations- Electric Traction Overhead Contact Lines

IEC 60913 is an international standard that defines the technical requirements for overhead contact line (OCL) systems, which supply electric power to trains via the contact line and pantograph. The standard focuses on critical aspects such as the electrical capacity of conductors, structural stability, and uniform elasticity to ensure smooth train operations. It also addresses environmental challenges by providing design guidelines and material specifications. It includes provisions for special national conditions to accommodate regional needs, such as specific wire height and alignment tolerances.

Tables 3-14 & 3-15 Describes the recommended electrical clearance for dynamic and static conditions.

Table 3-14 Electrical Clearance[53]

Nominal voltage	Recommended minimum clearance (mm)	
	Static	Dynamic
DC 600(720V)	100	50
DC 700 (900V)	100	50
DC 1500 (18000 kV)	100	50
DC 3000 (3600kV)	150	50
AC 15000(17.25kV)	150	100
AC 20000(24kV)	250	150
AC 25000 (27.5kV)	270	150
Ac 25000(30kV)	300	150

Table 3-15 Clearance between different phases[53]

Nominal voltage	The phase difference in degrees	Relative voltage (kV)	Recommended minimum clearance (mm)	
			Static	Dynamic
DC 600(720V)	120	26	260	175
DC 700 (900V)	180	30	300	200
DC 1.5kV (1.8kV)	90	28.2	300	200
DC 3kV (36kV)	120	34.6	300	200
AC 15kV(17.25kV)	120	43.3	400	230
AC 20kV(24kV)	180	50	540	300
AC 25kV (27.5kV)	90	35.3	400	350
AC 25kV(30kV)	120	43.3	400	350

Tables 3-16 Describe the wind load and ice load conditions.

Table 3-16 Wind Load and Ice Load[53]

Types of overhead contact lines	Wind and Ice load	Wind load
Contact and catenary wire are automatically tensioned	0.95	1
The contact wire is automatically tensioned, and the catenary wire fixed termination.	0.9	0.95
Single Contact wire automatically tensioned	0.9	0.95
Contact wire and catenary wire fixed termination	0.7	0.8

Tables 3-17 Describe the maximum current capacity with knee factor, which is used to calculate the minimum voltage.

Table 3-17 Maximum Current Carrying Capacity[53]

Power supply system	AC	AC	DC	DC	DC
	25000V,50Hz	15000V,16.7Hz	3000V	1500V	750V
Value of a (knee factor)	0.9	0.95	0.9	0.9	0.8

3. IEC 60364-4-41: Low Voltage Electrical Installations-Part 4-41: Protection for Safety-Protection Against Electric Shock

IEC 60364 is an international standard that provides comprehensive guidelines for the safe design, installation, and operation of electrical systems, particularly in low-voltage installations. Its primary focus is to protect people, animals, and property from electrical hazards, particularly electric shock. The standard outlines protective measures such as insulation of live parts, barriers and enclosures, equipotential bonding, residual current devices (RCDs), and electrical separation. It applies to all

electrical installations, including residential, commercial, and industrial settings, ensuring safety under normal and fault conditions. The standard also includes fault protection against direct and indirect electric shocks, with additional safety measures for installations requiring skilled supervision. Overall, IEC 60364 establishes a robust framework for electrical safety through its detailed and comprehensive protection measures.

4. IEC FDIS 63438: Railway Applications - Fixed Installations: Protection Principles for AC and DC Electric Traction Power Supply Systems

The IEC FDIS 63438 standard provides a comprehensive framework for protecting railway traction power supply systems. It covers AC (50 Hz and 16.7 Hz) and DC systems, focusing on fixed installations to ensure safety, reliability, and system integrity. The standard emphasizes designing and implementing protection systems that safeguard personnel and equipment, maintain power supply continuity, and comply with international standards. Core functionalities include fault detection, system isolation, selectivity, coordination, reliability, and routine maintenance and testing. It also introduces methods for grading time coordination and redundancy classifications (e.g., M1, M2, M4) to enhance reliability. Through examples of protection schemes tailored to various configurations, the standard enables adaptation to diverse system requirements while minimizing disruptions during faults.

Tables 3-18 Describe the protection scheme.

Table 3-18 Maximum disconnection time [54]

System	50V<U ₀ ≤ 120V		120V<U ₀ ≤ 230V		230V<U ₀ ≤ 400V		U ₀ ≥ 400V	
	AC	DC	AC	DC	AC	DC	AC	DC
TN (Terra Neutral)	0.8s	-	0.4s	5s	0.2s	0.4s	0.1s	0.1s
TT (Terra Terra)	0.3s	-	0.2s	0.4s	0.07s	0.2s	0.04s	0.1s

5. IEC 62621: Railway Applications – Fixed Installations – Electric Traction – Specific Requirements for Composite Insulators Used for Overhead Contact Line Systems

IEC 62621 defines the technical, design, and performance standards for composite insulators used in overhead contact line (OCL) systems for railway applications operating above 1,000 V AC or DC. These insulators are vital for electric traction systems, ensuring reliability, safety, and durability under mechanical, electrical, and environmental stresses. The standard includes rigorous testing protocols, damage limit verification, and guidance for managing non-standard mechanical loads like bending and torsion to enhance performance and minimize failure risks.

3.4.3. Chinese Standards for Railway Energy Subsystem

Chinese standards for railway energy subsystems are comprehensive guidelines that aim to enhance the efficiency, reliability, and sustainability of the country’s rapidly expanding railway network. These

standards cover electrification, energy efficiency, renewable energy integration, and electromagnetic compatibility. With China leading the world in high-speed rail development, its energy subsystem standards are tailored to support the unique demands of high-speed and long-distance railway operations.

1. TB 10009- 2005 Design Code of Railway Electric Traction Feeding

The Design Code for Railway Electric Traction Feeding (TB10009-2005) is a guideline for designing, installing, and operating electric traction systems in railways. It addresses components, including power supply systems, substations, overhead contact lines, and control systems, ensuring safe, efficient, and reliable power delivery. The code specifies standards for system design, power requirements, equipment specifications, safety protocols, and performance testing while encouraging the integration of advanced technologies. This standard is vital for engineers and professionals in railway electrification, ensuring consistency, reliability, and optimal performance of railway power networks.

Tables 3-19 Describes the operating voltage and frequency.

Table 3-19 Voltage Levels and Operating Frequency[55]

Parameter	Minimum	Nominal	Maximum
Voltage	19kV	25kV	29kV
Frequency	49 Hz	50Hz	51 Hz

Tables 3-20 Describes the maximum current capacity of a contact line.

Table 3-20 Maximum Current Carrying Capacity[55]

Parameter	Current carrying capacity	Voltage
Overhead line	500 – 1000A	25kV
Third rail	1500 – 4000A	750V DC/ 1500 DC

Tables 3-21 Describes the maximum overhead contact line and pantograph working range.

Table 3-21 Pantograph Clearance and Overhead Contact Line Alignment[55]

Parameter	Value	Voltage level
Minimum contact wire height	5.2 – 5.6 m	25 kV
Pantograph working range	4.8 – 6 m	25 kV

Tables 3-22 Describes the protection type with the sensitivity coefficient acting on the relay.

Table 3-22 Protection[55]

Protection type	Sensitivity coefficient	Time delay (s)
Current and voltage	1.3 - 1.5	≤ 1.5s
Zero and negative sequence	2.0	No delay

Distance protection	1.3 - 1.5	$\leq 1.5s$
Differential protection	2.0	No delay
Backup protection	1.3 – 2.0	0.5 – 2.0s
Auxiliary protection	≥ 1.2	No delay

Tables 3-23 Describes the clearance for 25kV in different categories.

Table 3-23 Clearance for 25kV[55]

Clearance category	Value (mm)
The minimum distance between the grid-type fence and the live parts	1050
The minimum distance between cross-live parts without a fence	400
Minimum distance between bare conductors	2600
Minimum distance between parallel live parts	2100
Minimum mounting distance between live parts and ground	4000

2. TB10501- 98 Code for Environmental Protection Design of Railway Engineering

The Code for Environmental Protection Design of Railway Engineering (TB 10501-98) provides detailed guidelines to minimize the environmental impact of railway infrastructure projects in China. Its primary objective is to ensure compliance with environmental regulations, promote sustainable development, and protect public health and safety. The code addresses areas such as air, water, and soil pollution prevention, waste management, noise and vibration reduction, and control of electromagnetic interference. It also provides specific recommendations for designing and placing railway infrastructure to reduce environmental harm, while ensuring that projects meet ecological standards. The code incorporates modern environmental practices, promotes long-term sustainability, and allows flexibility for different project requirements, making it an essential tool for environmentally responsible railway design.

3. TB 10063- 2007 Code for Design on Fire Prevention of Railway Engineering

The Code for Design on Fire Prevention of Railway Engineering (TB 10063-2007) is a set of guidelines ensuring fire safety across various railway facilities, including production buildings, maintenance depots, substations, fuel depots, and areas storing hazardous materials. Its primary goal is to prevent fires, limit their spread, and protect people and property in compliance with safety standards. The code includes classifications for different fire hazards, zoning for explosion and fire risks, fire protection distances, and specifications for fire extinguishers based on fire types. It also provides guidelines for electrical equipment safety and emphasizes the importance of fire safety training and emergency preparedness for railway personnel.

3.4.4. AREMA Standards for Railway Energy Subsystem

Chapter 33 of the AREMA standards provides essential guidelines for electrical energy utilization in railway electrification. It explores the economic feasibility of electrification, considering traffic volume, infrastructure costs, and the long-term environmental and operational benefits. The document outlines technical standards for clearances, voltage recommendations, and the design of overhead catenary systems to ensure efficient energy transfer and safe integration with existing infrastructure. It also addresses the compatibility of electrification systems with signaling, power supply requirements for AC and DC systems, and the role of rail bonding in maintaining a continuous electrical flow.

1. Electrical Energy Utilization

The chapter on Electrical Energy Utilization provides a detailed analysis of the economic feasibility of railway electrification. It looks at traffic volume, infrastructure costs, and operating expenses. Additionally, it highlights the environmental benefits and the potential for improved operational efficiency that electrification can bring.

2. Clearances

This chapter describes the clearance requirements for designing electrification systems, assuring safe installation of electrical equipment, and creating clearance standards to prevent interference with other railway components, resulting in seamless integration with existing infrastructure.

Tables 3-24 Describes the clearance for the overhead contact system.

Table 3-24 Clearance Requirements[56]

Nominal voltage	Energized OCS components				Additional clearance in polluted areas (mm)	Ancillary conductor's absolute minimum (mm)
	Normal minimum		Absolute minimum			
	Static (mm)	Dynamic (mm)	Static (mm)	Dynamic (mm)		
750 V DC	105	80	80	80	0	105
1.5kV DC	130	90	105	80	10	130
3kV DC	155	130	130	80	10	155
12.5kVAC	180	155	155	105	20	180
25 kV AC	270	205	205	155	50	270
50 kV AC	535	410	410	305	100	535

3. Recommended Voltages

This chapter outlines the recommended voltage levels for the electrification of new railways, highlighting the significance of standardised voltage standards to ensure compatibility across systems,

optimise energy efficiency, and improve operational performance. It provides practical guidance for planners and engineers to choose the appropriate voltage, considering factors such as the type of railway network, expected train loads, and operational distances

Tables 3-25 Describe the operating voltage and frequency.

Table 3-25 Operating Voltage and Frequency[56]

Nominal voltage	Maximum no-load substation voltage	Maximum operating voltage	Minimum operating voltage	Contingency minimum vehicle operating voltage	Frequency Hz
DC V					
750	900	975	525	450	-
1500	1800	1950	1050	900	-
3000	3600	3900	2100	1800	-
AC kV					
12.5	15	15	10	8.75	60
25	30	30	20	17.5	
50	60	60	40	35	

4. Railway Electrification Systems

This chapter focuses on the technical aspects of overhead catenary systems, a primary means of powering electric trains. It covers the design criteria for overhead lines, their installation, and operational considerations for maintaining an efficient and stable power supply to trains. The chapter provides technical details on the different components of catenary systems, including masts, conductors, and transformers, and ensures their reliability and safety during operation.

Tables 3-26 Describes the overhead contact line height with speed and voltage

Table 3-26 Contact wire height[56]

	Light rail	Electric multiple unit			Passenger			Freight
Speed (km/hr)	55-60	80	90	125	90	110	180	60-80
Contact wire height (mm)	4875,5800,6700	4875	5800	6700	4875	5800	5800	6700,5800

Voltage kV	50	25	12.5
Contact wire height m	7.3m	7m	6.7m

5. Railway Electrification Compatibility with Signal Systems

The chapter discusses the challenges of integrating railway electrification systems with signaling infrastructure, focusing on electrical interference mitigation, and offers strategies such as impedance bonding, filters, and grounding to ensure seamless integration while prioritizing safety and efficiency.

6. Traction Power Supply Requirements for AC Electrification

The chapter explores the technical requirements for AC electrification systems in railways, emphasizing the elements necessary for reliable and efficient power delivery. It addresses traction power demands, AC system configurations, and optimal substation placement. The importance of accurate load calculations, thorough engineering analyses, and minimizing electromagnetic interference is highlighted to ensure system stability and performance. Additionally, the chapter covers infrastructure components like power stations, transformers, and substations, while considering functional, environmental, and economic factors. With a focus on innovative and cost-effective solutions, it provides valuable guidance for designing and implementing AC electrification systems that meet the evolving needs of modern rail networks.

Tables 3-27 Describes the overhead contact line protection scheme.

Table 3-27 Catenary (Overhead Line) Protection[56]

Protection type	Function	Delay time
Distance Relay	Detects faults based on impedance	Instantaneous
Auto-reclosing Relay	Re-closes the breaker after a fault trip	3 to 15 sec (adjustable)
Thermal Overload Relay	Prevents the conductor from overheating	Adjustable
Transfer Trip Relay	Clears remote faults via the communication link	Instantaneous
High Voltage Circuit Breakers	Clears faults at a primary voltage level	Instantaneous or delayed
Disconnect Switches	Isolate equipment for maintenance	No delay (manual operation)
Overvoltage Protection	Protects against lightning & switching surges	Instantaneous

7. Rail Bonding

Rail bonding is essential for maintaining a reliable electrical connection between rails in electrified railway networks. The AREMA Manual for Railway Engineering provides specifications for bond sizing, material selection, and types of bonds, as well as installation, maintenance, and testing. This ensures consistent power distribution for signalling and electric traction.

8. Catenary and Locomotive Interaction

This chapter examines the electrical and mechanical interactions between locomotives and the catenary system. It covers the electrical connection, including traction motor control circuits and electrical characteristics, as well as the mechanical aspects, such as the pantograph's function in maintaining contact with the catenary. The scope includes ensuring reliable power transfer and the effective operation of electric traction systems.

3.5. Technical Parameters for Railway Electrification Energy Subsystem

Interoperability

The energy subsystem must be standardized or flexible across systems, locations, and technologies to achieve interoperability in railway electrification. A full explanation and reasoning for each critical parameter are provided below:

3.5.1. Electrical Parameters

3.5.1.1. Operating Frequency and Voltage Levels

Frequencies and voltage levels are required for railway electrification systems. Standardizing these parameters simplifies operations, improves efficiency, and ensures safety.

Operating Frequency: Alternating current (AC) is used in railway electrification, with common standards being 50 Hz in Europe and China, 60 Hz in North America, and some parts of South America, and 16.7 Hz in Germany, Austria, Switzerland, Sweden, and Norway.

Voltage Levels: The electrical voltage supplied to railway traction systems. Typical classifications include:

- **AC Systems:** 25 kV, 50 Hz is the most commonly utilized standard globally, including East Africa. And 15 kV, 16.7 Hz is used in parts of Europe.
- **DC Systems:** 750V, 1500V, and 3000V are used in urban transit, trams, and older mainline networks.

Standardizing frequency and voltage levels is crucial for East African countries to ensure cross-border operations, reduce costs, and ensure infrastructure compatibility. A uniform 50 Hz frequency improves system reliability and minimizes conversion losses. Additionally, for compatibility with future expansion and high-speed rail projects in East Africa, most modern high-speed rail systems adopt 25 kV, 50 Hz AC.

3.5.1.2. Maximum Current Carrying Capacity

The maximum current-carrying capacity is the highest amount of electrical current that a railway electrification system can safely give to trains without producing overheating, severe voltage dips, or infrastructure damage. Factors that impact this ability include:

- **Conductor Material and Cross-Section:** The resistance and current-carrying capacity of catenary wires or third rails are determined by the material used and its cross-sectional area.
- **Voltage Level:** The Higher voltage systems (25 kV AC) require less current to supply the same amount of power, reducing energy loss due to resistance while increasing efficiency.
Lower voltage systems (750V DC or 1500V DC) require more current to satisfy the same power demand, putting strain on the infrastructure.
- **Temperature and Environmental Conditions:** Temperature, humidity, dust, and environmental factors affect current capacity.
- **System Design and Configuration:** The spacing of substations, quality of transformers, and tensioning of the catenary system influence current distribution and capacity.
- **Train Power Demand:** High-speed and freight trains require more power, necessitating an adequate current supply to sustain their operations without performance limitations.

Standardizing the Maximum Current-Carrying Capacity is crucial for railway electrification to ensure rolling stock compatibility, prevent electrical bottlenecks, protect infrastructure, and ensure efficient power distribution. Mismatched current capacities can lead to operational inefficiencies, delays, and congestion. Overloading electrical components beyond their designed capacity can lead to overheating, increased maintenance costs, and failures.

Current Carrying Capacities in Different Electrification Systems

Table 3-28 DC Electrification Systems

DC		AC	
Voltage	Current	Voltage	Current
750 V	1000 - 3000 A	15 kV, 16.7Hz	1000 – 2000 A
1500 V	(3000-5000 A) Up to 6000 A	25kV, 50 Hz	500-1000A
3000 V	5000 – 8000A		

3.5.1.3. Regenerative Braking

Regenerative braking is a railway system's ability to recover braking energy, improving efficiency and minimizing mechanical wear, and is essential for interoperability across different networks. DC systems require energy storage or specialized substations to absorb excess energy, while AC systems can return energy directly to the grid. Different railway networks may have varying regenerative braking capabilities, which impact energy recovery during transitions. Inconsistent regenerative braking systems can lead to energy waste, operational inefficiencies, and infrastructure limitations.

3.5.1.4. Electrical Protection and Coordination

Electrical protection and coordination involve designing and implementing systems to protect the railway electrification infrastructure, rolling stock, and personnel from faults, such as short circuits, overvoltage, and power surges, ensuring efficient fault isolation and service continuity.

The impact of electrical protection and coordination on interoperability is discussed as follows:

1. Safety and Reliability of Networks

Protection Against Electrical Faults: Electrical protection systems detect and isolate faults, such as short circuits and overloads, preventing extensive damage to railway infrastructure and rolling stock.

2. Compatibility of Protection Systems Across Borders

Standardized protection protocols enhance safety and smooth train operations. Harmonizing protection equipment reduces power supply inconsistencies, promoting cross-border interoperability and smoother operations.

3. Selective Fault Isolation and Power Restoration

Coordinated protection minimizes service disruptions and enhances system resilience by isolating affected network sections and preventing system-wide failures due to inconsistent protection strategies.

4. Energy Efficiency and Regenerative Braking Integration

Coordinated protection ensures a stable power supply and optimizes regenerative braking, improving system efficiency by allowing bidirectional energy flow in the electrical network.

Non-standardized electrical protection in interoperability poses challenges such as uncoordinated fault detection, the risk of overlapping or incompatible settings, and operational limitations for cross-border trains.

3.5.1.5. Phase Synchronization and System Isolation

1. Phase Synchronization

Phase synchronization ensures the alignment of voltage and frequency in alternating current systems during power supply transitions. It delivers uniform frequency, voltage alignment, and timing coordination, making it useful in cross-border railway networks, transitions between electrified and non-electrified railway sections, and high-speed rail corridors.

2. System Isolation

System isolation separates railway power systems, preventing electrical interference and ensuring operational safety. It consists of neutral sections, switching stations, and protection devices. Applications include AC and DC power system separation, isolation of railway segments, and fault isolation to prevent power failures from spreading across the network.

Phase synchronization and system separation are crucial for railway electrification interoperability, seamless transitions, fault management, safety, and efficiency. They prevent train delays, power interruptions, phase mismatches, and uncontrolled power flows.

3.5.1.6. Real-Time Energy Data Acquisition and Monitoring Systems

Real-time energy monitoring is crucial for interoperability. It enables standardization to improve power quality, enhance fault detection, and optimize economic and operational efficiency. It collects energy-related parameters, including voltage, current, power consumption, and energy efficiency, from railway electrification infrastructure.

Monitoring systems include sensors, communication networks, data management platforms, and control systems. Standardization and compatibility are achieved through standardized data protocols, data formats, cross-border energy exchange, voltage and frequency monitoring, harmonics and load balancing, renewable energy integration, fault detection, and predictive maintenance. Challenges include managing diverse data sources, cybersecurity, high infrastructure costs, and the need for skilled personnel to design, implement, and maintain these systems.

3.5.2. Safety and Protection Parameters

3.5.2.1. Grounding and Earthing System Design

Grounding is the process of connecting electrical equipment to the earth to ensure safety, reduce electromagnetic interference, and stabilize voltage levels. It protects railway infrastructure from overvoltage and lightning strikes, facilitates system interoperability, and reduces electromagnetic disturbances. Railway grounding systems encompass substation grounding, overhead line grounding, track and return current systems, bonding, equipotential connections, surge protection, and lightning arresters. Adhering to international standards enhances compatibility and minimizes interference, ensuring the smooth operation of signaling and telecommunications.

3.5.2.2. Shock and Vibration Protection Mechanisms

Shock and Vibration Protection Mechanisms ensure the safety, reliability, and longevity of infrastructure, rolling stock, and onboard equipment. These mechanisms absorb and mitigate sudden impacts or forces, such as collisions, abrupt stops, or wheel-rail interactions, while dampening or isolating continuous oscillatory motions caused by train movement, track irregularities, or external sources. The components include track and infrastructure design, rolling stock protection mechanisms, overhead catenary and electrical components, isolation systems, shock-absorbing materials, structural reinforcements, and monitoring systems. These measures protect passengers, crew, and infrastructure from injuries or damage due to excessive shocks and vibrations, ensuring smooth operation and compliance with international safety and operational standards.

3.5.2.3. Emergency Power Cutoff and Fail-Safe Systems

Emergency Power Cutoff and fail-safe systems are crucial in railway networks to prevent further damage or hazards. Emergency Power Cutoff systems disconnect the power supply during emergencies, while fail-safe systems default to a safe state in case of failure. These systems consist of circuit breakers, relays and sensors, control systems, manual override, backup power systems, and monitoring and alarms. Interoperability considerations include standardizing power cutoff protocols, ensuring response time, incorporating redundant systems, collaborating with neighboring countries for cross-border coordination, and integrating with signaling and communication systems. Challenges include cross-border standardization issues, high costs of fail-safe infrastructure, false triggers, and environmental concerns. Solutions include adopting international standards, implementing redundant systems, conducting regular testing, training personnel, and collaborating with neighboring countries for interoperability.

3.5.3. Mechanical Parameters

3.5.3.1. Pantograph Clearance and Compatibility

Railway electrification involves maintaining a minimum distance between infrastructure and other railway components, such as overhead contact lines, support structures, and electrical equipment. This ensures safe operation, prevents electrical hazards, and facilitates efficient maintenance.

Pantograph clearance is the minimum spatial distance required between the pantograph and surrounding infrastructure to ensure safe operation. It includes overhead contact line (OCL) height, side clearance, vertical clearance, and wind and vibration effects.

Clearance requirements vary depending on the track gauge, rolling stock dimensions, and speed. Pantograph compatibility ensures that different railway networks can utilize the interoperable pantographs and OCL systems. Considerations include pantograph head geometry, contact force, voltage and current ratings, OCL design, and standardization compliance with IEC, EN, or UIC standards. Proper clearance design is essential for the safety and reliability of electrified railway networks.

3.5.3.2. Overhead Contact Line Structural Geometry and Alignment

The Overhead Contact Line (OCL) structural geometry and alignment are essential for maintaining uninterrupted power transfer, minimizing mechanical wear, and facilitating interoperability between railway electrification networks. Standardized OCL parameters mitigate compatibility issues, ensure continuous and reliable energy supply, and prevent mechanical failures. OCL alignment ensures proper power supply, enhances pantograph-OCL compatibility, and facilitates cross-network interoperability. The components of OCL structural geometry and alignment include contact wire height, stagger of

contact wire, tensioning system, span length, wire gradient, and transitions. Design considerations for interoperability include adopting the same height and stagger values, optimizing dynamic performance at varying speeds, and supporting passenger and freight trains with differing power demands. The challenges include variability in existing railway networks, high-speed rail operations, mixed-gauge networks, extreme weather conditions, and cross-border standardization issues. Solutions and best practices include adopting international standards such as EN 50119 and UIC 608, utilizing advanced tensioning systems, simulation, and digital monitoring tools, conducting routine inspections and maintenance, and fostering cross-border coordination through regional cooperation in OCL design and implementation.

3.5.4. Power Supply and Distribution Parameters

3.5.4.1. Substation Design and Capacity

Substation design for railway electrification interoperability, ensuring uniform power distribution, compatibility with multiple standards, prevention of power bottlenecks, scalability for future expansion, and compliance with international standards. Design considerations include standard voltage and frequency, effective load and power management, power quality control, and renewable energy integration.

However, challenges include heterogeneous standards, high capital costs, and integration with legacy infrastructure. Different national electrification standards complicate substation design and interoperability, while high capital costs and technical complexity make it difficult to retrofit older substations to meet modern interoperability standards.

3.5.4.2. Energy Losses and Efficiency of Power Distribution

Energy losses refer to the loss of electrical power during transmission and distribution from the grid to the railway system. Efficiency refers to the effectiveness of power distribution systems in delivering energy with minimal losses. Reducing energy losses can lead to cost optimization, enhanced system performance, and standardized energy efficiency standards. Factors affecting energy losses include conductor resistance, transformer and conversion efficiency, power factor correction, optimized substation placement, and high-voltage transmission for long-distance rail corridors.

Interoperability considerations include standardized efficiency metrics, advanced energy management systems, regenerative braking systems, and cross-border coordination on energy efficiency policies. Challenges include high implementation costs, technical complexity, and environmental and climatic variations. However, reducing energy losses and improving efficiency can lead to economic viability, improved system performance, and reduced greenhouse gas emissions.

3.5.5. Environmental Parameters

Environmental factors such as temperature, humidity, and altitude impact railway electrification systems, requiring standards that ensure adaptability to these conditions for cross-border interoperability. Challenges include wind loading, snow and ice loading, and temperature extremes. High winds can cause structural damage, while snow and ice accumulation can lead to disruptions and energy consumption. To address these issues, materials and designs should prioritize energy efficiency, using insulated cables or low-energy heating systems. Environmentally sustainable materials and designs that can withstand extreme temperatures are crucial. A comprehensive framework for assessing worldwide railway electrification standards is required, which includes electrical compatibility, infrastructural integration, environmental resilience, and financial viability.

3.5.6. Cost

The Railway electrification interoperability involves upfront investments in infrastructure, equipment, training, and ongoing operational and maintenance expenses. While initial costs can be high, the system's long-term financial viability depends on its efficiency, durability, and adaptability. Balancing cost with performance ensures the electrification standard is affordable and provides long-term value, supporting the sustainability of cross-border railway operations.

3.6. Analysis of Standards

The East African railway has electrified and non-electrified lines with different standards, including old legacy colonial standards, Chinese class I and II, European Norm (EN), IEC, and AREMA. This thesis analysed the appropriateness of the standards for modernization and expansion in current, ongoing, and planned projects for electrified line interoperability of the energy subsystem.

3.6.1. Comparison of Standards Based on Technical Parameters

In this section, a comparative analysis of technical parameters from European, Chinese, IEC, and AREMA railway network standards is conducted to find the best-fit standard for the East African energy subsystem's future technical standardization and policy coordination.

Table 3-29 Comparison of technical parameters

Parameter	European	Chinese	IEC	AREMA	Recommended for East Africa	Justification
Voltage and Frequency	25kV 50Hz	25kV 50Hz	25kV 50Hz	25kV 60Hz	25kV 50Hz	European, Chinese, and IEC are fitted

						with standard values.
Maximum Current Capacity	500-1000A	500-1000A	500-1000A	500-1000A	500-1000A	All are optimized for range.
Overhead Contact Line Height	5-6.5m	5.2-6.7m	5.5-6.5m	4.8-6.7m	5.2-6.7m	All are compatible ranges. But Chinese trains dominate in the region.
Trackside Clearance	2.6-2.8m	2.5-3m	2.6-2.8m	2.8-3.1m	2.5-3m	All are Compatible with the existing infrastructure.
Insulation Coordination	EN 50124	TB 10009	IEC 60071	AREMA	IEC 60071 EN 50124	IEC and EN provide clear guidelines, but IEC is globally accepted.
Pantograph Spacing	≥ 200 m-400m	≥ 200 m-400m	≥ 200 m-400m	≥ 250 m-500m	≥ 200 m-400m	All are suitable.
Electrical Clearance	Min 250 mm - 300 mm	300 mm - 400 mm	Min 250 mm - 300 mm	300 mm - 450 mm	300 mm – 400 mm	Chinese & AREMA are better for a higher safety margin.

Regenerative Breaking	up to 30% recovery	up to 35% recovery	up to 30% recovery	Rare	30-35% recovery	Chinese projects and infrastructure dominance in the region.
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Table 3-29 presents a comparative analysis of the technical parameters for four standards: European (EN), Chinese, IEC, and AREMA.

This thesis employs a performance scoring framework, a component of Multi-Criteria Decision Analysis[57], [58], to evaluate European (EN), Chinese, IEC, and AREMA standards.

The eight parameters were selected based on their influence on the technical parameter, and to maintain impartiality, each parameter has equal weight to avoid bias towards any parameter.

The standard is rated for each parameter by definite weighting values, where

- 1 indicates the best fit,
- 0.75 indicates a moderate fit,
- 0.5 indicates a modified fit, and
- 0.25 and 0 indicate non-fitting values for the East African railway in energy subsystem standardization.

The weighted values are consistent with engineering decision-making practice, where the qualitative assessments are transformed into quantitative values. The weights are assigned based on the documented technical standards and on the degree of alignment with the East African context.

From 8 (eight) parameters, the Chinese standard aligned with the East African railway energy subsystem in 7 (seven) parameters from those 6 best fitted 1 fitted and 1 fitted with modification, the European (EN) and IEC standard aligned with the East African railway energy subsystem in 6 (six) parameters from this for European (EN) 5 best fitted 2 fitted and 1 fitted with modification and for IEC 6 best fitted 1 fitted and 1 fitted with modification and the AREMA standard aligned with the East African railway energy subsystem in 5 (five) parameters those are 5 best fitted 1 fitted with modification and 2 parameters did not fit.

The total performance score for each standard is calculated as the arithmetic mean of the parameter's scoring or weighting, which produces a ranking.

The above method follows the Multi-Criteria Decision Analysis and performance scoring approach as outlined in Saaty's Analytic Hierarchy Process (AHP) [59] and expanded upon in the Multi-Criteria Decision Analysis literature[60].

Figure 3-13 below presents a comparative analysis of technical parameters with definite weighting values.

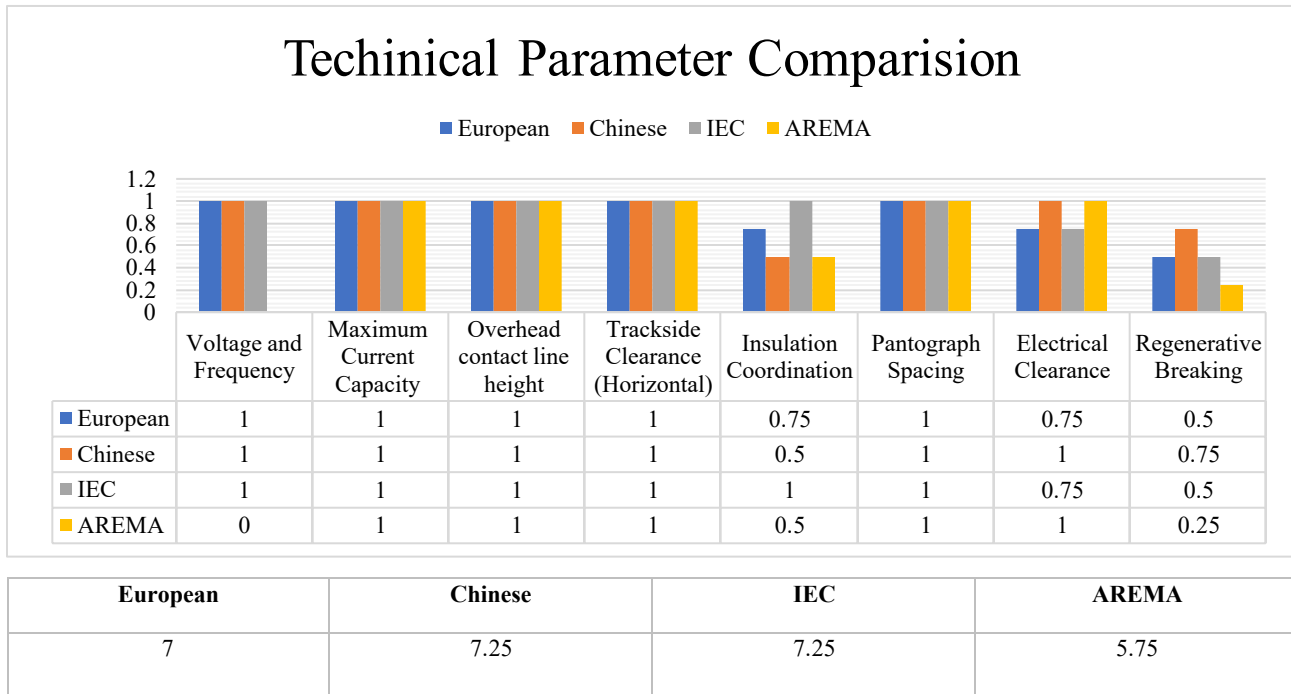


Figure 3-13 Technical Parameter Comparison using Weight Scoring

3.6.2. Comparison of Standards by Non-Technical Parameters

1. European Railway Electrification Standards

Scope: Define electrification standards for European railways that align with the technical specification for interoperability.

Strengths: The standards are widely adopted in Europe and have been implemented as a benchmark for interoperability.

Weaknesses: The standards are less compatible with non-European networks.

Gaps: The standards are limited to global adoption, and modifications are needed when applied to non-European countries.

Overlaps: The standards align with the principles of the IEC and compliance with UIC.

Geographical Coverage: The standards are widely used in Europe, the United Kingdom, Switzerland, and parts of North Africa, Turkey, and India.

Cost: The standards are costly due to their high design, maintenance, adaptation/training, construction, and operation costs.

Environmental Impact: The standards have a positive impact, supporting the green rail initiative by integrating their grid with renewable energy.

Adaptability: The Standards are hard to adopt due to the need for advanced institutions and financial capacity, while the standards are robust and promote interoperability.

2. China National Standard for Railway Electrification

Scope: The standard focused on China's railway electrification in a 25 kV AC system, high-speed railway network, and Belt and Road initiative projects.

Strengths: The Chinese standard is a proven choice for the most extensive high-speed rail network.

Weaknesses: The Chinese standard has limited interoperability; it focuses on China and China-funded projects and depends on Chinese equipment.

Gaps: The standards have limited adoption outside BRI-funded projects and compatibility issues with non-Chinese rolling stock, signaling systems, and infrastructure.

Overlaps: The Chinese standard is fully compatible with IEC but lacks international harmonization and shares partial similarities with EN.

Geographical Coverage: The standard is used in China, expanded to parts of Southeast Asia (Laos, Thailand), several African countries (SRG projects), and countries under the Belt and Road initiatives.

Cost: The standards have a balanced cost of electrification, medium capital expenditure and maintenance costs, low adoption and training costs due to their alignment with the projects and government funding.

Environmental Impact: The standards have an environmental impact because the Chinese electricity grid depends on coal, but they have a plan for the future to integrate renewable energy.

Adaptability: The standards are technically and economically adaptable in the region for long-term needs harmonization with international standards.

3. IEC Railway Electrification Standards

Scope: The International Electrotechnical Commission (IEC) is the global standard for rail electrification and is widely adopted as a national standard.

Strengths: IEC railway standards promote harmonization and are valuable for international railway projects.

Weaknesses: The International Electrotechnical Commission (IEC) standards have been inconsistently adopted because they are not legally enforceable.

Gaps: The International Electrotechnical Commission (IEC) standards need localization efforts for adaptation, while the standard is a global framework.

Overlaps: The standards are used as a global framework reference.

Geographical Coverage: The standards have global acceptance and are used in Europe (merged with EN), Asia (India, China), parts of Africa (Ethiopia), and some parts of North America (but prefer AREMA).

Cost: The standards have high design, adaptation/training, construction, and operation costs, but low maintenance costs due to the global availability of spare parts.

Environmental Impact: The standards promote renewable energy and energy efficiency, which depend on the national policies and the energy source of the grid.

Adaptability: The standards have high adaptability due to their balancing the compatibility of national standards with international frameworks.

AREMA (American Railway Standards)

Scope: AREMA standards primarily focus on the heavy freight railway network in North America, which depends on diesel-based railway operations and has limited provisions for electrification.

Strengths: AREMA standards are best for a heavy freight railway network.

Weaknesses: AREMA standards have limited interoperability and are less suitable for globally integrated railway networks.

Gaps: AREMA standards are more focused on diesel-heavy freight railway systems, limited to electrification, and lack compatibility with other standards focused on electrified railway lines.

Overlaps: AREMA standards have limited overlap with international and other standards.

Geographical Coverage: AREMA standards are used in North America, parts of Canada, and some sections of Mexico.

Cost: The standards have high operational, maintenance, adaptation/training costs, and low electrification line construction costs due to their diesel-dominated railway line.

Environmental Impact: AREMA standards are less environmentally friendly due to high carbon emissions from diesel locomotives.

Adaptability: The standards have limited adaptability; they focus on only the North American heavy freight system.

Table 3-30 Comparison of non-technical parameters

Category	European	Chinese	IEC	AREMA	Recommended for East Africa
Scope	Guideline for railway electrification and interoperability	Conventional , high-speed rail in China and the Belt and Road Initiative.	Guideline and global reference for railway electrification	Fright-based diesel dominant with some electrification	Chinese because East Africa is a part of the BRI project

Geographical Coverage	Almost all of Europe, some parts of North Africa, and Asia.	China, some parts of Africa, and the Belt and Road Initiative.	Used as a global reference	USA, part of Mexico, and Canada.	Chinese
Interoperability /Adaptability	Excellent, it has its guideline TSI and is aligned with IEC and UIC.	China-centric, China-financed projects and the Belt and Road Initiative.	Promote harmonization between standards.	Designed only for North America.	Chinese
Strength	Interoperability	Cost-effective	General reference	Best heavy freight transportation	EN, Chinese, and IEC
Weaknesses	High cost	China centric	Require the adoption of local standards.	less focused on electrification	
Environmental impact	Positive impact uses renewable energy	Used coal as a grid source for rail electrification	Depends on the country that adopted.	High emissions, diesel-dependent	EN
Gap	Limited adaptation outside Europe.	Limited global use.	No legal enforcement depends on local.	No harmonized policy, and no energy recovery support.	

Overlap	Fully with IEC and partially with UIC	Fully with IEC and partially with EN	General framework	Minimal overlap	Chinese and IEC
Current Adoption in East Africa	None	SRG projects (Ethiopia, Kenya, Tanzania)	Ethiopia (ES IEC)	None	Chinese and IEC
Cost	High, due to EU standards and requirements	Cost-effective due to Chinese funding support	Moderate – Costs vary based on implementation.	High	Chinese
Compatibility with East Africa	Require modification	Fully compatible	Compatible with modification	Not compatible due to frequency mismatch	Chinese and IEC

European norms (EN) standards are effective in the interoperability of the European railway system and have a positive environmental impact that supports the global green initiative. However, the standards need a higher cost due to upfront investment, European-certified components, and design requirements, and also needs more modification for compatibility with East Africa.

The Chinese standards are recommended for the East African region due to their cost-effectiveness and compatibility with existing and other standards, with modifications. The East African region is part of the Belt and Road Initiative project, and China has been the major investor in the region's projects, including the existing Ethio-Djibouti railway line, under construction, and planned standard-gauge railway lines.

The International Electrotechnical Commission (IEC) standards are considered the technical foundation due to their globally accepted guidelines and compatibility with other standards. However, they need a country to adopt them based on its national standard requirements.

The American Railway Engineering and Maintenance of Way Association (AREMA) standards are technically strong for diesel-operated heavy freight railways, but not suited to modern electrified railways that are also planned for East Africa, which have technical compatibility differences.

CHAPTER FOUR

4. Conclusion, Recommendation, and Future Work

4.1. Conclusion

This thesis presents a comparative analysis of interoperability standards for energy systems in the East African railway network, with a focus on harmonizing railway energy subsystem standards in the region. The adoption of different standards, less electrified lines, and old infrastructure has been demonstrated as a lack of uniformity.

The thesis conducted a descriptive and comparative analysis of four standards: European (EN), Chinese, International Electrotechnical Commission (IEC), and American Railway Engineering and Maintenance of Way Association (AREMA). The analysis was based on technical and non-technical defined parameters.

Based on the findings, Chinese standards are recommended for alignment with the region's existing, under-construction, and planned projects. Similarly, the International Electrotechnical Commission (IEC) standards are recommended with modifications for long-term use due to their global acceptance. The compatibility between Chinese and IEC standards enables the hybrid standardization of a system as Ethiopia adopts the ES IEC as its national standard, utilizing a Chinese-built system.

This thesis also identified persistent challenges with old meter gauges and the diesel-based traction system, which hinder cross-border integration.

4.2. Recommendation

This thesis recommends the adoption of the Chinese standard based on a comparison analysis of technical and non-technical parameters for East African railway system interoperability in the energy subsystem. Due to their proven adaptability and major investors in the region, including the Ethio-Djibouti operational line and other ongoing, planned standard-gauge railway projects. For long-term harmonization, this thesis recommends aligning the Chinese standard with the International Electrotechnical Commission (IEC) standard, with modifications. IEC standards ensure global interoperability. Ethiopia adopted the International Electrotechnical Commission (IEC) with modifications to local requirements as ES IEC (ES stands for Ethiopian Standard) standards, and it is a successful example of this hybrid method.

The recommended adoption of standardized technical parameters based on a comparative evaluation of IEC, Chinese, EN, and AREMA standards, and taking into account existing infrastructure, regional conditions, and future scalability, is below:

- Voltage and Frequency: 25 kV / 50 Hz
- Maximum Current Capacity: 500 – 1000 A
- Overhead Contact Line Height: 5.2 – 6.7 m
- Trackside Clearance (Horizontal): 2.5 – 3.0 m
- Insulation Coordination: IEC 60071 / EN 50124
- Pantograph Spacing: ≥ 200 – 400 m
- Electrical Clearance: 300 – 400 mm
- Regenerative Braking: 30–35% Energy Recovery

By standardizing these parameters, East African countries can lay the groundwork for a harmonized, interoperable, and future-ready railway electrification framework.

4.3. Future Work

This thesis focused on defined parameters of technical and non-technical comparisons of the integration of the East African railway energy subsystem interoperability standards. Future studies should focus on legal, political, and economic integration. Also, by creating a uniform and sustainable energy subsystem framework for interoperability specification for the region.

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APPENDIX

Appendix A: Standard Parameter Table

Table A1: Voltage and Frequency

Standard	Nominal Voltage	Nominal Frequency
EN 50163	25kV	50Hz
IEC 60850	25kV	50Hz
TB 10009	25kV	50Hz
AREMA	25kV	60Hz

Table A2: Maximum Current Capacity

Standard	Nominal Voltage	Maximum Current
EN 50367	25kV	500- 1000A
IEC 60850	25kV	500- 1000A
TB 10009	25kV	500- 1000A
AREMA	25kV	500- 1000A

Table A3: Electrical Clearance

Standard	Nominal Voltage	Dynamic (mm)	Static (mm)
EN 50124-1	25kV	270	150
IEC 60913	25kV	270	150
TB 10009	25kV	270	150
AREMA	25kV	270	205

Table A4: Contact Wire Height

Standard	Nominal Voltage	Contact Wire Height (m)
EN 50119	25kV	4.95 – 6.2
IEC 60913	25kV	4.95 – 6.2
TB 10009	25kV	4.9 – 6.7
AREMA	25kV	4.8 – 7

Appendix B: Methodology and Calculation

Table B1: Performance Scoring Framework

Parameter	European	Chinese	IEC	AREMA
Voltage and Frequency	1	1	1	0
Maximum Current Capacity	1	1	1	1
Overhead contact Line Height	1	1	1	1
Trackside Clearance	1	1	1	1
Insulation Coordination	0.75	0.5	1	0.5
Pantograph Spacing	1	1	1	1
Electrical Clearance	0.75	1	0.75	1
Regenerative Breaking	0.5	0.75	0.5	0.25

Parameter by definite weighting values, where

- 1 indicates the best fit,
- 0.75 indicates a moderate fit,
- 0.5 indicates a modified fit, and
- 0.25 and 0 indicate non-fitting values

B2: Formula

$$S = \sum(W_i * P_i)$$

Where S = Score of each standard

W_i = Weight of Parameter

P_i = Performance Score Per Standard

B3: Calculation

W_i = is 1 for each parameter, so, $S = \sum(1 * P_i) = \sum(P_i)$

European = $\sum(P_i) = (1 + 1 + 1 + 1 + 0.75 + 1 + 0.75 + 0.5) = 7$

Chinese = $\sum(P_i) = (1 + 1 + 1 + 1 + 0.5 + 1 + 1 + 0.75) = 7.25$

IEC = $\sum(P_i) = (1 + 1 + 1 + 1 + 1 + 1 + 0.75 + 0.5) = 7.25$

AREMA = $\sum(P_i) = (0 + 1 + 1 + 1 + 0.5 + 1 + 1 + 0.25) = 5.75$