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INTERNATIONAL PRACTICES IN THE DIGITAL AUTOMATION OF RAILWAY TRACTION POWER SYSTEMS

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Abstract. Digital automation of railway traction power supply is promoted as a way to reduce energy use and improve supply quality, but the evidence behind reported benefits is heterogeneous: measured results, pilot data, simulations, manufacturer claims and policy targets are often cited together. The aim was to compare international practices in the digital automation of traction power systems critically and to assess the conditions for their transfer to Kazakhstan. A structured scoping review reported according to PRISMA-ScR was combined with a comparative multiple-case analysis. OpenAlex was searched on 10 October 2026 (2016–2026) with five strings, supplemented by operator and agency sources. 292 unique records were screened in two independent passes (Cohen’s kappa 0.70); 56 studies were included, together with 7 documents from other sources. Only 10 studies reported field implementation or field experiments, 46 relied on models or hardware-in-the-loop tests driven by measured data, and 41 used data from China; no field evidence on the cybersecurity of traction power control was found. Of six national cases, four (Spain, Japan, Russia, South Africa) report measured effects for reversible substations, wayside storage and protection data analytics; the Chinese field experiments are not quantified, the Swiss case reports no outcome, and evidence on flexible traction substations and digital twins is mainly model-based. The novelty is an explicit evidence hierarchy combined with a criteria-based transferability assessment for Kazakhstan; a proposed six-stage framework can guide pilot selection on KTZ lines. The main limitation is the use of one open index, with most studies assessed at abstract level.

Keywords: railway traction power supply; digital automation; regenerative braking; energy storage; SCADA; scoping review; Kazakhstan

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ТЕМІРЖОЛДЫҢ ТАРТЫМДЫҚ ЭНЕРГЕТИКАЛЫҚ ЖҮЙЕЛЕРІН ЦИФРЛЫҚ АВТОМАТТАНДЫРУДЫҢ ХАЛЫҚАРАЛЫҚ ТӘЖІРИБЕСІ

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Аннотация. Теміржолдың тартымдық электрмен жабдықтауын цифрлық автоматтандыру энергия тұтынуды азайту және электрмен жабдықтау сапасын арттыру құралы ретінде ұсынылады, алайда жарияланған нәтижелердің дәлелдік негізі біркелкі емес: өлшемдер, пилоттық деректер, модельдеу, өндірушілердің мәлімдемелері және мақсатты көрсеткіштер жиі қатар келтіріледі. Зерттеудің мақсаты – тартымдық энергетикалық жүйелерді цифрлық автоматтандырудың халықаралық тәжірибесін анықтау, оны сыни тұрғыдан салыстыру және Қазақстанға көшіру шарттарын бағалау. PRISMA-ScR талаптарына сәйкес баяндалған құрылымдалған ауқымдық шолу (scoping review) бірнеше кейсті салыстырмалы талдаумен біріктірілді. 2026 жылғы 10 қазанда OpenAlex индексында (2016–2026) бес сұраныспен іздеу жүргізіліп, операторлар мен органдардың дереккөздерімен толықтырылды. 292 бірегей жазба екі тәуелсіз кезеңде іріктелді (Коэн каппасы 0,70); 56 зерттеу енгізілді, оларға басқа көздерден алынған 7 құжат қосылды. Тек 10 зерттеу далалық енгізу немесе далалық эксперимент нәтижелерін ұсынды, 46 зерттеу өлшенген деректерге негізделген модельдерге немесе HIL-сынақтарға сүйенді, 41 зерттеу Қытай деректерін пайдаланды; тартымдық электрмен жабдықтауды басқарудың киберқауіпсіздігі бойынша далалық деректер табылмады. Алты ұлттық кейстің төртеуі (Испания, Жапония, Ресей, Оңтүстік Африка) реверсивті қосалқы станциялар, стационарлық энергия жинақтау жүйелері және релелік қорғаныс деректерін талдау бойынша өлшенген әсерлерді көрсетеді; Қытайдағы далалық эксперименттердің әсері сандық түрде берілмеген, Швейцария кейсінде нәтиже жарияланбаған, ал икемді тартымдық қосалқы станциялар мен цифрлық егіздер бойынша дәлелдер негізінен модельдеуге сүйенеді. Жаңалығы – дәлелдердің айқын иерархиясы мен Қазақстан үшін критерийлерге негізделген көшіру мүмкіндігін бағалау; ұсынылған алты кезеңді шеңбер ҚТЖ желілерінде пилоттық учаскені таңдауға бағдар бола алады. Негізгі шектеу – бір ашық индекс пайдаланылды, зерттеулердің көпшілігі аннотация деңгейінде бағаланды.

Түйін сөздер: теміржолдың тартымдық электрмен жабдықтауы; цифрлық автоматтандыру; рекуперативтік тежеу; энергия жинақтау жүйесі; SCADA; ауқымдық шолу; Қазақстан

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МЕЖДУНАРОДНЫЙ ОПЫТ ЦИФРОВОЙ АВТОМАТИЗАЦИИ ТЯГОВЫХ ЭНЕРГЕТИЧЕСКИХ СИСТЕМ ЖЕЛЕЗНОДОРОЖНОГО ТРАНСПОРТА

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Аннотация. Цифровая автоматизация тягового электроснабжения железных дорог рассматривается как способ снизить энергопотребление и повысить качество электроснабжения, однако доказательная база заявленных эффектов неоднородна: измерения, пилотные данные, моделирование, заявления производителей и целевые показатели нередко приводятся вместе. Цель исследования – выявить и критически сопоставить международную практику цифровой автоматизации тяговых энергетических систем и оценить условия её переноса в Казахстан. Структурированный скоупинг-обзор, оформленный по PRISMA-ScR, объединён со сравнительным анализом нескольких кейсов. Поиск в OpenAlex выполнен 10 октября 2026 г. (2016–2026 гг.) по пяти запросам и дополнен источниками операторов и ведомств. 292 уникальные записи отобраны в два независимых прохода (каппа Коэна 0,70); включены 56 исследований, к ним добавлены 7 документов из других источников. Лишь 10 исследований сообщают о полевом внедрении или полевых экспериментах, 46 основаны на моделях или НЛ-испытаниях с использованием измеренных данных, 41 использует данные Китая; полевых данных о кибербезопасности управления тяговым электроснабжением не обнаружено. Из шести национальных кейсов четыре (Испания, Япония, Россия, ЮАР) показывают измеренные эффекты для реверсивных подстанций, стационарных накопителей энергии и анализа данных релейной защиты; эффекты полевых экспериментов в Китае количественно не приведены, по Швейцарии результаты не опубликованы, а доказательства по гибким тяговым подстанциям и цифровым двойникам в основном модельные. Новизна состоит в явной иерархии доказательств и критериальной оценке переносимости для Казахстана; предложенная шестиэтапная схема может использоваться при выборе пилотного участка на линиях КТЖ. Основное ограничение – использован один открытый индекс, большинство исследований оценено на уровне аннотаций.

Ключевые слова: тяговое электроснабжение железных дорог; цифровая автоматизация; рекуперативное торможение; накопители энергии; SCADA; скоупинг-обзор; Казахстан

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Introduction.

Railway traction power supply is changing from a passive, grid-fed infrastructure into an actively controlled energy system with storage, power-electronic converters and local generation (Li, 2026). The main technical driver is regenerative braking. Energy that cannot be absorbed by other trains or returned to the grid is dissipated in braking resistors (Khodaparastan et al., 2019:

2831–2847). Timetable coordination, on-board and wayside storage and reversible substations have been proposed to recover it (González-Gil et al., 2013: 374–388), and the choice of storage technology depends on whether it is installed on board or at the wayside (Domínguez et al., 2025).

Published claims about these options mix measured operational results, pilot data, simulations, manufacturers' statements, policy targets and projections, and a percentage reported for one line cannot be converted into an expected effect for another network. Comparisons that keep the type of evidence visible are therefore needed, including in Kazakhstan. The operational length of the national network was 16,005 route-km at the end of 2023, and more than a fifth of the approximately 21,000 track-km is electrified (AIIB, 2026). Kazakhstan Temir Zholy (KTZ) reports 4,237 km of electrified sections; after the replacement of the Lisna telemetry system by the AMT system, telemetry control of dispatch circles will cover 2,448 km of them, and similar work is planned on further power supply sections by 2029 (KTZ, 2025). The split of the network between direct-current (DC) and alternating-current (AC) traction could not be confirmed from an official source during this study, so transferability is assessed conditionally for both systems.

The aim of this study was to identify, compare and critically assess international practices in the digital automation of railway traction power systems and to determine which technical and institutional elements may be transferable to Kazakhstan. The research question was: which digital automation technologies have been implemented in international railway traction power systems, what verifiable outcomes have been reported, and under what conditions could these practices be transferred to Kazakhstan? The object is foreign digital control of traction power; the subject is its technologies, outcomes and conditions of transfer. The analytical proposition was that the strength of evidence differs more between technologies than between countries, and that transferability depends mainly on the electrification system and on the digital readiness of substations.

Reviews of regenerative braking energy group recovery methods into operational measures (timetable and driving), storage on board or at the wayside, and reversible substations that return energy to the public grid (González-Gil et al., 2013: 374–388; Khodaparastan et al., 2019: 2831–2847). A recent review of railway storage finds supercapacitors and lithium-ion batteries viable on board and recommends supercapacitors and flywheels for wayside use (Domínguez et al., 2025). A 2026 review of distributed photovoltaic and storage integration distinguishes substation-side, wayside-distributed and hybrid multi-port schemes and argues that single-phase, highly dynamic traction loads and strict voltage and protection constraints make energy management of traction systems distinct from that of conventional microgrids (Li, 2026).

Monitoring and digital-twin research forms a second stream. A systematic review of railway digital twins covering 91 papers addresses four primary subsystems of the railway (Thompson et al., 2025: 238–250). These reviews are organised by technology rather than by the strength of field evidence.

The third stream concerns communication and security. Communication for power utility automation is standardised in the IEC 61850 series (IEC, 2026). Railway-specific cybersecurity requirements are set out in CLC/TS 50701:2023 (CENELEC, 2023). A 2026 systematic review of cybersecurity in intelligent railway systems maps research trends and challenges at system level (Abukeshek et al., 2026). Russian-language work on the digital traction substation describes digital substations based on IEC 61850 and a pilot project for a digital traction substation at Inskaya station commissioned in 2020 (Ryzhova, 2023: 15–31).

None of the reviews identified here compares national cases with an explicit grading of evidence types or assesses transferability to a 1,520 mm network such as that of Kazakhstan.

Materials and Methods.

The study combined a structured scoping review with a comparative multiple-case analysis. The review followed the methodological framework for scoping studies (Arksey, O'Malley, 2005: 19–32) and was reported according to the PRISMA extension for scoping reviews, PRISMA-ScR (Tricco et al., 2018: 467–473). The term systematic review is not used, because no protocol was registered and most studies were charted from abstracts.

The database search was run in the open bibliographic index OpenAlex on 10 October 2026. OpenAlex allows the query, filters and results to be reproduced without subscription access. The search covered titles and abstracts, publication dates from 1 January 2016 to 10 October 2026, and the document types article and review; no language filter was applied. Five strings combined traction-power terms with terms for storage and regenerative energy (S1), substation automation and SCADA (S2), monitoring and digital twins (S3), energy management, metering and microgrids (S4) and cybersecurity (S5); the full Boolean strings are given in Supplementary file S1.

Other sources were identified by targeted searches of operator and agency websites (RFI, JR East, the Swiss Federal Office of Energy, CORDIS) and by citation tracking.

Eligibility was defined by population, concept and evidence. The population was the fixed installations of electrified heavy rail, metro and light rail. The concept was one of the technologies of digital automation at the level of the traction power system: energy storage, reversible substations and control or energy management of storage and converters; railway microgrids and renewable integration; protection, SCADA and condition monitoring; smart metering; digital twins and state estimation; load forecasting; or cybersecurity of power-supply control. The evidence criterion required an outcome from an identified real system, either from field implementation or a field experiment, or from a model or hardware-in-the-loop (HIL) test driven by or validated against measured data from that system.

Records were excluded for five reasons: E1, not a railway traction fixed installation or transport mode unclear; E2, no data from an identifiable real system (synthetic simulation or concept only); E3, outside the concept (power-electronic topology without an automation function, train-operation optimisation, signalling, rolling stock, or mechanical inspection of the catenary); E4, incomplete bibliographic record without DOI or identifiable venue; E5, retracted publication. Mechanical and image-based catenary inspection was excluded because it addresses geometry rather than control of the electrical system. Reviews were retained as background only.

Titles and abstracts were screened in two independent, AI-assisted passes, with final decisions verified by the authors. The first pass used an automated flag for evidence terms (for example, measured, field, in service); the second, blind to the first, read every full abstract. Disagreements were arbitrated against the protocol. Full texts were sought for field-implementation studies and for all sources used to define national cases. Charted fields included country, system, electrification, technology, scale, evidence type, reported outcomes with units and their location in the source, validation and reading level.

Six evidence types were distinguished and not combined: measured operational results; pilot or field-experiment results; simulation or HIL results driven by measured data; manufacturer claims; policy targets; and projected benefits. Case-defining sources were appraised against five criteria: the system is identified; data provenance is stated; a baseline is reported; validation is described; and the authors are independent of the operator and the supplier. Evidence quality was rated high (at least four criteria met), moderate (three) or low (two or fewer). The full screening log, extraction sheet and appraisal are provided as Supplementary file S1.

A country was treated as a national case if at least one included source identified a real system and reported quantified measured operational or field-experiment results, or if an official operator or agency document described an operational system. Countries represented only by model-based or projected evidence were used as supporting evidence.

Transferability was assessed against fourteen criteria for Kazakhstan, grouped into four domains: technical compatibility (electrification system and voltage, condition of substations, compatibility with existing SCADA, interoperability, communication coverage); geography and environment (gauge, climate, distance between facilities); institutions (regulation including grid-code rules for reverse power flow and tariffs, cybersecurity readiness, technical workforce,

maintenance capacity, capital costs); and data availability (including traffic and substation load data). The resulting matrix is given in Supplementary file S1. Each criterion was recorded as supported by official Kazakhstani evidence, contradicted or unknown; no numerical weights were assigned, because no expert survey was conducted. Synthesis was narrative with frequency counts; effect sizes were not pooled because the metrics are not commensurable.

Results.

The five strings returned 310 records (S1, 45; S2, 13; S3, 127; S4, 118; S5, 7). After removal of 18 duplicates, 292 records were screened. The two passes agreed on 267 of them (91.4%; Cohen's $\kappa = 0.70$); 25 disagreements were arbitrated, of which 15 led to inclusion and 2 to exclusion of records first retained. In total, 235 records were excluded (E1, 32; E2, 103; E3, 81; E5, 1; reviews, 18). Of the 57 records assessed for eligibility, full texts were retrieved for 5; the remaining 52 were assessed on abstract and bibliographic metadata. One study was excluded because it described an implemented monitoring system without outcome data. In total, 56 database studies and 7 documents from other sources were included (Figure 1); all 63 are listed in Supplementary file S1.

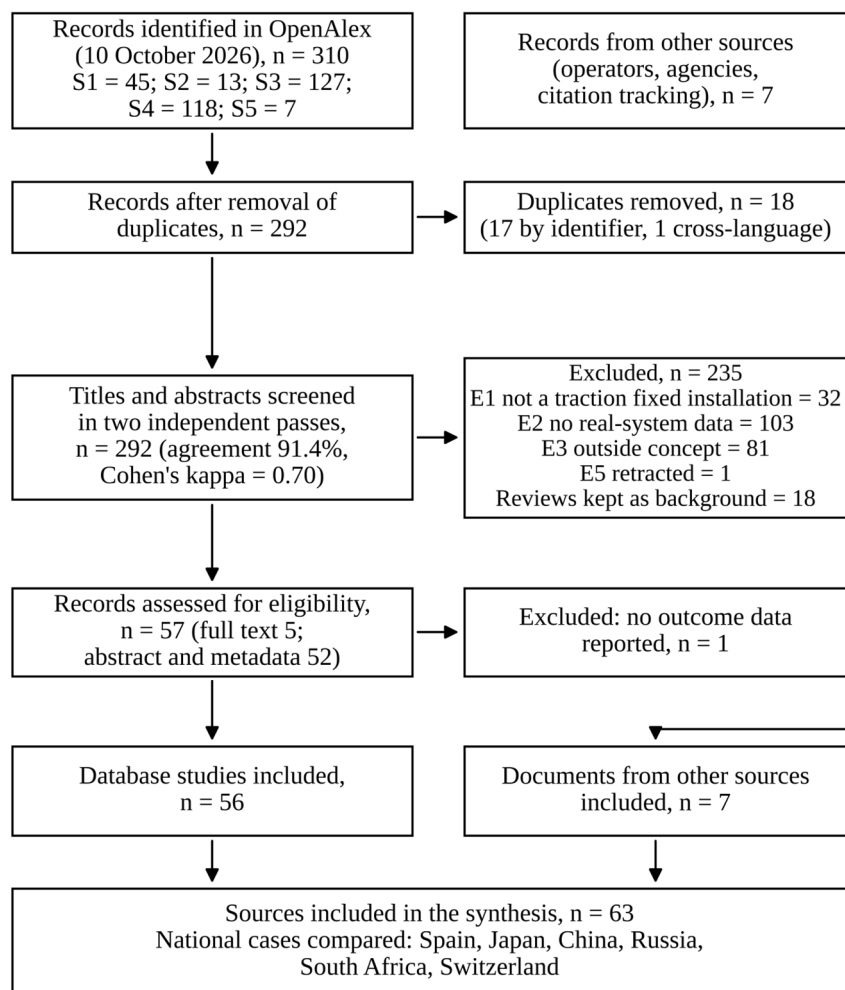


Fig. 1. PRISMA-ScR flow of source selection

Of the 56 database studies, 48 were published from 2021 onwards (by OpenAlex publication year). By country of data, or of author affiliation where the system was not named, 41 studies came from China, three from Poland and two from Russia; Croatia, France, Italy, Morocco, Romania, South Africa, Ukraine, the United Kingdom and Viet Nam contributed one each, and one study could not be assigned. AC systems were studied in 33 studies (including one dual AC/DC system) and DC systems in 18; in five the electrification was not stated or not applicable.

Only 10 studies reported field implementation or field experiments; 46 relied on models or HIL tests driven by measured data. Storage, energy management and converter control dominated (45 studies), while protection, monitoring and SCADA (4), digital twins and state estimation (4), load forecasting (2) and smart metering (1) were rare. The cybersecurity string returned 7 records, none of which was included; one dataset from a traction substation was excluded because the installation was not identified as an operating system. No included study reported field evidence on the cybersecurity of traction power control.

Six national cases met the selection rule: Spain, Japan, China, Russia, South Africa and Switzerland. Their evidence is summarised in Table 1 and described below.

Table 1 – Evidence for the six national cases

Country	System	Technology	Scale	Reported outcome	Evidence quality	Transferability to Kazakhstan	Limitations
Spain (Cascetta et al., 2021)	Metro de Madrid line 10B, 1500 V DC	Reversible substation: 2 MVA DC/AC converter in anti-parallel with 3 MVA rectifier	1 substation; 1 train; 18 days; about 6,951 braking events	On-board dissipated energy 202 → 159 kWh (−21.4%)	Measured operational; peer-reviewed; high (4/5)	Conditional: DC sections; requires permission for reverse power flow	One line; short campaign; converter below rated use
Japan (Sekijima et al., 2019)	JR East DC sections; Joban Line (Ushiku)	Wayside battery storage; power interchange device; station demand response	2 storage sites; 1 sectioning post	About 400 MWh/yr (4%) and 750 MWh/yr (8%) discharged; about 2,500 MWh/yr regenerative energy used; peak −3–12% in verification tests	Measured operational; operator report; low (2/5)	Conditional: storage on DC, interchange device on AC sections	Not peer-reviewed; baseline method not stated
China (Li et al., 2021; Liu et al., 2021; Wu, Wu, 2024)	Ningbo Metro Line 4; Beijing Batong line; AC sections	Converter energy management over 4G; fuzzy-logic storage control; power conditioner between sections	6.4 MW field test; 6 field studies; 35 model studies	Field effects not quantified in abstracts; more than half of regenerative energy can be used in adjacent sections (authors)	Field experiment; model with measured data; abstract level; low	Conditional to low: needs converter-based substations and data links	Abstract-level data; Ningbo study authored mainly by a supplier
Russia (Shevlyugin et al., 2017)	Moscow metro Filevskaya line, substations T-23 and T-24 (DC)	Uncontrolled supercapacitor storage on substation buses	In service since 2014; several months of measurement	Peak power −13.4%; peak current 7 → 5.5 kA; energy saving 0.5–2.5% (winter), 5.6% (spring)	Measured operational; peer-reviewed; high (4/5)	Conditional: DC sections; no control software required	Small, seasonal savings; one line
South Africa (Moyo et al., 2021)	Gautrain, 2 × 25 kV autotransformer system	Protection IEDs with disturbance recorders; SCADA links	5 substations	Test trip times 42.4–62.0 ms above settings; recorded trip times up to 100 ms above test times	Measured operational and on-site tests; high (4/5)	Conditional: AC sections; consistent with KTZ telemetry renewal	No energy outcomes; one system
Switzerland (SFOE, 2021)	SBB, 16.7 Hz network	Digital load management by short shedding of heating loads	About half of rolling stock; target ≥ 70 MW	No measured outcome published	Operational deployment and target; low (1/5)	Insufficient data: tariff structure in Kazakhstan unknown	No outcome data

Spain. On line 10B of the Madrid metro (1500 V DC, about 15 km, 11 stations), a 2 MVA DC/AC converter was installed in anti-parallel with the 3 MVA rectifier of the La Moraleja

substation. On-board measurements on one train during 18 days of commercial service from October 2019, covering about 6,951 braking events, showed that energy dissipated in on-board resistors fell from 202 kWh in conventional mode to 159 kWh in reversible mode, a reduction of 21.4 % (Cascetta et al., 2021). The converter operated below capacity because grid injection was not yet permitted (Cascetta et al., 2021).

Japan. The East Japan Railway Company reports annual discharged energy of about 400 MWh, about 4% of feeding energy, for the battery storage at Haijima substation, and about 750 MWh, about 8%, at Okegawa substation (Sekijima et al., 2019: 18). A power interchange device at the Ushiku sectioning post on the Joban Line, in full operation since April 2015, made about 2,500 MWh of regenerative energy usable per year (Sekijima et al., 2019: 19). In verification tests, demand response reduced peak power by 3–12% at single stations (Sekijima et al., 2019: 22). The storage and interchange-device figures are measured operational results, but they are published by the operator itself and not peer-reviewed.

China. Six studies reported field-level evidence. A converter-based energy management system linked trains, ground bidirectional converters and a supervisory level over 4G communication and was tested at full power scale (6.4 MW) on Ningbo Metro Line 4 (Li et al., 2021: 798–807). A fuzzy-logic energy management strategy that adapts the charge and discharge thresholds of a ground storage system was tested in the field on the Beijing Batong line (Liu et al., 2021: 9945–9956). For a regenerative braking power conditioner between adjacent AC power sections, the authors report a case study and an engineering application and state that more than half of the regenerative energy can be utilised in adjacent sections (Wu, Wu, 2024: 174–184). Three further field studies cover storage control on a metro main track, short-circuit capacity identification and a maintenance platform on the Wuhan–Guangzhou line (Supplementary file S1). The other 35 Chinese studies used measured load data in models or HIL tests, for example on the Beijing–Shanghai high-speed line (Ying et al., 2021: 64127–64141) and the Lanzhou–Xinjiang line (Wang et al., 2023). The abstracts of the field studies do not quantify energy savings.

Russia. On the Filevskaya line of the Moscow metro, an uncontrolled supercapacitor storage system connected directly to the buses of traction substations has been in regular operation since January 2014 (Shevlyugin et al., 2017: 81). Measurements showed a reduction in peak substation power of about 13.4%, a fall in peak current from 7 kA to 5.5 kA, and traction energy savings of 0.5–2.5% in winter and 5.6% in spring (Shevlyugin et al., 2017: 81–82). Russian research also reports a digital-twin method for identifying load-capacity violations on DC lines, using operational indicators recorded during transport operations and test runs (Garanin et al., 2026: 100–109).

South Africa. On the Gautrain 2×25 kV autotransformer system, disturbance records from protection intelligent electronic devices (IEDs), linked to SCADA, were analysed together with on-site primary-injection tests (Moyo et al., 2021: 5704–5713). In the tests, relay trip times exceeded the settings by 42.4–62.0 ms, and the disturbance records showed trip times up to 100 ms longer than in the tests; a fibre break was located 6,100 m from a substation.

Switzerland. On the 16.7 Hz traction network of Swiss Federal Railways (SBB), digital load management switches off train and points heating for seconds to about a minute at peaks. About half of the rolling stock is available for this purpose, and the stated target was at least 70 MW of flexible load by 2023; demand can swing by up to 300 MW within 15 minutes (SFOE, 2021). No measured outcome has been published.

Other countries provided unquantified field implementations (smart metering in Ukraine, remote SCADA access in Romania; Supplementary file S1) or model-based, pilot or projected evidence. A Polish study sized hybrid storage for a 3 kV DC substation with a model checked against one year of 15-minute data (average daily energy 31.00 MWh simulated against 34.46 MWh measured) (Szeląg et al., 2025). In Viet Nam, a hybrid digital twin reconstructed second-level substation power from SCADA readings logged every 3–5 minutes on the 750 V DC Cat

Linh–Ha Dong line, in a simulation validated against SCADA data (Tran, An, 2026: 983–993). Rete Ferroviaria Italiana projected savings of 100 MWh per year, or 10–15% of a substation's consumption, from a 3 kV DC braking-energy recovery prototype at Forlì (RFI, 2021). In the European IN2STEMPO project, tests at a 16.7 Hz 110 kV switchgear station of DB Energie showed that 50 Hz merging units can be adapted to a 16.7 Hz environment, but no quantified operational results were reported, so Germany was not treated as a national case (CORDIS, 2024).

Measured effects exist for reversible substations, wayside storage and protection data analytics; evidence for flexible traction substations, reinforcement-learning energy management and digital twins remains largely model-based; and reported magnitudes use incompatible metrics, so the figures in Table 1 cannot be ranked or transferred.

Discussion.

The data are consistent with the analytical proposition: evidence strength followed the technology more than the country, since China contributed both field experiments and model-based studies, while reversible substations and wayside storage had measured results in three countries. The Chinese evidence (41 of 56 studies) was assessed at abstract level and has not been independently replicated, and the Japanese case rests on one operator report that is not peer-reviewed.

Table 2 applies the transferability criteria to five technology groups. The criteria supported by official Kazakhstani evidence are few: the construction of new lines to the 1,520 mm broad gauge standard (AIIB, 2026), the length of the electrified network and the planned extension of telemetry (KTZ, 2025). Other critical criteria could not be confirmed from official sources, so all five groups are at most conditionally transferable.

Table 2 – Transferability of technology groups to Kazakhstan.

Technology group	Strongest evidence (type, case)	Kazakhstani criteria supported by official evidence	Critical criteria unknown	Assessment
A. Monitoring and telecontrol from IED and SCADA data	Measured operational (South Africa); field implementation (China, Wuhan–Guangzhou line); demonstration (Germany, IN2STEMPO)	Telemetry renewal planned to cover 2,448 of 4,237 km of electrified sections (KTZ, 2025)	Condition of substations; SCADA protocols; communication coverage; cybersecurity readiness	Conditional; candidate for early pilot
B. Wayside storage with rule-based or fuzzy control	Measured operational (Japan, Russia); field experiment (China, Batong)	Length of electrified network (KTZ, 2025)	Electrification system by section; data availability (traffic, substation load)	Conditional; candidate for a DC pilot
C. Reversible substations and energy feedback	Measured operational (Spain); projection (Italy)	None identified	Regulation (grid code for reverse power flow; tariffs)	Conditional on regulation
D. Converter-based energy management, flexible and co-phase substations	Field experiment (China, Ningbo); otherwise models with measured data	None identified	Condition of substations; data availability; technical workforce; capital costs	Low at present
E. Load management and demand response	Operational deployment without outcomes (Switzerland); measured at stations (Japan)	None identified	Regulation (tariff structure); data availability (controllable loads)	Insufficient data

Note: climate and distances between facilities were not assessed with official data for any group.

Two groups appear most suitable for early piloting: monitoring and telecontrol based on IED and SCADA data, because KTZ is already modernising telemetry and no reverse power flow is required; and wayside storage with rule-based or fuzzy control on a DC section, because

Moscow, Japan and Beijing provide measured or field-tested results. Reversible substations depend on permission to inject energy into the public grid, which limited the Madrid converter (Cascetta et al., 2021). Flexible substations and learning-based energy management need converter-based substations and data infrastructure not yet documented in Kazakhstan, and their evidence is mostly model-based.

Based on these findings, a six-stage framework is proposed (Figure 2) as a basis for discussion, not as an implemented or approved programme. It moves from a digital audit and a measured baseline of at least one year on one pilot section, so that seasonal variation of the kind reported in Moscow is captured, through SCADA and monitoring integration under IEC 61850 and CLC/TS 50701, to energy management, forecasting and a calibrated digital twin, and ends with an independent evaluation before any scaling. Each decision gate uses measured results from the pilot section rather than results reported for other networks.

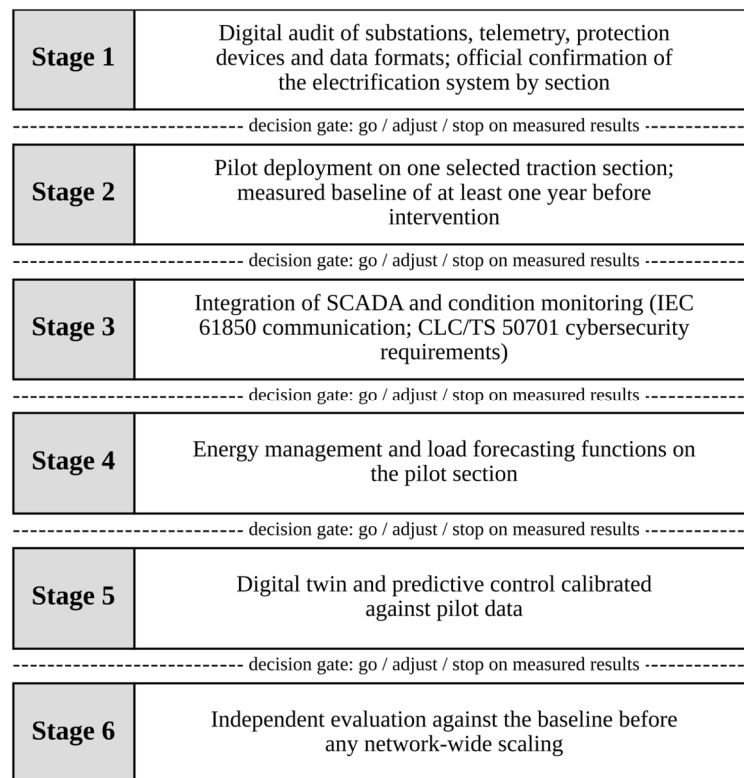


Fig. 2. Proposed phased framework for digital automation of traction power supply in Kazakhstan

The search used one open index; Scopus, Web of Science and IEEE Xplore were not searched directly, so relevant records may have been missed. Screening used two passes, but charting and appraisal one. Full texts were retrieved for only 5 of the 57 records assessed for eligibility, so quantitative outcomes of the Chinese field studies could not be extracted. Official Kazakhstani data on electrification systems, substation condition and SCADA were not available, and no cost data were analysed.

Conclusion.

Measured operational evidence exists for reversible substations (Spain), wayside storage (Japan and Russia) and protection-device data (South Africa); China provides field experiments on converter-based energy management and adaptive storage control. Flexible substations, learning-based energy management and digital twins rest mainly on models, and no field evidence on the cybersecurity of traction power control was found.

For Kazakhstan, the available evidence is consistent with a staged approach that starts with a digital audit and a measured baseline, then pilots monitoring and telecontrol functions and, on a suitable DC section, wayside storage with transparent control rules. Transferability depends on

information that is not yet publicly available, above all the electrification system by section, the condition and communication capability of substations, and the grid-code rules for reverse power flow. Further work should obtain these data from KTZ, repeat the search in subscription databases and evaluate a pilot against a measured baseline.

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