

Digital transformation of education in Kryvyi Rih, Ukraine (2019–2025): a multi-framework comparative analysis of infrastructure development and digital learning ecosystems

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Abstract. Wartime digitization in Kryvyi Rih, Ukraine (2019–2025), reveals extensions to established education technology frameworks. Documentary analysis maps infrastructure deployment (11,614 Chromebooks, 150 Starlink units, universal xPON connectivity) and digital ecosystem development (Educational Portal with 15,409 publications, 100% electronic journal adoption) against EU Digital Education Action Plan and UNESCO ICT Competency Framework indicators. Results show infrastructure investment with connectivity resilience unique to conflict contexts, but reveal limitations in applying standard frameworks to war-affected settings: device ratios remain below targets, and no outcome data link inputs to learning improvements. The case identifies boundary conditions for framework transferability and proposes resilience indicators missing from existing models.

Keywords: digital transformation, education digitization, EU Digital Education Action Plan, UNESCO ICT Competency Framework, digital infrastructure, learning ecosystems, STEM education, Ukraine

1. Introduction

Education systems worldwide have adopted digital technologies at varying paces over the past two decades, with the COVID-19 pandemic creating unprecedented pressure for rapid adoption. The EU Digital Education Action Plan (2021–2027) sets out two strategic priorities: developing digital education ecosystems and building digital skills [1]. UNESCO’s ICT Competency Framework defines progression levels for teacher digital competence [13]. These policy frameworks, while designed for EU member states, provide comparison points for assessing digitization in other contexts.

Ukraine presents a notable case for studying education digitization. The combination of pre-existing modernization efforts, pandemic-driven acceleration, and the challenges of wartime continuity creates a unique context for understanding how digital infrastructure and learning ecosystems develop under extreme conditions [10]. Within Ukraine, Kryvyi Rih, a major industrial city of approximately 650,000 residents, offers an instructive example of city-wide education digitization implemented systematically over a six-year period (2019–2025).

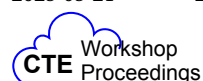
Our research addresses a gap in the literature: the absence of documented case studies analyzing education digitization journeys in Eastern European transition economies. While numerous studies examine individual components of digital education (device deployment, platform adoption, teacher training), few provide integrated analysis of infrastructure, ecosystems, and human capacity development [7]. The Ukrainian context, with its EU aspirations and ongoing conflict, adds dimensions rarely captured in digitization research.

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The research questions guiding this study are:

1. How does Kryvyi Rih’s digital education infrastructure development compare to international benchmarks established by the EU Digital Education Action Plan?
2. What level of maturity has the digital learning ecosystem achieved according to UNESCO ICT Competency Framework indicators?
3. What transferable lessons emerge from this city-wide digitization case study for similar contexts?

The article makes three contributions. First, it documents framework extensions required for conflict contexts: resilience indicators (backup connectivity), crisis-adapted competency assessment, and boundary conditions for transferability. Second, it identifies limitations in existing frameworks: EU benchmarks lack resilience provisions, and UNESCO competency levels insufficiently capture innovation under resource scarcity. Third, it proposes testable propositions for comparative research on digitization under disruption.

The paper is structured as follows. Section 2 synthesizes literature on infrastructure-pedagogy relationships, wartime adaptation, and framework applications. Section 3 presents the theoretical framework with critique for conflict contexts. Section 4 describes the documentary analysis methodology. Section 5 outlines case context. Sections 6 and 7 analyze infrastructure and digital learning ecosystems. Section 8 examines teacher competence. Section 9 synthesizes findings. Section 10 discusses implications, and section 11 concludes.

2. Literature review

This review synthesizes three themes: infrastructure-to-pedagogy pipeline, wartime digital adaptation, and framework applications in non-EU contexts. Table 1 summarizes key studies and their contributions.

Table 1

Literature synthesis: key themes and studies.

Theme	Key studies	Findings	Gap addressed
Infrastructure-pedagogy	Mårell-Olsson and Bergström [6], Tupag and Ubayubay [12]	Infrastructure alone insufficient; leadership and pedagogy essential	Input-output gap
Wartime adaptation	Galynska and Bilous [5], Shparyk [10], Stukalo [11]	Continuity through platforms; resilience under disruption	Conflict context
Framework applications	Bitegeko, Lawrent and Cosmas [2], Mtebe [9]	UNESCO framework adaptable; limited conflict guidance	Non-EU validation

2.1. Theme 1: Infrastructure-to-pedagogy pipeline

The relationship between technology deployment and educational improvement remains contested. EU policy frameworks emphasize ecosystem development (connectivity, equipment, platforms, teacher competence) as interconnected elements [4, 14]. Mihovska et al. [7] argue that successful implementations require simultaneous attention to multiple components rather than sequential development. However, this “ecosystem” approach presumes stable conditions and sustained investment.

Teacher competence mediates infrastructure impact. Moreira, Nunes and Casanova [8] find significant variation in digital competence among Portuguese teachers, suggesting that device provision alone does not ensure effective integration. Mårell-Olsson and Bergström [6] demonstrate that organizational leadership – not just hardware – enables transformation in Swedish schools. Tupag

and Ubayubay [12] show that schools' digital capacity depends on pedagogical practices that leverage technology, not merely infrastructure availability.

A contradiction emerges: policy frameworks (EU DEAP, UNESCO) emphasize ecosystem development, but research consistently shows that teacher competence and leadership matter more than device ratios. The Kryvyi Rih case can address this contradiction by examining whether training completion (93%) translates into classroom integration in a context where device access remains limited (1:8.4 ratio).

2.2. Theme 2: Wartime digital adaptation

Ukrainian education digitization accelerated under two pressures: COVID-19 pandemic (2020–2021) and full-scale invasion (2022–present). Cone et al. [3] term this “pandemic acceleration” – rapid adoption that both advanced and stressed existing capacity. Stukalo [11] identifies systemic gaps in Ukrainian remote education preparedness revealed by the pandemic transition.

Wartime conditions introduce distinct challenges. Shparyk [10] documents how Ukrainian schools maintained continuity through digital platforms despite infrastructure damage. Galynska and Bilous [5] analyze higher education adaptation to disrupted conditions. These studies reveal resilience mechanisms absent from standard framework discussions: backup connectivity, asynchronous resource development, psychosocial support.

The literature gap: existing studies document wartime adaptation but do not systematically compare against peacetime frameworks. The Kryvyi Rih case offers opportunity to identify framework extensions required for conflict contexts – resilience indicators, crisis-adapted competencies, and boundary conditions for transferability.

2.3. Theme 3: Framework applications in non-EU contexts

UNESCO's ICT Competency Framework [13] provides assessment levels (Technology Literacy, Knowledge Deepening, Knowledge Creation) designed for diverse contexts. Mtebe [9] applies it in Tanzania, demonstrating adaptability to resource-constrained settings. Bitegeko, Lawrent and Cosmas [2] extend analysis to undergraduate teacher education, validating the framework beyond in-service teachers.

However, framework applications in conflict-affected settings remain limited. EU Digital Education Action Plan targets assume functioning governance, reliable infrastructure, and policy continuity – conditions disrupted in wartime. The Ukrainian case can test framework applicability: Do standard competency levels capture innovation under resource scarcity and air-raid disruptions? Do EU benchmarks account for resilience investments like Starlink backup?

This review positions Kryvyi Rih not merely as “an undocumented case” but as an opportunity to extend frameworks for conflict contexts, identify infrastructure-pedagogy gaps in resource-limited settings, and contribute to wartime digitization literature beyond the Ukrainian context.

3. Theoretical framework

A multi-framework comparative approach combines the EU Digital Education Action Plan (2021–2027) and UNESCO ICT Competency Framework for Teachers. The integration of these frameworks enables assessment across policy, infrastructure, and human capacity dimensions.

The EU Digital Education Action Plan establishes two strategic priorities for member states and partner countries [4]:

Priority 1. A high-performing digital education ecosystem encompasses connectivity infrastructure, digital equipment, organizational capacity, and digital governance through Actions 1–5: strategic leadership, connectivity and equipment provision, capacity building, EU Code Week initiatives, and digital transformation planning.

Priority 2. *Digital skills and competences for digital transformation* addresses digital literacy, advanced digital skills, and teacher competence through Actions 6–13, covering citizen skills, labor market needs, teacher training, education leadership, gender equity, inclusion, and pandemic support.

For this analysis, we focus on Actions 2, 3, 8, and 13 as most relevant to infrastructure deployment, capacity building, and teacher development in a city-wide digitization context.

The UNESCO ICT Competency Framework offers a structured approach to assessing and developing teacher digital competence across three progressive levels [13]:

1. *Technology literacy level*: Basic ability to use digital tools for administrative efficiency and standard pedagogical tasks. Teachers can operate devices, access information, and communicate digitally.
2. *Knowledge deepening level*: Application of technology to support deeper understanding of subject matter. Teachers integrate digital tools into curriculum design, use technology for knowledge creation, and guide students in technology-enhanced inquiry.
3. *Knowledge creation level*: Advanced competence enabling teachers to design innovative learning experiences, create digital content, and lead colleagues in technology integration. Teachers exhibit professional leadership in digital pedagogy.

Each level is assessed across six aspects: (1) understanding ICT in education policy, (2) curriculum and assessment, (3) pedagogy, (4) ICT tools and digital resources, (5) organization and administration, and (6) teacher professional learning.

The analysis maps Kryvyi Rih data points against both frameworks (figure 1), creating an integration matrix for benchmark comparison (quantitative metrics against EU targets), maturity assessment (UNESCO competency level classification), gap identification (areas requiring investment), and context integration (unique factors affecting framework applicability).

This multi-framework approach addresses limitations of single-framework analyses. The EU Action Plan offers policy-oriented benchmarks for infrastructure and governance, while the UNESCO Framework enables granular assessment of human capacity development.

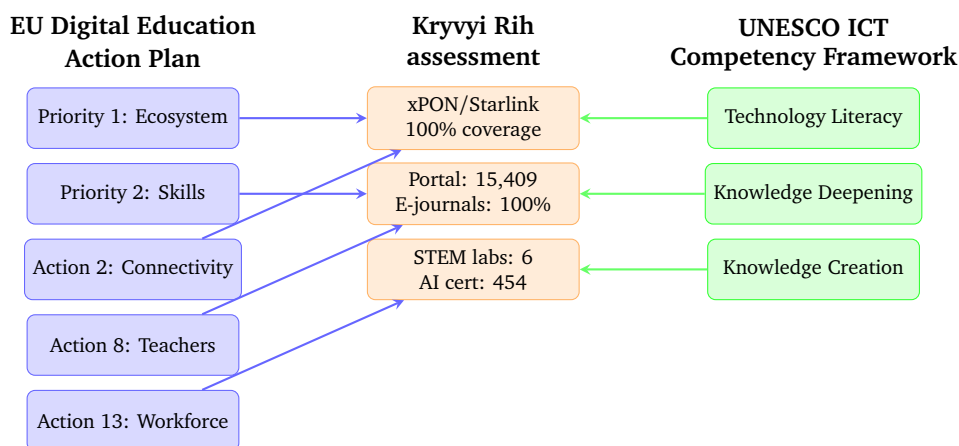


Figure 1: Multi-framework integration: EU Digital Education Action Plan and UNESCO ICT Competency Framework applied to Kryvyi Rih assessment.

Both frameworks were designed for stable contexts and may insufficiently capture wartime digitization dynamics. The EU Action Plan assumes functioning infrastructure and governance without disruption; it lacks indicators for resilience measures (backup connectivity, power outage adaptation). UNESCO competency levels emphasize classroom integration and content creation but do not address learning under air-raid interruptions or asynchronous resource development for crisis conditions.

For this analysis, we identify framework extensions: (1) resilience indicators (backup connectivity, device accessibility during disruptions) that extend EU Priority 1; (2) crisis-adapted competency assessment that recognizes innovation under resource scarcity; and (3) boundary conditions identifying when standard frameworks transfer to conflict-affected settings. These extensions inform the analysis and discussion sections below.

4. Methodology

This study employs documentary analysis and comparative assessment to examine Kryvyi Rih's education digitization. The approach extracts quantitative metrics from municipal reports and compares them against international framework benchmarks. No primary data collection (surveys, interviews, observations) was conducted; the analysis relies entirely on existing documents.

Table 2 summarizes sources, their content, limitations, and verification attempts.

Table 2

Data sources, limitations, and verification.

Source type	Content	Limitations	Verification
Municipal reports	Infrastructure statistics, platform metrics, training numbers	Self-reported data; potential social desirability bias	Cross-referenced multiple departmental documents
EU framework docs	DEAP priorities, targets, monitoring indicators	Designed for EU members; may not fit Ukrainian context	Compared with official 2023–2024 monitoring reports
UNESCO framework	Competency levels, assessment indicators	Generic framework; limited conflict-context guidance	Cross-referenced with Tanzania case study
Academic literature	Digital education research, Ukrainian context	Limited English-language sources on Ukraine	Systematic database search

Primary sources: Kryvyi Rih Department of Education and Science documents (2019–2025): annual reports, infrastructure deployment statistics, platform usage metrics, training program records, and electronic journal adoption data.

Benchmark sources: EU Digital Education Action Plan official documentation, UNESCO ICT Competency Framework specifications, and EU progress reports.

Contextual sources: Academic literature on digital education transformation, Ukrainian education context, and teacher digital competence frameworks.

The analysis proceeded in three stages. First, extraction of quantitative metrics from municipal reports: deployment counts, adoption rates, participation numbers. Second, mapping of these metrics to EU and UNESCO framework indicators. Third, gap identification through comparison with stated targets and international benchmarks.

Both authors are affiliated with Kryvyi Rih State Pedagogical University, and the second author is affiliated with Department of Education and Science of the Executive Committee of the Kryvyi Rih City Council. This insider position provides access to municipal data and contextual understanding but risks confirmation bias toward a “success narrative”. We attempted to mitigate this through systematic framework application, explicit gap identification, and acknowledgment of data limitations. However, readers should interpret findings with awareness of our institutional affiliation and the self-reported nature of primary sources.

Several constraints affect findings. First, the single case design limits generalizability. Second, reliance on municipal self-reports without independent verification creates potential bias. Third, no outcome data (student achievement, teacher effectiveness, learning quality) were available; the analysis documents inputs and outputs but cannot assess educational impact. Fourth, war conditions

and industrial city characteristics create unique contextual factors. Fifth, benchmark comparison is constrained by limited comparable data from peer cities or Ukrainian national aggregates.

5. Case context: Kryvyi Rih

Kryvyi Rih (population approximately 650,000) is Ukraine's eighth-largest city and a major industrial center in Dnipropetrovsk Oblast. Known primarily for iron ore mining and metallurgy, the city hosts significant extractive and processing industries that shape both its economy and workforce development needs. This industrial heritage has implications for education digitization: technical traditions, infrastructure capabilities, and specific STEM emphasis.

The municipal education system encompasses 371 educational institutions: 152 preschools, 125 general secondary schools, 12 vocational-technical institutions, 14 professional pre-higher education institutions, 5 higher education institutions, 30 extracurricular institutions, 11 youth sports schools, 3 children's health camps, 1 Center for Professional Development, 2 Inclusive Resource Centers, 12 regional institutions, and 4 private institutions. Additionally, 97,839 students use electronic identification cards (Kryvyi Rih Citizen Card project, initiated 2019), with approximately 22,000 students served by extracurricular institutions. The Department of Education and Science oversees policy implementation, infrastructure investment, and professional development coordination through centralized governance.

Education digitization in Kryvyi Rih progressed through four phases (figure 2). Phase 1 (Foundation, 2019–early 2020) launched the Citizen Card project for student identification, invested in school connectivity, and adopted administrative platforms. Phase 2 (Pandemic acceleration, March 2020–2021) created the Educational Portal for distance learning, delivered STEAM-CAMP training to 148 teachers (390 hours), and rapidly adopted remote instruction platforms. Phase 3 (Consolidation, 2022) achieved 100% electronic journal adoption, integrated state registries (EDEBO, AIKOM), and expanded Portal content. Phase 4 (War-context adaptation, 2022–2025) deployed 11,614 Chromebooks and 4,104 laptops, established 150 Starlink units for connectivity resilience, achieved universal xPON coverage, continued professional development in AI and cybersecurity, and established STEM laboratories in six schools.

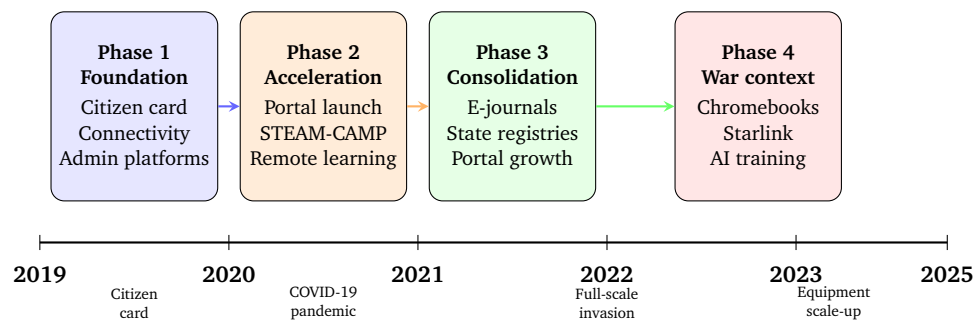


Figure 2: Digitization timeline: four phases of education technology development in Kryvyi Rih (2019–2025).

Russia's full-scale invasion of Ukraine beginning February 2022 created unprecedented challenges for education continuity. Kryvyi Rih, while not subject to direct ground combat, experienced air raid alerts requiring shelter protocols, power outages affecting connectivity and device charging, population displacement affecting student enrollment, and infrastructure stress from refugee accommodation. These conditions necessitated specific adaptations: Starlink for backup connectivity, mobile device classes for flexibility, and emphasis on asynchronous learning resources. The war context also accelerated digitization efforts as remote learning became essential for educational continuity.

International organizations supplemented municipal resources and introduced best practices. USAID provided equipment and training programs; UNICEF supported digital educational centers

and inclusive education; Save the Children contributed educational materials and psychosocial support; and Google-Ukraine delivered Gemini for Education certification and Chromebook training. These partnerships extended capacity beyond local resources.

6. Infrastructure and access analysis

This section analyzes Kryvyi Rih’s digital education infrastructure deployment through the lens of EU Digital Education Action Plan Priority 1 (digital education ecosystem) and international benchmarks.

Table 3 shows substantial hardware deployment concentrated in 2022–2025, reflecting war-driven infrastructure investment. The Chromebook dominance (11,614 units vs. 4,104 laptops) suggests a platform choice aligned with Google Workspace adoption (53% of platforms), while Starlink deployment (150 units) represents resilience investment absent from EU benchmarks.

Table 3

Infrastructure deployment in Kryvyi Rih education system (2019–2025).

Category	Item	Quantity	Period
Connectivity	xPON fixed internet	All schools	2025
	Starlink devices	150 units	2022–2025
Chromebooks	Total deployed	11,614	2022–2025
	For teachers	1,647	2022–2025
	Received 2024–2025	9,861	2024–2025
Laptops	Total deployed	4,104	2022–2025
	For teachers	1,914	2022–2025
	Received 2024–2025	1,251	2024–2025
Desktop PCs	For computer labs	2,096	2024–2025
Labs equipped	131 facilities	–	2024–2025
Tablets	Total deployed	825	2022–2025
	Received 2024–2025	340	2024–2025
	Mobile classes (12 schools)	108	April 2024
Interactive panels		375	2024–2025
Multifunction devices		575	2022–2025

Universal connectivity is a foundational requirement for digital education. Kryvyi Rih achieved 100% school coverage through two complementary approaches: fixed xPON connectivity providing stable, high-bandwidth internet access, and resilient Starlink backup (150 units) for connectivity independent of ground-based infrastructure – a war-context adaptation addressing power outages and infrastructure damage.

The dual-connectivity approach represents a unique adaptation to Ukrainian circumstances not typically required in EU contexts. While EU Action Plan Action 2 emphasizes universal connectivity, it does not specifically address backup systems. The Starlink deployment exemplifies context-appropriate innovation.

Device deployment proceeded systematically across multiple categories (table 3). Chromebooks (11,614 units) constitute the primary student computing platform, offering lower cost, simplified Google Workspace management, and web-based applications; the 1:8.4 ratio suggests partial rather than universal coverage. Laptops (4,104 units, with 46.6% allocated to teachers) support professional tasks requiring full computing capability. Desktop computers (2,096 units) equipped 131 computer laboratories for specialized instruction including computer science. Tablets (825 units) include mobile class deployments (108 devices in 12 schools) with accessibility accessories for students with disabilities. Interactive panels (375 units) replace traditional blackboards for digital instruction. This pattern reflects strategic prioritization: student computing via Chromebooks, teacher computing via

laptops, specialized functions via desktops, accessibility via tablets, and classroom modernization via panels.

Infrastructure deployment addressed equity through several mechanisms. School-wide distribution allocated equipment across all 150+ educational institutions rather than concentrating in select schools, ensuring baseline access across the city. Mobile tablet classes targeted 12 schools specifically, providing flexible resources for emerging needs and students with limited home technology access. Accessibility provisions for students with disabilities (joystick overlays, specialized mice) reflected attention to inclusive requirements often overlooked in standard deployments. International partnership support from USAID, UNICEF, and Save the Children directed resources toward underserved populations and educational loss recovery.

However, the device-to-student ratio (approximately 1:8.4 for Chromebooks) indicates less than universal individual access. Students likely share devices across class periods or grades, limiting opportunities for personalized, extended device use.

EU Digital Education Action Plan targets and international comparisons provide benchmarks for assessment. EU connectivity targets specify minimum 100 Mbps (aspirational 1 Gbps) for schools; Kryvyi Rih's xPON deployment appears to meet this standard, while Starlink backup exceeds typical EU provisions. Device ratios at 1:8.4 fall significantly below EU best practices targeting 1:1, though 2024–2025 equipment intake suggests acceleration. Laboratory access with 131 facilities across approximately 150 schools indicates near-universal specialized computing capacity. Teacher equipment provision of 1,914 laptops supports professional use for digital pedagogy and administrative functions.

7. Digital learning ecosystems analysis

This section examines the digital learning ecosystem – the interconnected platforms, content resources, and administrative systems supporting teaching and learning. Analysis follows EU Action Plan Priority 1 dimensions and UNESCO competency framework aspects.

Table 4 reveals platform concentration: electronic journals cluster around “Novi znannia” (86%), while learning platforms favor Google Workspace (53%) with Ukrainian alternatives (“Novi znannia” 23%, “Human” 20%). This concentration raises questions about platform lock-in versus resilience through diversity.

The Educational Portal “Let’s Color the World Together” (Rozfarbuimo Svit Razom), launched in March 2020, represents the centralized content hub for Kryvyi Rih education. Over four years, it accumulated 15,409+ publications with approximately 270,000 visits from 482 contributing educators (137 secondary, 240 preschool, 105 extracurricular). Content includes lessons organized by grade level and subject, materials aligned with calendar planning, video materials, presentations, self-assessment tasks, and digital textbook integration. Specialized sections offer “Step to Olympus” distance school for Olympiad preparation (12 subjects, 244 contributing teachers), psychological support service (since January 2021), preschool education resources, and extracurricular activities (932 sessions from 277 educators).

The Portal exemplifies the “knowledge deepening” level of UNESCO competency framework: educators create and share content, organize learning sequences, and develop specialized resources for particular educational purposes. The volunteer contributor model (482 educators from a larger teaching population) shows emerging “knowledge creation” capacity among a subset of highly engaged teachers.

Administrative digitalization achieved broad coverage through electronic journals (100% adoption since 2022 across five platforms, with “Novi znannia” dominant at 86%), state registry integration (EDEBO for student records, AIKOM for administrative management), and document management (Megapolis system introduced 2025). The administrative ecosystem shows “knowledge deepening” to “knowledge creation” transition: from using existing systems to participating in system-wide implementation.

Table 4
Digital platform adoption in Kryvyi Rih education system (2025).

Category	Platform/tool	Adoption rate
Electronic journals	Novi znannia	86%
	Moya shkola	3%
	Yedyna shkola	1%
	HUMAN	5%
	Mriya	5%
Learning platforms	Google Workspace	53%
	Novi znannia	23%
	Human	20%
Video conferencing	Google Meet	85%
	Zoom	15%
All-Ukrainian School Online	Teacher registration	90%
	Systematic use	63%
Interactive tools	MIRO	In use
	Jamboard	In use
	Padlet	In use
	Learning Apps	In use
	WordWall	In use
	Google tools	In use

Learning platforms show a multi-layered structure (table 4). Google Workspace (53%) offers core productivity tools with 85% Google Meet usage indicating ecosystem integration. Ukrainian platforms “Novi znannia” (23%) and “Human” (20%) provide Ukrainian-language learning management, reducing dependence on international platforms while maintaining platform diversity. This ecosystem architecture reflects pragmatic adaptation: leveraging robust international tools while developing national alternatives.

Beyond the Educational Portal, content availability includes All-Ukrainian School Online (90% teacher registration with 63% systematic usage), digital textbook adoption across subjects, and interactive tools (MIRO, Jamboard, Padlet, Learning Apps, WordWall, Google tools) supporting active learning pedagogy beyond passive content consumption.

UNESCO competency levels provide an assessment framework. Technology Literacy is achieved: universal connectivity, device access, and platform availability indicate educators can use digital technologies for routine tasks. Knowledge Deepening is achieved through Portal content creation, electronic journal management, and systematic platform use integrating technology into pedagogy. Knowledge Creation is emerging (482 Portal contributors, 454 Gemini-certified teachers, STEM laboratory development) but concentrated among innovative educators rather than system-wide. EU ecosystem indicators suggest moderate maturity with broad infrastructure coverage but incomplete advanced integration.

8. Teacher digital competence

Teacher digital competence development represents the third critical dimension of digitization. Without corresponding human capacity, infrastructure investments yield limited educational returns.

Professional development programs achieved substantial reach. STEAM-CAMP (2020) delivered 390 hours of STEM training to 148 teachers in partnership with Metinvest Group. “Digigram for Teachers” achieved 93% completion, indicating near-universal baseline digital competence. AI integration training reached over 10,000 teachers covering artificial intelligence, cybersecurity, gamification, and academic integrity, with specific certifications including Gemini for Education (454

teachers), Chromebook training (approximately 400 registered for planned November 2025 course), Chromebook Educational Practices (approximately 900 trained), and Microsoft 365 (approximately 900 trained). This scale reflects recognition that advanced digital competence now encompasses emerging technologies beyond traditional productivity tools.

Training delivery occurred through multiple channels: municipal coordination via the Center for Professional Development, international partnerships (Google-Ukraine, UNICEF), self-directed learning through Educational Portal resources, and peer learning from 482 Portal contributors.

Mapping training achievements against UNESCO competency levels shows Technology Literacy achieved universally (93% Digigram completion), Knowledge Deepening substantially present (148 STEAM-CAMP graduates, systematic platform users, Portal content creators), and Knowledge Creation emerging among innovators (454 Gemini-certified teachers, STEM laboratory facilitators). However, advanced competence remains concentrated among a subset rather than system-wide capacity.

International teacher digital competence frameworks (DigCompEdu, UNESCO ICT-CFT) identify strengths (universal baseline competence through Digigram, substantial advanced training investment, emerging AI and STEM specialization, peer learning structures) and gaps (no systematic assessment of competence levels, unclear training-to-classroom implementation translation, advanced competence concentration, limited outcome data on pedagogical impact). Without systematic assessment, it is unclear whether training investment translates into pedagogical change.

9. Comparative synthesis

This section synthesizes findings across infrastructure, ecosystems, and competence dimensions, comparing Kryvyi Rih achievements against EU and UNESCO frameworks.

Comparison with EU Digital Education Action Plan targets requires careful interpretation, as the DEAP emphasizes “equitable access” and “connectivity for all” rather than universal device ratios. Official targets include: broadband connectivity ≥ 100 Mbps (aspirational 1 Gbps) for schools; digital equipment for teaching and learning; and effective digital governance [4]. Table 5 maps Kryvyi Rih against these targets.

Table 5
Infrastructure gap analysis: Kryvyi Rih vs. EU DEAP targets.

Dimension	EU target	Kryvyi Rih	Distance
School connectivity	≥ 100 Mbps broadband (DEAP Action 2)	100% xPON; Starlink backup	Meets/exceeds
Device access	Equitable access (no 1:1 mandate)	1:8.4 ratio	Below aspiration
Teacher equipment	Digital tools for educators	1,914 laptops	Substantial
Specialized labs	Computer science facilities	131 labs for ≈ 150 schools	Near-universal
Interactive displays	Classroom modernization	375 panels	Partial coverage
Accessibility tech	Inclusive education support	12 schools with mobile classes	Limited reach

The connectivity achievement (100% xPON with Starlink backup) reflects war-driven resilience investment absent from EU benchmarks. The device ratio (1:8.4) falls below aspirational 1:1 models in some EU contexts, but the DEAP does not mandate universal ratios – it emphasizes “equitable access,” which shared devices can provide. Computer lab coverage meets expectations for specialized computing instruction.

Table 6 shows “Knowledge deepening” achievement across administrative systems, content creation, and platform integration, with “Knowledge creation” emerging in advanced pedagogy and teacher innovation.

Infrastructure gaps require continued hardware investment; 2024–2025 equipment inflow (9,861 Chromebooks, 1,251 laptops) indicates acceleration but sustained funding remains essential. Adoption optimization demands attention: the gap between All-Ukrainian School Online registration (90%) and systematic use (63%) suggests implementation barriers requiring policy intervention. Competence distribution shows advanced skills concentrated among subsets (454 Gemini-certified,

Table 6

Ecosystem maturity assessment.

Component	Level	Evidence
Administrative systems	Knowledge deepening	100% e-journal adoption, registry integration
Content creation	Knowledge deepening	15,409 Portal publications, 482 contributors
Platform integration	Knowledge deepening	Multi-platform ecosystem, systematic use
Advanced pedagogy	Emerging creation	STEM labs, AI training, interactive tools
Teacher innovation	Emerging creation	454 Gemini-certified, content leaders

148 STEAM-CAMP graduates); peer mentoring could extend innovation reach. Contextual factors reveal war conditions created both challenges (accelerated remote learning need) and opportunities (international support, digital adoption acceleration).

10. Discussion

This case study documents integrated infrastructure, ecosystem, and human capacity development within a single city context, revealing how components interact. The combination of EU and UNESCO frameworks offers a transferable assessment methodology, revealing strengths (connectivity resilience, ecosystem breadth) and gaps (device ratios, adoption optimization). War-context factors absent from most literature – Starlink resilience, accelerated adoption, international partnership integration – demonstrate that digitization models must account for local conditions.

For policymakers in similar contexts, phased infrastructure development (connectivity → devices → platforms → advanced tools) offers a sequencing template. Multi-platform ecosystem design (Google with Ukrainian alternatives) balances capability and sovereignty. Tiered professional development (universal baseline plus targeted advanced programs) efficiently distributes resources while creating career pathways. Content creation infrastructure (Educational Portal with 482 contributors) demonstrates distributed teacher expertise leverage. International partnership strategic engagement supplements municipal resources while introducing standards.

The analysis documents inputs and outputs but lacks outcome data (student achievement, teacher effectiveness, learning quality). Single-case findings cannot be automatically generalized; comparative multi-city studies would identify transferable elements. Municipal self-reports without independent verification limit reliability. Data cover 2019–2025 without pre-baseline or post-trajectory. Administrative data lacks teacher, student, and parent perspectives. Future research should prioritize outcome-based assessment, comparative studies, stakeholder perspectives, longitudinal tracking, and cost-effectiveness analysis.

11. Conclusion

This documentary analysis examines Kryvyi Rih’s education digitization (2019–2025) through EU and UNESCO framework lenses. The case reveals substantial infrastructure investment (connectivity, devices, platforms) and training completion (93% baseline certification), but cannot assess educational outcomes due to absent impact data. Framework comparison identifies both alignment (connectivity targets) and gaps (device ratios, outcome measurement) while highlighting limitations of applying standard frameworks to conflict contexts.

Three contributions emerge from this analysis. First, the case documents framework extensions required for conflict-affected settings: resilience indicators (backup connectivity), wartime adaptation pathways, and boundary conditions for transferability. Second, the analysis identifies limitations in existing frameworks: EU benchmarks do not account for disruption resilience, and UNESCO competency levels insufficiently capture innovation under resource scarcity. Third, the study proposes testable propositions for future comparative research: (a) cities with industrial bases and international

partnerships achieve faster infrastructure deployment than those without; (b) conflict contexts require resilience indicators absent from standard frameworks; (c) training completion does not predict classroom technology integration without outcome assessment.

The Ukrainian context limits generalizability. War conditions, industrial economy, and EU aspirations create specific characteristics. Future research should include outcome measurement (student achievement, teacher effectiveness), stakeholder perspectives (teachers, students, parents), and comparative designs across Ukrainian cities or international contexts. As digitization continues globally, evidence on educational effectiveness – not merely input deployment – remains essential for informed policy.

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