Enterprise Architecture Software Tools for Sustainable Smart Energy Governance, Information Systems and Infrastructure: A Multi Criteria Evaluation Across Regulated Sectors from the Czech Republic

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Abstract: Digital transformation (DT) in smart energy systems requires Enterprise Architecture (EA) tools capable of modeling complex digital energy infrastructures, including smart metering ecosystems, distributed energy resources (DERs), flexibility market platforms, and grid-edge systems. To support these increasingly data-driven environments, EA tools must provide strong modeling capabilities, interoperability, and governance functions suitable for smart grid and energy platform development. This study applies a structured multi-criteria evaluation of seven widely used EA tools (Enterprise Architect - Sparx, Archi - freeware, Horizzon - BizzDesign, LeanIX - SAP, Hopex - MEGA International, VisualParadigm - Visual Paradigm, Abacus - Avolution: based on modeling expressiveness, repository features, usability, visualization, and decision-support functions. Using the Analytic Hierarchy Process (AHP), weights were assigned to reflect priorities of digital energy infrastructures, including DER integration, energy data governance, lifecycle planning, and regulatory compliance. The evaluation, conducted in the energy utilities and public administration sectors in the Czech Republic, highlights significant variation in standards support, integration with smart metering, and collaborative modeling functions relevant to smart grid planning. Findings show that EA tools differ notably in their suitability for representing energy system architectures and supporting sustainable digital transformation. The study offers practical guidance for selecting EA tools aligned with the needs of smart energy organizations pursuing scalable, interoperable, and resilient digital energy ecosystems.

Keywords: Smart Energy Systems, Digital Energy Platforms, Multi Criteria Decision Making, Analytic Hierarchy Process, Energy Infrastructure Digitalization, Sustainable Digital Transformation.

1. INTRODUCTION

The digital transformation (DT) of energy systems—driven by smart grid deployment, the rising penetration of distributed energy resources (DER), real time flexibility and balancing markets, and increasingly stringent cybersecurity requirements—has substantially amplified the need for coherent, transparent, and traceable governance across utility enterprises. These developments extend beyond core grid operations to encompass diversified sales channels and customer centric service models tailored to heterogeneous customer segments, including retail consumers, prosumers, corporate clients, and energy communities. Utilities increasingly manage on demand electricity purchasing contracts linked to wholesale and spot markets, offer mobile applications for retail customers, and operate advanced smart metering infrastructures enabling remote electricity meter readings, dynamic pricing, and near real time consumption transparency. Furthermore, the integration of photovoltaic power stations operated by both retail & corporate customers, alongside community shared energy schemes, introduces new layers of architectural complexity related to data flows, settlement mechanisms, and regulatory compliance.

These dynamics unfold within highly regulated environments characterized by strict reliability, security, and compliance obligations, while the progressive convergence of information technology (IT) and operational technology (OT) reshapes how utilities plan, operate, and modernize critical infrastructure. As energy ecosystems become increasingly decentralized, data-intensive, and market-driven, utilities face heightened coordination demands across sales, market operations, asset management, and customer engagement. In such contexts, organizations require a systematic, enterprise-wide capability to align strategic intent with portfolio level execution, orchestrate heterogeneous digital solutions, ensure regulatory compliance, and sustain operational resilience throughout transformation initiatives.

In regulated energy environments, sustainability goals (*e.g.*, decarbonization, renewable integration, demand flexibility, and resilience) are operationalized through portfolios of interdependent digital, data, and grid-edge initiatives rather than isolated IT projects. Within this context, motivations, goals, requirements, and related challenges constitute core elements of strategic motivation and critical thinking that shape transformation trajectories. EA tools support these

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processes by enabling traceable translation of sustainability objectives into capability roadmaps, data governance structures, interoperability constraints, and implementation states. Moreover, the systematic roadmapping of strategic initiatives—via capabilities, digital initiatives, and coordinated program portfolios—represents a key mechanism for managing progress in regulated environments and aligning transformation with compliance requirements. Accordingly, the suitability of EA tools in smart energy contexts should be assessed not merely as modeling instruments but as governance mechanisms that enable auditable decision-making across IT/OT/DER ecosystems and support lifecycle planning for sustainable transformation.

In this context of increasing technological convergence, market dynamism, and regulatory pressure, Enterprise Architecture (EA) has reemerged as a central governance and design capability for organizations undergoing digital transformation (DT), particularly in regulated and asset-intensive sectors such as energy. DT can be understood as an organization-level process in which the adoption of digital technologies triggers strategic responses and structural adaptations to create new value pathways, reshape operating models, and redefine stakeholder relationships. Within this perspective, EA functions as a socio-technical coordination mechanism that systematically connects diverse stakeholder concerns with architecture descriptions and decision-making across interconnected business, application, data, technology, and infrastructure layers [1, 2].

The ongoing digitalization of energy systems intensifies the need for such coordination, as utilities must align IT/OT integration—exemplified by smart-grid governance within regulated electricity systems—with evolving business strategies, customer-centric service models, and participation in competitive energy markets, all while complying with strict regulatory, safety, and reliability constraints. EA provides a structured means to explicitly represent AS-IS architectural constraints, including legacy systems, regulatory dependencies, and physical asset limitations, while enabling the systematic design of TO-BE target states that support smart grids, renewable energy integration, advanced metering infrastructures, and sustainability initiatives. By linking strategic objectives with portfolio-level investments and transformation roadmaps, EA supports coherent decision-making across organizational boundaries and temporal horizons.

Against this backdrop, this study examines selected EA software tools with a particular focus on their functions, capabilities, and practical potential to support the modeling of complex and heterogeneous AS-IS and TO-BE architectural states within energy utilities. The study investigates how these tools enable continuous architectural visibility, traceability, and scenario modeling across business, application, data, and technology layers in environments characterized by regulatory constraints and rapid digital change. Empirical findings from Czech energy utilities are situated within a broader comparative context, relating sector-specific requirements to insights from finance and public administration, thereby highlighting both domain-specific challenges and cross-sectoral mechanisms through which EA tooling supports DT. From a methodological perspective, contemporary EA increasingly relies on methodological standardization, formal decision-support approaches, and tool-enabled evaluation frameworks. The TOGAF® Standard, 10th Edition, provides configurable and method-driven guidance aligned with agile and DT programs, while preserving stable architectural principles and governance mechanisms [3, 4]. In parallel, the ArchiMate® 3.2 Specification defines an open, tool-supported modeling language with explicit layers, relationships, and transformation constructs, enabling consistent representation of AS-IS and TO-BE architectural states and their transitions. Together, these standards establish a coherent foundation for systematic architecture development, visualization, and traceable decision-making in accordance with ISO/IEC/IEEE 42010 requirements for stakeholder-oriented architecture descriptions, while supporting IT/OT integration in smart grids, energy systems, DER, and sustainability initiatives.

To evaluate the extent to which contemporary EA software tools effectively support these methodological and architectural requirements, this study applies the Analytic Hierarchy Process (AHP) introduced by Saaty as a multi-criteria decision-making (MCDA) method [5–7]. AHP enables the decomposition of the complex EA tool selection problem into a hierarchical structure of evaluation criteria and sub-criteria, followed by systematic pairwise comparisons reflecting expert judgments. This approach combines both in a multi-criteria decision-making technique that transforms qualitative expert judgments into quantitative priority weights through structured pairwise comparisons and mathematical aggregation. The criteria allow consistency checking of preferences and yield priority weights that make trade-offs among competing EA tool capabilities explicit. By employing AHP, the evaluation framework ensures transparency, methodological rigor, and reproducibility, providing robust decision support for assessing the ability of EA software tools to sustain dynamic architectures in regulated, asset-intensive utility environments.

The study is structured as follows: the literature review synthesizes theoretical perspectives on DT and EA in the energy sector, EA as a socio-technical coordination mechanism, and its interplay with DT, emphasizing the relevance of governance frameworks such as TOGAF and modeling languages like ArchiMate for asset-intensive industries [8, 9] and EA software tools. The methodology applies a structured research design that combines survey-based empirical evidence with a Multi-Criteria Decision Making approach using the Analytic Hierarchy Process to identify business–IT alignment constraints and evaluate the role of EA artifacts. Results detail EA tool usage, modeling practices, and governance challenges, while the discussion interprets these findings in light of regulatory obligations and organizational complexity (smart-grid and energy system modernization covering DER), proposing actionable recommendations for integrating EA governance with project and program management [10, 11].

A. Illustrative Smart-grid Implementation Vignettes

To illustrate how EA governance and tooling support smart-grid implementation, three typical utility scenarios can serve as illustrative vignettes. (i) DER integration: grid operators introduce DER orchestration and forecasting services that require explicit modeling of data flows, cybersecurity boundaries, and interoperability constraints across IT/OT; repository-based EA tooling supports dependency management, stakeholder viewpoints, and impact analysis across asset, application, and data layers. (ii) Advanced metering infrastructure: smart metering programs create long-lived integration landscapes (head-end systems, meter data management system, billing, customer portals) where traceability and standardized viewpoints reduce integration risk and support regulatory reporting; EA tools with strong modeling standards and export/reporting capabilities improve auditability and stakeholder communication. (iii) Flexibility markets: market platforms (*e.g.*, demand response aggregation, flexibility bidding) require capability-roadmap alignment and migration planning across multiple actors; EA tooling supports consistent AS-IS/TO-BE modeling and decision traceability during phased rollouts under regulatory constraints.

2. LITERATURE REVIEW

A. Digital Transformation in the Energy Sector

The energy transition and smart grid modernization generate governance challenges related to cybersecurity, data protection, interoperability, and market design. These challenges intersect with EA, which helps internalize regulatory and architectural constraints and ensures that portfolio decisions and migration paths comply with regulatory and reliability requirements. Digital transformation (DT), as introduced in the preceding chapter, is understood as an organization-level process in which the adoption of digital technologies triggers strategic responses and structural adaptations to create new value pathways, reshape operating models, and redefine stakeholder relationships. Within the energy sector, this understanding is further specified by the systematic integration of digital and information-communication technologies into energy companies' strategies, operational processes, and business models. Such integration enables automated and data-driven communication, real-time system monitoring and control, enhanced operational efficiency, and the progressive transition toward a reliable, resilient, and low-carbon energy system [12]. Digitalization is driving significant changes in the energy sector, fostering innovation and reshaping business models. Future drivers of the energy market will establish a digital backbone that supports the transition from fossil fuels to renewable energy, thereby creating an energy system interconnected with our personal and local ecosystems [13]. Digitalization plays a key role in implementing the new 3D model of energy development. Effective digitalization will enable the development of increasingly advanced technologies, enabling diversified energy production and the utilization of decentralized renewable sources [14]. Energy DT refers to the systematic integration of digital technologies into energy systems and governance frameworks through coordinated policy objectives, regulatory instruments, institutional capacity, and stakeholder engagement, aiming to enhance energy efficiency, system resilience, renewable integration, and sustainable energy governance [2].

DT is defined as 'a new development in the use of digital artifacts, systems, and symbols within and around organizations' and has been considered one of the main drivers of economic growth and sustainable development in today's business world [15]. DT has become a cornerstone of the modern energy sector by enabling the evolution of smart energy systems that integrate data, intelligence, and connectivity across generation, networks, and consumption. By synergistically deploying technologies such as artificial intelligence (AI), the Internet of Things (IoT), blockchain (BC), and digital twins (DTW), DT enhances system efficiency, flexibility, and resilience while supporting renewable energy integration and active demand response. Its effective realization, however, depends on coherent governance, interoperability, and robust cybersecurity frameworks [16]. The power industry is moving towards a more decentralized model, where electricity is generated from renewable sources and distributed through microgrids and smart grids, supported by digital technologies such as IoT, AI, and Big Data analytics [17]

B. Enterprise Architecture in the Energy Sector

In the energy sector, EA represents a structured governance and design framework that aligns business objectives, regulatory requirements, and technological capabilities to manage the transition from centralized power systems to distributed, renewable-rich smart grids. It provides a coherent blueprint for integrating smart grids, demand response, and distributed energy resources by orchestrating data, applications, infrastructure, and security across complex cyber-physical environments. Through standardized, modular, and secure architectures, EA enables utilities to maintain grid stability, interoperability, and resilience while adopting advanced digital technologies such as artificial intelligence, DTW, and BC [18]. EA is understood as a structured collection of explicit artifacts that describe an organization from an integrated business and IT perspective, with the primary purpose of enabling coordinated decision-making and alignment between business and IT. These artifacts act as boundary objects that support communication between stakeholders, facilitate strategic planning, guide solution design, and help manage organizational complexity. EA is not merely documentation but a practice embedded in organizational planning processes, implemented through dedicated EA functions that govern both enterprise-level direction and solution-level consistency [19]. Applied to the energy sector, EA provides a coherent framework for aligning business objectives, regulatory constraints, and digital infrastructures across complex, capital-intensive, and increasingly DERs. EA supports the integration of operational technology (OP) and information systems by coordinating planning across generation, transmission, distribution, and market functions. Through structured architectural artifacts and governance mechanisms, EA enables energy organizations to manage system complexity, support DT initiatives, and ensure alignment between long-term strategic goals and the design of individual energy solutions in a highly regulated, technology-dependent environment [2, 14, 20, 21].

C. Enterprise Architecture Framework TOGAF

Foundational contributions frame EA as a route to consistent execution through standardization and integration, aligned with an explicit operating model [9]. Subsequent TOGAF material emphasizes configurable adoption, stakeholder engagement, and integration with portfolio/program management—capabilities frequently cited as prerequisites for DT at scale. The Architecture Development Method (ADM) in [4] provides a structured, iterative framework for creating and maintaining enterprise architectures. It consists of sequential phases—from Preliminary and Architecture Vision through Business, Data, Application, and Technology architectures to Implementation and Change Management—ensuring alignment with organizational strategy and governance. ADM's adaptability supports continuous refinement, making it a cornerstone for enterprise architecture practice [4]. In the energy and utility sector, EA is commonly operationalized using TOGAF®, which provides a structured architectural development method for aligning business strategy, regulatory obligations, and IT/OT landscapes across generation, grid operations, and market functions [22].

D. Graphical Notation Language Archi Mate

ArchiMate® 3.2 specifies a layered metamodel (motivation, strategy, business, application, technology, implementation/migration) and viewpoint mechanism that supports AS-IS and TO-BE modeling, traceability, and stakeholder-specific visualizations [4,8]. In organizational communication theory, such visual artefacts can operate as boundary objects—simultaneously robust and plastic—enabling collaboration across heterogeneous communities without requiring full consensus. This is particularly relevant for energy utilities, where operations, engineering, IT, compliance, and market functions must coordinate closely around grid modernization or asset digitization programs. EA boundary objects in the energy sector are mostly represented, including capability maps, reference architectures, integration diagrams, data models, and roadmaps—enabling coordination among business, IT, OT, and regulatory communities by providing shared yet flexible representations of complex, regulated, and cyber-physical energy systems [3].

ArchiMate plays a central role in effective communication within EA practice by capturing key stages of the TOGAF Architecture Development Method (ADM) and incorporating both motivation and implementation extensions. It connects architectural elements across multiple layers, enabling a holistic organizational view and supporting systematic impact analysis. Purely oral or textual descriptions are insufficient for conveying EA; graphical modeling offers a clearer and more effective means of representation. Widely adopted in recent years, ArchiMate structures EA into four layers: Strategy, Business, Application, and Technology. The strategy layer represents capabilities, resources, and courses of action that underpin organizational objectives. The business layer models processes, services, and functions, the application layer describes software systems supporting business operations, and the technology layer encompasses infrastructure and communication components. [8]. EA modeling involves two perspectives: AS-IS (current state) and TO-BE (future state). Although AS-IS is often overlooked, both states are essential for designing scalable, adaptable initiatives. A holistic EA approach enables organizations to plan long-term transformations through programs, projects, and portfolios within defined constraints (scope, quality, resources), ensuring alignment with strategic objectives [23].

E. EA Software Tools

Contemporary EA tools are widely recognized as mature, enterprise-wide platforms that support governance, design, and decision-making in complex transformation contexts. From a market-definitional perspective, EA tools enable organizations to model, manage, and analyze interdependencies across business capabilities, processes, roles, applications, data, and technology landscapes, serving as centralized repositories that maintain consistent representations of current and future enterprise states. Analyst research consistently highlights strong convergence in the functional scope of EA software: despite differences in vendor positioning and user interfaces, most tools provide a standardized set of foundational capabilities that extend well beyond diagramming to structured enterprise governance and transformation enablement. At their core, EA tools support integrated multi-layer modeling based on shared metamodels (materialization of boundary objects), relationship and dependency management, and impact and scenario analysis to assess change implications and guide transformation roadmaps. These platforms further emphasize visualization through stakeholder specific viewpoints, dashboards, and heatmaps, promote collaboration among business and IT stakeholders throughout the architecture lifecycle, and embed governance mechanisms that ensure consistency, controlled evolution, and strategic alignment. Advanced analytical features support trend, gap, and risk identification, while extensibility via custom metamodels and integration interfaces enables alignment with adjacent enterprise systems such as portfolio management, CMDBs, process mining, and agile planning tools. Collectively, these capabilities position EA tools as decision-support platforms that connect strategy, architecture, and execution, reflecting both the maturation of the EA discipline and the growing demand for scalable, tool-supported alignment in DT initiatives [24-26].

3. METHODOLOGY

The energy sector—encompassing electricity generation, transmission, distribution, and retail supply—faces distinctive challenges in achieving digital maturity due to its dependence on large-scale physical infrastructures, tightly coupled cyber-physical systems, and long-standing legacy technologies. These challenges are further intensified by the rapid deployment of smart metering systems, smart grid architectures, and the integration of photovoltaic and other distributed renewable energy sources across transmission and distribution networks. EA enables systematic alignment across strategic, business, technological, and physical layers, providing a structured foundation for integrating advanced grid management, digital monitoring, data-driven energy sales platforms, and interoperable market systems. Despite ongoing progress, energy organizations continue to encounter persistent barriers, including regulatory requirements, interoperability constraints, and gaps in architectural and digital competencies. Similar limitations affect the adoption of holistic EA practices intended to support project and program management of large-scale DT initiatives, even in contexts such as the Czech Republic, where EA adoption within the energy sector is comparatively advanced.

Taken together, the increasing architectural complexity, regulatory intensity, and pace of DT in regulated sectors—most notably energy and utilities, finance and banking, and public administration—create demands that cannot be effectively addressed through manual, fragmented, or document centric EA practices. As these sectors confront simultaneous pressures arising from smart grid expansion, advanced metering infrastructures, cybersecurity obligations, data-driven service models, and cross organizational interoperability, the ability to maintain architectural coherence and decision traceability becomes critically dependent on the availability of cutting edge EA software tools. Such tools provide the necessary capabilities for large-scale architectural modeling, repository based governance, scenario and impact analysis, and integration with project and program management, thereby enabling regulated organizations to respond to escalating EA requirements in a structurally sustainable and operationally resilient manner.

Based on the following, research questions were formulated. **RQ#1:** What kind of software tool is more suitable for modeling regulated heterogeneous EA, with an emphasis on the energy sector? **RQ#2:** What are the key differentiators between software tools for modeling regulated heterogeneous EA with an emphasis on the energy sector? **RQ#3:** What are the recommendations for small, medium, and large energy companies for selecting a suitable software tool for modeling EA in a regulated environment? The methodology adopts a hybrid approach combining empirical investigation with structured multi-criteria evaluation to address the complexity of EA tool assessment in regulated sectors. The methodology integrates exploratory cross sector data collection (sub-chapter A) with formal decision-support techniques (sub-chapter B) to ensure analytical rigor, transparency, and comparability across contexts.

A. Quantitative Survey

This Sub-chapter A establishes the empirical foundation of the study by examining how EA tools are adopted and used across regulated sectors, including energy, banking, and public administration, reflecting real-world regulatory, organizational, and technological conditions. The survey was designed to capture key aspects of EA practice, including EA adoption, the use of the ArchiMate language for AS-IS and TO-BE modeling, and the selection of EA software tools. To ensure conceptual coherence and analytical focus, the questionnaire followed a structured and concise design, with clearly defined constructs directly aligned with the research questions. The survey was administered online via Google Forms between April and June 2023 and was preceded by a pilot study, which enabled refinement of question wording and improved overall clarity and consistency of the instrument. A total of 105 invitations were distributed, resulting in 55 valid responses from professionals operating in the energy, finance, and public administration sectors.

Table 1: Respondents by Job Title

Job title	#	%
Chief Executive Officer (non EA & non-IT stakeholder)	2	3,6
Delivery director (non EA & non-IT stakeholder)	1	1,8
Enterprise Architect	7	12,8
IT Administrator	10	18,2
IT Analyst	4	7,3
IT Consultant	1	1,8
IT Coordinator	7	12,7
IT Director	16	29,1
IT Engineer	2	3,6
IT Specialist	4	7,3
Project manager (non EA & non-IT stakeholder)	1	1,8
Total	**55**	**100**

The dataset included information on respondents' professional roles, sectoral affiliations, and enterprise size, enabling a coherent classification of organizational contexts while maintaining a parsimonious data structure suitable for subsequent analysis. The data analyzed in this article originate from a survey conducted in the Czech Republic between April and June 2023, specifically designed to collect coherent, comparable evidence on EA adoption, ArchiMate usage for AS-IS and TO-BE modeling, and EA tool selection in domestically regulated organizational environments. The survey constitutes the initial empirical dataset for a series of mutually reinforcing research studies addressing EA governance and digital transformation in Czech-regulated sectors, with particular attention to energy and utilities. A first set of results derived from this nationally bounded dataset has been published in an earlier volume of this journal. To ensure methodological continuity and analytical rigor, the present study deliberately reuses the same core dataset and respondent structure (Tables **1** and **2**) while extending the analysis and addressing follow-up research questions. The findings are therefore interpreted within the Czech regulatory and institutional context and are not intended to provide generalizations for the global context.

Table 2: Enterprise Per Industry Sector

Industry sector	#	%
Energy (power supply)	13	23,6
Finance/banking/insurance	23	41,8
Public administration	19	34,6
Total	**55**	**100,0**

The survey was distributed to 105 potential respondents, and the demographic characteristics of the resulting sample are summarized in Tables **1** - **2**. In total, 55 complete responses were obtained, corresponding to a response rate of 52%. Participants were recruited primarily through electronic communication channels, and the sample included respondents from multiple regions. Despite these efforts, the resulting dataset cannot be considered fully representative of the entire Czech energy management sector, a limitation that should be borne in mind when interpreting the findings. The distribution of respondents by job position is presented in Table **1**, while sectoral affiliation is summarized in Table **2**. To achieve the reported response rate, participation was encouraged through targeted outreach leveraging professional networks and personal contacts. Respondents demonstrated a clear understanding of the survey's objectives and engaged with the questionnaire consistently and contextually, suggesting that the concise, well-structured design supported both data quality and respondent comprehension.

Table 3: Enterprise Size by Number of Employees

Enterprise Size	#	%
0–19 employees	3	5.45
20–49 employees	2	3.64
50–99 employees	9	16.37
100–1000 employees	20	36.36
1001+ employees	21	38.18
Total	**55**	**100.00**

The electronic distribution method may have introduced bias by favoring respondents with reliable internet access and higher digital literacy. However, internet availability among respondents is high. And he participation was voluntary, which could lead to self-selection bias and limit the generalizability.

Table 4: Employees Involved in EA

Employees involved in EA	#	%
1–3 employees	18	32.73
4–6 employees	17	30.90
7–10 employees	7	12.73
11+ employees	13	23.64
Total	**55**	**100.00**

Table 5: Type of EA Software Tool

EA software (Vendor)	#	%
Enterprise Architect (Sparx)	22	40.00
Archi (freeware)	13	23.63
Horizzon (BizzDesign)	7	12.73
LeanIX (SAP)	5	9.09
Hopex (MEGA International)	2	3.64
VisualParadigm (Visual Paradigm)	2	3.64
Abacus (Avolution)	1	1.82
None	3	5.45
Total	**55**	**100.00**

B. Multi-Criteria Decision Making & Analytic Hierarchy Process

To systematically evaluate EA software tools in regulated, heterogeneous organizational environments, this study employs Multi-Criteria Decision Making (MCDM) via the Analytic Hierarchy Process (AHP). AHP was selected for its ability to decompose complex decision problems into a transparent hierarchical structure, integrate qualitative judgments, and produce reproducible quantitative results.

The decision hierarchy is organized around five evaluation criteria reflecting core EA tool capabilities. **Criterion 1 (C#1)** (Modeling and Frameworks) assesses support for ArchiMate and complementary modeling languages, compliance with architectural frameworks (TOGAF, Zachman, DoDAF, FEAF), and standardized export formats. **Criterion 2 (C#2)** (Repository and Collaboration) evaluates repository robustness, database and cloud integration, and collaborative features that support shared architectural governance. **Criterion 3 (C#3)** (Presentation) captures the ability to communicate architectural insights through exports and integration with presentation tools. **Criterion 4 (C#4)** (Usability) addresses configurability, interoperability through imports, model reuse, and efficient navigation. **Criterion 5 (C#5)** (Decision Support and Project Management) examines support for AS-IS/TO-BE gap analysis and project-oriented transformation planning. Each criterion is operationalized through explicitly defined sub-criteria with uniform scoring scales (Tables **6**–**10**).

Table 6: Criterion C#1 - Modeling and Frameworks

C#1 - Modeling and Frameworks	MaxScore
C#1.1 - Support for the ArchiMate 3.2+ notation	10
C#1.2 - Support for other modeling languages for Enterprise Architecture (UML, BPMN, ERD)	10
C#1.3 - Graphical compliance with the National Enterprise Architecture Framework	10
C#1.4 - Export of XML models, EAP, and ArchiMate model	10
C#1.5 - Support for the TOGAF architectural framework	10
C#1.6 - Support for additional frameworks (Zachman, DoDAF, FEAF)	10

Legend: UML = Unified Modeling Language, BPMN = Business Process Management Notation, ERD = Entity Relationship Diagram, XML = eXtended Markup Language, EAP = Enterprise Architecture Planning, ArchiMate = graphical language notation, TOGAF = The Open Group Architecture Framework DoDAF = Department of Defense Architecture Framework, FEAF = Federal Architecture Framework.

AHP is applied in two stages. First, pairwise comparisons are used to determine the relative weights of the five criteria using Saaty's fundamental scale, allowing differentiation between core architectural functions and supportive capabilities. Second, alternative EA tools are scored against each sub-criterion, and the resulting local scores are aggregated using the derived weights to compute an overall ranking. This methodological approach ensures transparency, consistency, and traceability of evaluation logic. It is particularly suitable for regulated sectors such as energy, finance, and public administration, where EA tools must support standardized modeling, governance, interoperability, and long-term DT under regulatory constraints.

Table 7: Criterion C#2 - Repository

C#2 - Repository	Max Score
C#2.1 - Connection to DBMS-based repositories	10
C#2.2 - Integration with cloud environments	10
C#2.3 - In-repository commenting	10

Legend: DBMS = DataBase Management System.

Table 8: Criterion C#3 - Presentation

C#3 - Presentation	Max Score
C#3.1 - Integration with presentation applications (PowerPoint, Microsoft Word)	10
C#3.2 - Export in PDF, Excel, HTML, or JPG formats	10

Legend: PDF = Portable Document Format, HTML = Hypertext Markup Language, JPEG = Joint Photographic Experts Group.

Table 9: Criterion C#4 - Usability

C#4 - Usability	Max Score
C#4.1 - User-specific configuration options	10
C#4.2 - Import formats (XML, MS Excel, CSV, and other formats)	10
C#4.3 - Import of models from other EA tools (MS Visio, ArchiMate, Enterprise Architect)	10
C#4.4 - Search and filtering by name, relationships, attributes, and object types	10

Legend: XML = eXtended Markup Language, CSV = Comma Separated Values.

Table 10: Criterion C#5 - Decision Support and Project Management

C#5 - Decision Support and PM	Max Score
C#5.1 - Gap analysis support (AS-IS / TO-BE)	10
C#5.2 - Project management support (Gantt charts, project calendars, resource allocation)	10

Legend: AS-IS = current state of EA, TO-BE = future state of EA.

The AHP pairwise comparisons were conducted by an expert panel (n = 3) representing decision-relevant perspectives in regulated sectors. Experts were selected based on (a) involvement in EA governance, (b) ≥5 years of experience with architecture modeling and repository governance, and (c) familiarity with regulated domains (primarily energy utilities, complemented by finance and public administration for cross-sector insight). To mitigate bias, panel members had no affiliation with evaluated vendors and followed a consistent scoring rubric across tools. Pairwise comparison matrices were aggregated using the geometric mean, enhancing transparency and reproducibility of the Saaty-based AHP weighting procedure.

1) Saaty Method

Criteria weights were determined using the Analytic AHP according to Saaty, enabling systematic prioritization of evaluation criteria based on expert judgment. Five criteria were compared pairwise to determine an EA tool suitable for regulated environments.

Using Saaty's nine-point scale, each criterion was assessed against all others, resulting in a reciprocal pairwise comparison matrix. The relative importance values were processed using the geometric mean, and the resulting priorities were normalized so that their sum equals one. The derived weights, including geometric means and final preference values, are presented in Table **11**. Criteria weights were determined using the AHP, which derives priorities through structured pairwise comparisons and geometric aggregation of expert judgments [27–29].

The weighting results indicate that Modeling and Frameworks is the most influential criterion, reflecting the central role of architectural modeling and framework compliance in EA practice. Usability follows as the second most important criterion, emphasizing efficiency and accessibility for both architects and stakeholders. Repository and Presentation have moderate influence, while Decision Support and Project Management are assigned the lowest weight, as they represent a complementary rather than core EA capability. By explicitly documenting pairwise judgments, geometric means, and normalized weights (Table **11**), the Saaty method ensures transparency, logical consistency, and reproducibility of the weighting process, providing a robust foundation for subsequent multi-criteria evaluation of alternatives. The evaluation combined a criteria-driven framework with AHP-based weighting to compare EA tools across regulated environments in the energy, banking, and public administration sectors. The approach integrates authors' and experts' judgment and structured scoring to reflect regulatory, architectural, and governance requirements.

4. RESULTS

The results chapter begins with a descriptive overview of the respondent sample to contextualize the subsequent analytical findings. Tables **1**–**5** summarize key structural characteristics of the dataset, including respondents' job roles, industry affiliations, enterprise sizes, the extent of EA staffing, and the distribution of EA tools. Together, these dimensions establish the

Table 11: Determination of Criteria Weights Using the Saaty Method

Criterion	C#1	C#2	C#3	C#4	C#5	GM	WP
Modeling and Frameworks	1	5	3	3	5	2.95	0.45
Repository	1/5	1	3	1/3	3	0.90	0.14
Presentation	1/3	1/3	1	1/3	3	0.64	0.10
Usability	1/3	3	3	1	5	1.72	0.26
Decision Support and PM	1/5	1/3	1/3	1/5	1	0.34	0.05
Sum						**6.56**	**1.00**

Legend: PM = Project Management, GM = Geometric Means, WP =Weight Preference.

organizational and institutional setting in which EA practices evolve across regulated sectors.

The distribution of job titles indicates that responses are primarily provided by IT-management and architecture-related roles, particularly within energy and public-sector organizations, where architectural coordination and regulatory compliance are closely intertwined. At the same time, representation from banking and public administration ensures cross-sector comparability and highlights shared governance challenges despite sector-specific regulatory regimes.

Enterprise size and EA staffing levels further underscore the impact of regulatory intensity and system complexity. Large energy enterprises and public institutions exhibit higher levels of EA workforce involvement and more systematic tool usage, reflecting the need to manage heterogeneous IT/OT/DER landscapes, compliance obligations, and long-term infrastructure planning. While financial institutions demonstrate similar governance maturity, energy-sector respondents show the strongest alignment between organizational scale, EA capacity, and tool adoption.

These structural patterns (shown in Table **1** – **5** and explained in section A) provide the empirical foundation for the subsequent multi-criteria analysis. Accordingly, Section B presents the AHP-based evaluation results, in which EA tools are assessed against weighted criteria that reflect the governance, modeling, and operational demands observed, particularly those characteristic of smart energy systems and regulated infrastructure environments.

A. Quantitative survey results

1) Respondent Roles and Decision Relevance (Table 1)

The respondent profile is dominated by IT-oriented and architecture-adjacent roles, with IT Directors, IT Administrators, Enterprise Architects, and IT Coordinators forming the largest groups. This composition indicates that the data primarily reflect decision-relevant perspectives, with direct exposure to EA governance, tool selection, and architectural coordination. The presence of senior management and non-EA stakeholders, although limited, reinforces the cross-functional relevance of EA beyond purely technical domains.

2) Sectoral Distribution and Regulatory Context (Table 2)

Respondents are distributed across three regulated sectors: energy, public administration, finance, and banking. While financial institutions represent the largest share, energy and public administration together account for a substantial proportion of the sample. This distribution supports a comparative interpretation of EA practices across regulation-intensive domains, with energy enterprises contributing a distinct perspective shaped by infrastructure criticality, IT/OT/DER integration, and long-term system reliability requirements.

3) Enterprise Size and Organizational Complexity (Table 3)

The sample is strongly skewed toward medium-to-large enterprises, with the majority of respondents working in organizations employing more than 100 employees, and a substantial proportion exceeding 1,000 employees. This size profile suggests that the reported EA practices are predominantly in organizationally complex environments, where architectural coordination, governance structures, and tool support play critical roles in managing scale, heterogeneity, and regulatory compliance.

4) Enterprise Architecture Staffing Levels (Table 4)

Data on EA staffing reveal that most organizations employ small to medium-sized EA teams, typically involving 1 to 6 employees. Larger EA teams are less common but are more prevalent in larger enterprises. This pattern indicates that EA is often implemented as a lean governance function, even within large, regulated organizations, underscoring the importance of tool support to compensate for limited architectural human capacity—particularly in energy and public sector contexts.

5) EA Tool Adoption Patterns (Table 5)

EA tool usage is concentrated around a limited set of platforms. As summarized in Table **5**, Enterprise Architect/Sparx is the most frequently reported tool, used by 22 respondents (40.0%), followed by Archi/freeware with 13 respondents (23.63%) and Horizon/BizzDesign with 7 respondents (12.73%). Other solutions, including LeanIX/SAP (9.09%), Hopex/MEGA and Visual Paradigm/Visual Paradigm (both 3.64%), and Abacus/Avolution (1.82%), are considerably less prevalent, and 3 respondents (5.45%) report using no dedicated EA tool. The continued reliance on diagramming-centric tools, along with the absence of EA tooling in some organizations, indicates uneven EA maturity and diverse adoption strategies across sectors. This distribution is particularly evident in energy and other regulated domains, where organizational scale and compliance requirements favor stable, widely adopted EA platforms, although similar patterns are also observable in finance and public administration. These variations provide a realistic empirical baseline for interpreting the subsequent AHP-based tool evaluation.

Taken together, Tables **1**–**5** reveal that EA tool usage and governance practices are shaped by organizational scale, regulatory intensity, and limited EA staffing capacity, particularly in energy and public-sector organizations. These structural conditions provide the empirical backdrop against which the following AHP-based multi-criteria evaluation assesses the relative suitability of EA tools for regulated, infrastructure-centric environments.

B. MCDM & AHP (Saaty method) results

This chapter presents the results of the selected EA software tools introduced in Table **5** against the criteria C#1–C#5 presented in Tables **6**–**10** by using MCDM & AHP. The analytical methods were conducted separately for each EA tool. The evaluation of each alternative concludes with a summary table that presents the scores for each criterion.

1) Enterprise Architecture (Sparx)

a) AHP score summary (C#1–C#5)

Enterprise Architect (Sparx) represents Alternative (1) in the multi-criteria evaluation and achieves the highest total score (153). This result is primarily driven by strong performance in C#1 Modeling and

Table 12: AHP – Saaty Method

Criterion	Sub- Criterion	Alternative						
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
C#1	C#1.1	10	10	10	10	10	10	10
	C#1.2	10	0	10	10	10	10	10
	C#1.3	10	10	10	5	10	10	5
	C#1.4	8	8	10	4	8	8	7
	C#1.5	10	10	10	10	10	10	10
	C#1.6	10	0	0	0	10	10	10
C#2	C#2.1	10	10	10	10	10	10	10
	C#2.2	10	0	10	10	10	0	10
	C#2.3	10	10	10	10	10	10	10
C#3	C#3.1	10	5	10	0	10	10	5
	C#3.2	10	5	10	10	10	10	10
C#4	C#4.1	10	10	10	0	10	10	10
	C#4.2	10	8	8	8	10	8	10
	C#4.3	0	10	10	0	10	10	10
	C#4.4	10	10	10	10	5	10	10
C#5	C#5.1	10	0	0	0	0	0	0
	C#5.2	5	0	10	8	5	10	10
Total		**153**	**106**	**148**	**105**	**148**	**146**	**147**

Legend for EA Tool Alternative: (1) = Enterprise Architect (SPARX), (2) = Archi (freeware), (3) = Horizzon (BizzDesign), (4) = LeanIX (SAP), (5) = Hopex (MEGA International), (6) = VisualParadigm (VisualParadigm), (7) Abacus (Avolution).

Frameworks (0.45) and C#4 Usability (0.26), which together dominate the AHP preference structure. Consistently high scores across these criteria materially enhance the tool's overall suitability for regulated-sector EA use.

b) C#1 Modeling and Frameworks

Enterprise Architect (Sparx) provides comprehensive modeling support, including full ArchiMate compliance (C#1.1=10), support for UML/BPMN (C#1.2=10), and native TOGAF enablement (C#1.5=10). Graphical alignment with the National Enterprise Architecture Framework is complete (C#1.3=10). Export interoperability is strong though not exhaustive (C#1.4=8), while support for additional frameworks achieves the maximum score (C#1.6=10).

c) C#2 Repository and Collaboration

Repository capabilities reach the maximum across all sub-criteria, encompassing DBMS-based repositories (C#2.1=10), cloud integration (C#2.2=10), and in-repository collaboration (C#2.3=10). This profile reflects mature, repository-centric governance and effective support for collaborative EA practices.

d) C#3 Presentation

Presentation functionality is fully covered through direct integration with PowerPoint and Microsoft Word (C#3.1=10) and comprehensive export options (C#3.2=10). These capabilities facilitate stakeholder communication and report-driven governance as defined by the evaluation framework.

e) C#4 Usability

Usability is a key strength, supported by user-specific configuration (C#4.1=10), broad import formats (C#4.2=10), and advanced search and filtering (C#4.4=10). The primary limitation under this criterion is the absence of cross-tool model import (C#4.3=0), which represents the main usability-adjacent constraint in the AHP rubric.

f) C#5 Decision Support and Project Management

Decision-support functionality for architecture state transitions is fully supported via native gap analysis (C#5.1=10), while project-management support is moderate (C#5.2=5). Given its low AHP weight, this criterion has limited influence on the final score but remains relevant for transformation planning contexts.

2) Archi Tool (freeware)

a) AHP score summary (C#1–C#5)

Archi represents Alternative (2) in the multi-criteria evaluation and achieves a total score of 106, which is substantially lower than repository-centric and commercially oriented EA platforms. This outcome is primarily attributable to weak performance in C#1 Modeling and Frameworks (0.45) and the complete absence of C#5 Decision Support and Project Management (0.05), both of which constrain the aggregated AHP score despite strong usability characteristics.

b) C#1 Modeling and Frameworks

Archi provides full ArchiMate compliance (C#1.1=10) and conforms to national graphical conventions (C#1.3=10). However, it is intentionally restricted to ArchiMate and does not support complementary modeling languages such as UML or BPMN (C#1.2=0).

Export interoperability is partial (C#1.4=8), limited to XML and ArchiMate formats, while Enterprise Architecture Project (EAP) export is not supported. TOGAF support is available (C#1.5=10), but no additional EA frameworks are supported (C#1.6=0), significantly limiting framework diversity under the evaluation rubric.

c) C#2 Repository and Collaboration

By default, Archi does not provide a DBMS-based repository; however, this capability can be enabled via optional extensions (C#2.1=10 in the evaluation). In contrast, cloud-based repository integration is not supported (C#2.2=0). Collaborative functions, including in-repository commenting (C#2.3=10) and search, are available but dependent on additional modules, reflecting a modular rather than repository-centric governance approach.

d) C#3 Presentation

Presentation capabilities are assessed as moderate. Basic exports to presentation and documentation environments are supported (C#3.1=5), but without advanced integration or automation features. Exports to common dissemination formats such as PDF, HTML, JPG, and XML are available (C#3.2=5), enabling basic stakeholder communication but offering limited support for report-driven governance.

e) C#4 Usability (weight preference: 0.26)

Usability represents a relative strength of Archi. The tool supports user-level configuration and model styling (C#4.1=10) and provides broad import capabilities for XML, CSV, ArchiMate, and selected third-party formats (C#4.2=8; C#4.3=10). Search and filtering across model elements and attributes are fully supported (C#

4.4=10), particularly when repository extensions are deployed, which positively contributes to navigation and day-to-day modeling efficiency.

f) C#5 Decision Support and Project Management

Archi provides no native support for AS-IS/TO-BE gap analysis (C#5.1=0) and no project-management functionality (C#5.2=0). These limitations are consistent with the tool's design philosophy, which prioritizes lightweight, standards-compliant EA modeling over governance, decision support, or transformation management capabilities.

3) Horizzon (Bizzdesign)

a) AHP score summary (C#1–C#5)

Horizzon (Bizzdesign) represents Alternative (3) in the multi-criteria evaluation and achieves a total score of 148, placing it among the higher-ranked EA tools. This result is primarily driven by strong performance in C#1 Modeling and Frameworks and C#4 Usability, which together account for the majority of the total AHP preference weight, while the absence of native gap-analysis support under C#5 slightly moderates its overall ranking.

b) C#1 Modeling and Frameworks

Horizzon provides full support for ArchiMate 3.1 (C#1.1=10), including syntax, semantics, and viewpoints, and additionally supports UML and BPMN (C#1.2=10). Graphical conventions fully align with the National Enterprise Architecture Framework (C#1.3=10). Export interoperability is comprehensive (C#1.4=10), covering XML, ArchiMate models, and Enterprise Architecture Project (EAP) files. TOGAF is natively supported (C#1.5=10); however, additional EA frameworks are not supported (C#1.6=0), limiting the diversity of frameworks within the evaluation rubric.

c) C#2 Repository and Collaboration

Horizzon operates as a cloud-native platform with a relational repository architecture (C#2.1=10). It supports integration with enterprise DBMS platforms and provides full connectivity to major cloud platforms, including Azure, AWS, and Google Cloud (C# 2.2 = 10). Collaborative functionality is mature, encompassing in-repository commenting, notifications, and comment management (C#2.3=10), which supports distributed and multi-stakeholder architectural governance.

d) C#3 Presentation

Presentation capabilities are fully supported through direct integration with PowerPoint and Microsoft Word (C# 3.1 = 10), facilitating stakeholder communication and documentation. Additional export formats, including JPG, PDF, HTML, and Excel, are fully supported (C#3.2=10), enabling broad dissemination of architectural artifacts.

e) C#4 Usability

Usability is a major strength of Horizzon. The platform supports role-based configuration, interface customization, and access control (C#4.1=10). Import functionality covers XML and Excel (C#4.2=8) and enables direct imports from other EA tools, including Sparx Enterprise Architect and Visual Paradigm (C#4.3=10). Search and filtering capabilities are comprehensive, spanning model content, metadata, and authorship (C#4.4=10), supporting efficient navigation in large-scale repositories.

f) C#5 Decision Support and Project Management

Horizzon does not provide native AS-IS/TO-BE gap-analysis functionality (C#5.1=0). In contrast, project-management support is advanced (C#5.2=10), incorporating Scrum and Kanban methodologies, project roadmaps, task planning, and integration with external project-management systems.

4) LeanIX (SAP)

a) AHP score summary (C#1–C#5)

LeanIX (SAP) represents Alternative (4) in the multi-criteria evaluation and achieves a total score of 105, placing it among the lower-ranked EA tools. This outcome reflects strong performance in C#2 Repository and Collaboration and C#4 Usability, but comparatively weaker results in C#1 Modeling and Frameworks and C#3 Presentation, which together carry a higher combined weight in the AHP preference structure.

b) C#1 Modeling and Frameworks

LeanIX supports ArchiMate 3.1 (C#1.1=10) and enables modeling using UML and BPMN (C#1.2=10). However, default graphical configurations do not fully align with the National Enterprise Architecture Framework (C#1.3=5), although alignment can be achieved through manual customization. Export interoperability is limited to XML only (C#1.4=4), with no support for ArchiMate Model or Enterprise Architecture Project formats. TOGAF-compliant diagramming is supported (C#1.5=10), while no additional EA frameworks are available (C#1.6=0), constraining framework extensibility under the evaluation rubric.

c) C#2 Repository and Collaboration

LeanIX implements a relational repository architecture that supports enterprise DBMS platforms and integrates fully with major cloud environments, including Azure, AWS, and Google Cloud (C#2.1=10; C#2.2=10). Native in-repository commenting is complemented by a ticket-based coordination mechanism (C#2.3=10) that supports structured stakeholder communication and issue tracking in large organizations.

d) C#3 Presentation

LeanIX does not provide direct integration with PowerPoint or Microsoft Word (C#3.1=0). Presentation, therefore, relies on exporting diagrams and models for external use. Supported export formats include XML, PDF, JPG, and Excel (C#3.2=10), enabling indirect reporting and documentation despite the absence of native presentation-tool integration.

e) C#4 Usability

Usability is a relative strength of LeanIX. The platform provides role-based configuration, interface customization, and access-rights management (C#4.1=10). Import functionality is limited to Excel and XML (C#4.2=8), and cross-tool EA model import is not supported (C#4.3=0). Search and filtering capabilities are comprehensive, enabling queries across models, elements, and metadata (C#4.4=10).

f) C#5 Decision Support and Project Management (weight preference: 0.05)

LeanIX does not provide native AS-IS/TO-BE gap-analysis functionality (C#5.1=0). Project-management support is moderate (C#5.2=8) and is primarily achieved through integration with external tools such as Jira or Asana, complemented by internal roadmapping and maturity-assessment features.

5) Hopex (BizzDesign)

a) AHP score summary (C#1–C#5)

HOPEX (Bizzdesign) represents Alternative (5) in the multi-criteria evaluation and achieves a total score of 148, positioning it among the higher-ranked EA tools. This result is primarily driven by strong performance in C#1 Modeling and Frameworks and C#2 Repository, which together carry substantial weight in the AHP hierarchy, while limitations in C#5 Decision Support have only a marginal impact due to its low assigned weight.

b) C#1 Modeling and Frameworks

HOPEX provides full support for ArchiMate 3.1 (C#1.1=10) and supports additional modeling languages, including BPMN, UML, and ERD (C#1.2=10). Graphical conventions are fully aligned with the National Enterprise Architecture Framework (C#1.3=10). Export interoperability is strong (C#1.4=8), supporting XML and Enterprise Architecture Project (EAP) formats. The platform includes dedicated TOGAF functionality (C#1.5=10) and supports additional EA frameworks such as DoDAF and Zachman (C#1.6=10), resulting in one of the broadest framework coverages among the evaluated tools.

c) C#2 Repository and Collaboration

The HOPEX repository is implemented on a relational database architecture with broad DBMS support, including SQL Server, Oracle, PostgreSQL, and MongoDB (C#2.1=10). Integration with major cloud platforms such as Azure, AWS, and Google Cloud is supported (C#2.2=10). Native in-repository commenting enables the creation and modification of comments (C#2.3=10), supporting documentation and collaborative architectural review.

d) C#3 Presentation

HOPEX offers optional extensions for integration with PowerPoint and Microsoft Word (C#3.1=10), enabling presentation generation with macro support and structured reporting. Additional export formats, including PDF, XML, HTML, JPG, and Excel, are fully available (C#3.2=10), ensuring broad dissemination of architectural artifacts.

e) C#4 Usability

Usability is assessed as moderate. HOPEX supports user-level customization, color configuration, and access control (C#4.1=10). Import functionality covers XML and Excel (C#4.2=10) and supports imports from Microsoft Visio (C#4.3=10). However, search functionality is limited, primarily to file and diagram names (C#4.4=5), reducing navigability in large, heterogeneous repositories compared to some competing platforms.

f) C#5 Decision Support and Project Management

HOPEX does not provide native AS-IS/TO-BE gap-analysis functionality (C#5.1=0). Project-management support is limited (C#5.2=5) and focuses mainly on agile approaches such as Scrum and Kanban, with additional integration available via Jira.

6) Visual Paradigm (Visual Paradigm)

a) 4.U.0 AHP score summary (C#1–C#5)

Visual Paradigm represents Alternative (6) in the multi-criteria evaluation and achieves a total score of

146, positioning it among the higher-scoring EA tools. This outcome is primarily supported by strong performance in C#1 Modeling and Frameworks, C#4 Usability, and C#5 Project Management, while limitations in C#2 Repository (cloud integration) and C#3 Presentation slightly constrain its overall aggregation under the AHP weighting scheme.

b) C#1 Modeling and Frameworks

Visual Paradigm provides full support for ArchiMate 3.1 (C#1.1=10) and also supports UML and BPMN (C#1.2=10). Graphical conventions are aligned with the National Enterprise Architecture Framework (C#1.3=10). Export interoperability supports XML, ArchiMate models, and proprietary project formats (C#1.4=8), while Enterprise Architecture Project (EAP) export is not available. Built-in support for TOGAF and ADM (C#1.5=10) is complemented by broad framework coverage, including DoDAF, NAF, MODAF, and Zachman (C#1.6=10).

c) C#2 Repository and Collaboration

The repository is implemented on a relational database architecture supporting multiple DBMS platforms, including MySQL, MariaDB, PostgreSQL, and Firebird (C# 2.1=10). However, cloud-based repository connectivity is not supported (C#2.2=0). Native commenting and collaboration features are available and support comment editing, project metadata management, and model descriptions (C#2.3=10).

d) C#3 Presentation

Visual Paradigm supports direct integration with PowerPoint and Microsoft Word (C#3.1=10), allowing diagrams to be embedded and updated within documents. Export flexibility is more limited, supporting JPG and Excel but not PDF or HTML, resulting in a constrained dissemination profile under the evaluation rubric (C#3.2=10).

e) C#4 Usability

Usability is a core strength of Visual Paradigm. The tool offers extensive user-level customization, workspace configuration, and access-rights management (C#4.1=10).

Import functionality supports XML and Excel (C#4.2=10) and enables imports from other EA tools, including Sparx Enterprise Architect (C#4.3=10). Search functionality is comprehensive, enabling both file-level searches and in-diagram element queries (C#4.4=10), which supports efficient navigation of complex models.

f) C#5 Decision Support and Project Management

Visual Paradigm does not provide native AS-IS/TO-BE gap-analysis functionality (C#5.1=0). In contrast, project-management support is advanced (C#5.2=10), including calendars, Gantt charts, SCRUM tooling, sprint planning, backlog management, and integration with external systems such as Jira.

7) Abacus (Avolution)

a) AHP score summary (C#1–C#5)

Abacus (Avolution) represents Alternative (7) in the multi-criteria evaluation and achieves a total score of 147, positioning it among the higher-scoring EA tools. Under the AHP weighting scheme, this result is primarily driven by strong performance in C#1 Modeling and Frameworks (0.45) and C#4 Usability (0.26). The absence of native gap-analysis functionality under C#5 has only a limited impact on the overall ranking due to the low weight assigned to this criterion.

b) C#1 Modeling and Frameworks

Abacus achieves maximum scores for core modeling capabilities, including ArchiMate support (C#1.1=10), UML/BPMN support (C#1.2=10), TOGAF compliance (C#1.5=10), and additional framework coverage (C#1.6=10). Graphical alignment with the National Enterprise Architecture Framework is partial (C#1.3=5), while export interoperability is high but not complete (C#1.4=7). Overall, the tool demonstrates alignment with broad standards and a framework under the applied rubric.

c) C#2 Repository and Collaboration

Repository capabilities are assessed at the maximum level across all sub-criteria (C#2.1=10; C#2.2=10; C#2.3=10), reflecting strong repository-centric operation, cloud connectivity, and collaboration support. Abacus supports both on-premise and cloud deployments, enabling scalable repository use across organizational contexts.

d) C#3 Presentation

Presentation capabilities are characterized by limited direct integration with PowerPoint and Microsoft Word (C#3.1=5), while export support for common dissemination formats remains strong (C#3.2=10). As a result, stakeholder communication is primarily facilitated through exportable artifacts rather than through integration with presentation.

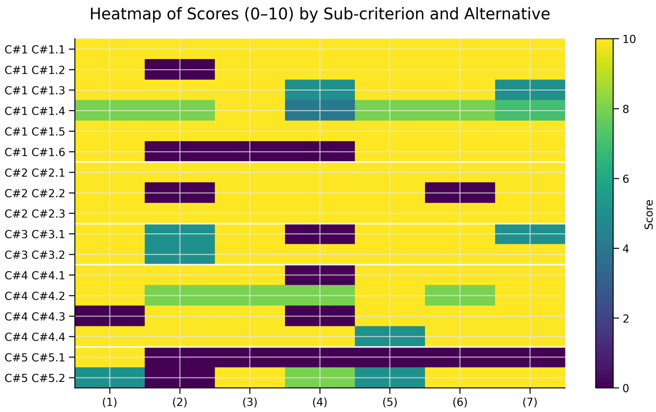
e) C#4 Usability

Usability represents a core strength of Abacus. The tool scores the maximum across configuration

(C#4.1=10), data import (C#4.2=10), cross-tool interoperability (C#4.3=10), and search and navigation (C#4.4=10). Avolution emphasizes the extensive configurability of repositories and metamodels, including adaptable terminology, structures, and frameworks, supporting user-oriented tailoring at scale.

f) C#5 Decision Support and Project Management

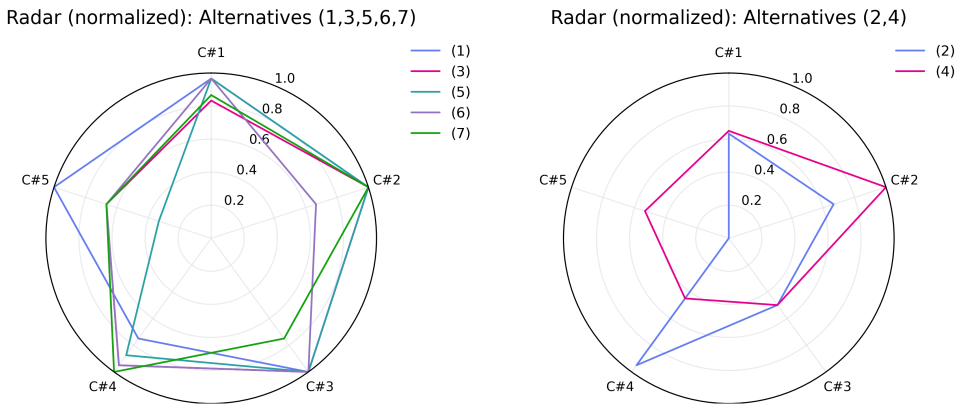
Abacus does not provide native AS-IS/TO-BE gap-analysis functionality (C#5.1=0), but it demonstrates strong project-management support (C#5.2=10) within the applied evaluation. Given C #5's low AHP weight, this criterion contributes less to the final ranking than the highly weighted modeling and usability dimensions.



Schema 1: Heatmap of EA tool scores across AHP sub-criteria (C#1.1–C#5.2), highlighting capability strengths and structural gaps.

Schema **1** presents a heatmap visualization of the sub-criteria-level scores (0–10) assigned to each evaluated EA tool across criteria C#1–C#5. Rows represent individual sub-criteria (*e.g.*, C#1.1–C#5.2), while columns correspond to the analyzed alternatives (1–7). Color intensity reflects the magnitude of scores, enabling rapid identification of strong and weak capability areas at a granular level. The heatmap reveals clear patterns of contrast between tools. Repository-centric and standards-oriented platforms exhibit broadly high scores across modeling (C#1), repository (C#2), and usability (C#4) sub-criteria, while other tools display selective gaps, particularly in framework breadth (C#1.6), cloud repository integration (C#2.2), and decision-support functionality (C#5.1). These gaps appear as isolated darker regions, highlighting sub-criteria that are systematically unsupported rather than marginally weaker. Importantly, the heatmap highlights heterogeneity in capabilities within otherwise high-scoring tools. For example, certain tools achieve uniformly high modeling and usability scores while simultaneously exhibiting zero scores in gap analysis or cross-tool interoperability. This visualization, therefore, complements aggregated AHP scores by exposing structural trade-offs that are not directly visible in total rankings, thereby supporting transparent comparison under the applied multi-criteria decision framework.

Schema **2** illustrates radar (spider) charts depicting normalized AHP criterion scores for the evaluated EA tools. Scores are aggregated at the criterion level (C#1–C#5) and normalized against the maximum possible score for each criterion, enabling direct comparison of capability profiles independent of absolute scale. To preserve readability, higher-scoring alternatives are visualized separately from lower-scoring ones. The radar visualization highlights distinct capability profiles rather than simple rankings. Tools with repository-centric architectures display wide, balanced polygons across modeling (C#1), repository (C#2), and usability (C#4) dimensions, whereas lighter-weight or modeling-focused tools show narrower profiles with pronounced weaknesses in decision support and project management (C#5). These geometric differences reflect underlying architectural design philosophies rather than scoring artifacts. From an analytical perspective, the radar charts make explicit that tools with comparable total AHP scores may differ substantially in their capability



Schema 2: Radar (spider) charts of normalized AHP criterion scores (C#1–C#5) illustrating comparative capability profiles of evaluated EA tools (Alternatives).

distributions. For example, some alternatives compensate for weaker decision-support functionality with strong modeling and usability coverage, while others exhibit balanced but less specialized profiles. As such, the radar visualization supports RQ-driven interpretation, particularly in assessing tool suitability for different organizational contexts and governance priorities under regulated conditions.

In combination, Schema **1** and Schema **2** provide a structured visual basis for answering RQ#1–RQ#3 within the AHP evaluation framework. For RQ#1 (tool suitability for modeling regulated heterogeneous EA (with the emphasize to energy environment), Schema **1** operationalizes suitability at the most granular level by showing where each alternative exhibits full, partial, or absent support across sub-criteria C#1.1–C#5.2, while Schema **2** consolidates these findings into normalized criterion-level profiles (C#1–C#5) that can be directly interpreted against the AHP decision hierarchy. For RQ#2 (key differentiators), Schema **1** exposes differentiating capability gaps and trade-offs—particularly in framework breadth and interoperability (C#1), repository/cloud integration (C#2), presentation coupling versus export dependence (C#3), cross-tool model import and navigation (C#4), and the presence or absence of gap analysis and transformation planning support (C#5). Schema **2** demonstrates how these differences aggregate into distinct capability "shapes" that separate modeling-centric, repository-centric, and execution-oriented tool profiles. Finally, for RQ#3 (recommendations by enterprise size in regulated energy environments), the two visualizations jointly support decision-oriented guidance by indicating which sub-criteria shortfalls would require compensating processes or complementary tools (Schema **1**), and by clarifying whether a tool's overall capability distribution aligns with the study's weighted priorities—most notably the higher emphasis placed on C#1 Modeling and Frameworks and C#4 Usability in the AHP weighting scheme (Schema **2**) - thereby enabling recommendations to be differentiated by organizational scale and governance intensity.

DISCUSSION

Interpretation of the results for answering RQ#1

The AHP-based evaluation provides an evidence-based answer to RQ#1 by identifying which tool profiles best match the requirements for regulated, heterogeneous EA modeling in the Czech energy sector and comparable regulated contexts. The weighting model assigns the highest influence to C#1 Modeling and Frameworks (WP=0.45) and the second-highest to C#4 Usability (WP=0.26), implying that tool suitability is driven primarily by standards-compliant modeling (ArchiMate/TOGAF, framework breadth, export interoperability) and operational usability (configuration, imports, navigation), while repository and presentation have moderate influence and project/decision support has the lowest weight.

Under this structure, the results indicate that repository-centric, standards-rich tools with consistently high coverage in C#1 and C#4 achieve the strongest overall suitability signals. The tool scoring highest is Enterprise Architect (Sparx) (Total=153), supported by maximum scores across most sub-criteria, including C#1 and C#4, and full repository and presentation coverage. The next group: Horizzon (148), HOPEX (148), Abacus (147), Visual Paradigm (146), shows similarly strong overall capability profiles, although with identifiable trade-offs in specific sub-criteria (*e.g.*, varying support for gap analysis, cloud repository integration, or search depth).

In contrast, LeanIX (105) and Archi (106) score substantially lower. In LeanIX, the reduced score is associated with constrained export interoperability and weaker presentation integration (*e.g.*, limited direct Office integration), while in Archi the low score reflects deliberate design focus on ArchiMate-only modeling and the absence of decision-support and project management features. The visual analytics reinforce this interpretation: Schema **1** shows capability gaps concentrated in particular sub-criteria (not uniformly weak performance), while Schema **2** highlights that higher-scoring alternatives exhibit broader criterion-level coverage, especially across C#1–C#4.

Interpretation of the results for answering RQ#2

RQ#2 asks for the key differentiators between EA tools (Alternatives) for regulated heterogeneous modeling. The results show that differentiation is not primarily driven by "general quality," but by structural capability gaps that appear repeatedly in specific sub-criteria and then propagate to overall rankings under the AHP weights.

First, within C#1 Modeling and Frameworks, the most discriminating elements are framework breadth (C#1.6) and export interoperability (C#1.4). Several tools score highly on baseline modeling (C#1.1 and C#1.5 are frequently 10), yet diverge when broader framework support or exchange formats (*e.g.*, EAP/ArchiMate model formats beyond XML) are required. This is critical because C#1 carries the largest weight (0.45), meaning small reductions in C#1.4/C#1.6 materially affect suitability assessments.

Second, C#2 Repository and Collaboration differentiates tools by cloud repository integration

(C#2.2) and collaboration mechanisms (C#2.3). Some alternatives offer full DBMS support but do not support cloud repository connectivity, which is crucial for organizations seeking shared governance and distributed collaboration. This distinction is visible in the heatmap as discrete “missing capability” blocks rather than gradual performance declines.

Third, C#3 Presentation separates tools with native Office integration (C#3.1) from tools relying on export-only workflows. In regulated environments, where decision traceability and stakeholder communication are central, native integration with Word/PowerPoint can reduce friction in reporting and governance routines, even though C#3 has moderate weight (0.10).

Fourth, C#4 Usability reveals a major differentiator in cross-tool model import (C#4.3) and the depth of search/filtering (C#4.4). The results show that some tools are highly configurable yet score low in interoperability with other EA tools—an issue that can affect migration, consolidation, or multi-tool environments. Because C#4 is highly weighted (0.26), this becomes a strong discriminator.

Finally, C#5 Decision Support and Project Management differentiates tools via the presence/absence of gap analysis (C#5.1) and the maturity of project planning support (C#5.2). Although C#5 has the lowest weight (0.05), it still separates modeling-centric tools from platforms that connect architecture to execution. The radar charts make this explicit by showing narrower profiles for tools with absent C#5 capabilities. In sum, the key differentiators are concentrated in a small set of recurring capability dimensions—framework breadth and export interoperability (C#1), cloud repository connectivity (C#2), Office integration (C#3), cross-tool import and navigability (C#4), and the presence of gap-analysis/execution support (C#5).

Interpretation of the results for answering RQ#3

RQ#3 requests recommendations for small, medium, and large energy companies when selecting an EA tool for regulated environments. The manuscript’s results support differentiated recommendations by combining: (i) the AHP weighting logic (C#1 and C#4 dominate), (ii) the capability profiles revealed in Schema **1** and Schema **2**, and (iii) the observed context that EA staffing is often lean even in regulated settings, increasing dependence on tool support for governance and traceability.

(1) For small energy organizations (limited EA staffing and lower architectural operational capacity), the results suggest prioritizing tools that maximize ease of use and fast time-to-value while still meeting baseline standards (ArchiMate/TOGAF). Under the AHP structure, this implies emphasis on C#4 usability and “sufficient” C#1 modeling rather than deep governance automation. Lightweight tools can be defensible when the organization’s primary goal is consistent modeling and documentation rather than full repository governance and integration with execution. However, the heatmap highlights that such tools may systematically lack decision-support functions (C#5.1) and broader framework coverage (C#1.6), which should be treated as explicit constraints rather than overlooked gaps.

(2) For medium-sized energy companies, the results support choosing tools with balanced profiles across C#1–C#4, because architectural coordination typically expands beyond individual modelers to cross-functional stakeholders. Here, the radar charts (Schema **2**) are particularly informative: alternatives with broad polygons across modeling, repository, presentation, and usability reduce the need for compensating tools and lower coordination overhead. Given the high weights on C#1 and C#4, tools that meet the standards and have robust navigation/import/search capabilities align best with the evaluation logic.

(3) For large utilities (high complexity, distributed stakeholders, strong compliance obligations, and IT/OT/DER heterogeneity), the results indicate the strongest fit for repository-centric platforms that sustain continuous architectural visibility and governance. In these settings, full repository collaboration (C#2) and communication capability (C#3) become practically important, even with moderate weights, because they support auditability, shared understanding, and portfolio-level decision traceability. The tool evaluations show that higher-ranking alternatives combine strong C#1/C#4 performance with mature repository functions, while lower-ranking tools may require external compensations (*e.g.*, for Office integration or exchange formats). Overall, RQ#3 can be answered as a size-sensitive rule: small firms should select usability-forward tools with sufficient standards compliance; medium firms should select balanced platforms with strong C#1–C#4 coverage; and large utilities should select repository-centric tools that maintain governance, collaboration, and traceability at scale, consistent with the AHP priorities and observed capability gaps.

Summary of key findings from RQ#1–RQ#3

The analysis demonstrates that EA tool suitability in regulated energy environments is primarily determined by strong performance in Modeling and Frameworks

(C#1) and Usability (C#4), which together dominate the AHP weighting structure. Repository-centric, standards-rich tools therefore achieve superior overall suitability, while lightweight or narrowly focused tools are constrained despite strengths in individual dimensions. Tool rankings reflect a balance of capabilities rather than isolated excellence, confirming that heterogeneous EA requires broad, not specialized, support.

The principal differentiators across tools are not absolute performance levels, but systematic capability gaps in specific sub-criteria that materially affect aggregated suitability. These include: (i) breadth of supported EA frameworks and export interoperability within C#1, (ii) cloud-enabled repository collaboration in C#2, (iii) native stakeholder communication support versus export-only workflows in C#3, (iv) cross-tool model import and advanced navigation in C#4, and (v) the presence or absence of AS-IS/TO-BE gap analysis and execution support in C#5. Together, these dimensions separate modeling-centric, repository-centric, and execution-oriented tool profiles.

Recommendations for Energy Firms in Smart Energy and Sustainable Technology Contexts

First, EA tools should be selected and used as SmartGrid governance backbones (to document AS-IS and TO-BE status), not as standalone modeling utilities. The evaluation shows that suitability in regulated, heterogeneous environments is driven primarily by Modeling & Frameworks (C#1) and Usability (C#4), *i.e.*, standards-compliant representation (ArchiMate/ TOGAF, framework coverage, exchange formats) combined with operationally efficient use (role-based configuration, import/interoperability, search). These capabilities are essential to maintain coherence across smart metering, grid-edge platforms, DER coordination layers, and AI-enabled energy management, while preserving traceability from regulatory constraints and decarbonization targets to concrete digital implementations.

Second, SmartGrid and DER-intensive contexts require deliberate support for IT/OT/DER convergence through repository-centric governance. Utilities should prioritize EA platforms that sustain collaborative repositories and structured views (C#2), enabling shared interpretation across grid operations, OT engineering, ICT teams, cybersecurity, and compliance. Where repository collaboration or cloud connectivity is limited, compensating controls (data-integration routines, governance workflows, complementary platforms) should be defined explicitly to prevent fragmentation and “repository decay.”

Third, architectural transparency should be treated as a practical enabler of sustainability and carbon-reduction decision-making. EA tools with strong dissemination capabilities (C#3)—either via native Office integration or robust export pipelines—support repeatable reporting for executives, regulators, and sustainability stakeholders, strengthening auditability, ESG-aligned documentation, and low-carbon investment planning.

Fourth, tool choice should be aligned with organizational scale and SmartGrid maturity (RQ#3). Small DSOs and smaller energy firms typically benefit from usability-forward tools that enable rapid AS-IS/TO-BE modeling; medium-sized firms should prefer balanced coverage across C#1–C#4 to support cross-functional coordination; large utilities should prioritize repository-centric platforms capable of sustaining long-horizon governance, DER portfolio traceability, and audit-ready reporting across IT/OT landscapes.

Finally, because Smart Energy Systems increasingly rely on ICT and AI, EA tools should integrate with the broader digital ecosystem rather than remain static repositories. Strong usability and interoperability (C#4) better support the adoption of AI-driven forecasting, predictive maintenance, and consumption modeling workflows that sit at the intersection of SmartGrids, sustainability targets, and operational reliability.

C. Implications for Sustainable Smart Energy Ecosystems

This study suggests that EA tools should be interpreted as governance infrastructures that help operationalize sustainability goals in smart energy ecosystems. Under the AHP weighting, Modeling and Frameworks (C#1) and Usability (C#4) dominate suitability, implying that sustainability-relevant governance depends on standards-compliant representations that remain usable in daily practice. In decarbonization and renewable integration programs, these capabilities support traceable target architectures and migration roadmaps for DER-rich portfolios. In energy-efficiency and smart-metering ecosystems, repository and presentation capabilities (C#2–C#3) strengthen auditability and stakeholder reporting by maintaining consistent views across data, applications, and integration layers. Finally, resilience requirements—amplified by cybersecurity governance obligations in regulated utilities—are supported when tooling enables explicit boundary modeling, dependency analysis, and controlled evolution of architectures across IT/OT interfaces.

5. CONCLUSION

This study evaluated how EA software tools can support smart energy governance and sustainable digital transformation in regulated, asset-intensive environments, with emphasis on energy utilities facing SmartGrid modernization, IT/OT convergence, advanced metering, and rising DER penetration under strict reliability and compliance constraints. The research combined survey evidence from regulated sectors in the Czech Republic with a structured AHP-based multi-criteria evaluation of seven EA tools using a transparent hierarchy of criteria and sub-criteria.

Regarding the research questions, the findings suggest that tools are most suitable for regulated heterogeneous EA modeling (RQ#1) when strong standards-compliant modeling and interoperability (C#1) are combined with high usability and navigability (C#4), supported by repository-centric collaboration (C#2) and stakeholder-ready dissemination (C#3). Key differentiators (RQ#2) are recurring gaps affecting governance and traceability—framework and exchange-format coverage (C#1), repository/cloud collaboration (C#2), Office/reporting integration versus export-only workflows (C#3), cross-tool interoperability and search (C#4), and formal support for AS-IS/TO-BE transition reasoning (C#5). For size-sensitive recommendations (RQ#3), the results support a pragmatic selection logic: smaller firms benefit from usability-forward tools for rapid modeling and documentation; medium organizations benefit from balanced C#1–C#4 coverage to enable cross-stakeholder coordination; and large utilities benefit most from repository-centric platforms that sustain long-term visibility, collaboration, and audit-ready reporting across complex IT/OT/DER portfolios.

Table **13** summarizes the key managerial implications derived from RQ#1–RQ#3.

Limitations of the research and call for further research

This study contributes a transparent and reproducible AHP-based evaluation framework combined with an empirically grounded comparison of EA tools, providing practical guidance for SmartGrid, IT/OT, DER, and sustainability programs in regulated energy environments. At the same time, the findings must be interpreted in light of several limitations. First, the empirical evidence is derived exclusively from respondents in the Czech Republic, and therefore reflects country-specific regulatory, institutional, and organizational conditions rather than international contexts. Second, the graphical notation language ArchiMate is treated as a de facto national-level standard for EA modeling in the Czech Republic [12, 13, 30, 31], which may influence tool suitability assessments in environments where alternative standards prevail. Third, the study relies on non-probability (convenience) sampling through

Table 13: Managerial Implications for EA Tool Selection in Smart Energy Systems

Implication	Focus (RQ)	Relevant AHP Criteria	Managerial Meaning for Energy Firms (SmartGrid / IT / OT / DER)	Practical Action
#1: Prioritize EA capabilities enabling SmartGrid and sustainability governance	RQ#1	C#1, C#4	Tool suitability in regulated energy environments depends on standards-compliant modeling and high usability to manage heterogeneous SmartGrid, IT/OT, and DER architectures while maintaining traceability to regulatory and decarbonization goals.	Select EA tools with strong ArchiMate/TOGAF support, interoperability, and efficient day-to-day use as the baseline for SmartGrid governance.
#2: Treat EA capability gaps as governance risks	RQ#2	C#1–C#5	Systematic gaps (framework breadth, cloud collaboration, reporting, interoperability, gap analysis) translate into risks for compliance, transparency, and digital-energy governance.	Explicitly identify missing sub-criteria during selection; accept, mitigate, or compensate gaps via complementary tools or governance processes.
#3: Align EA tool archetype with SmartGrid maturity and organizational scale	RQ#3	C#1–C#4	Different organizational sizes and SmartGrid maturity levels require different EA tool profiles, from usability-focused tools to repository-centric governance platforms.	Apply size-sensitive selection: lightweight tools for small DSOs, balanced tools for mid-scale utilities, repository-centric platforms for large utilities.
#4: Institutionalize AHP-based selection in SmartGrid and sustainability programs	Cross-RQ	C#1–C#5	Structured, transparent AHP-based evaluation improves managerial decision quality and alignment between EA tooling, AI/ICT integration, and sustainability objectives.	Embed AHP scoring, criteria mapping, and visual analytics (heatmaps, radar charts) into procurement, adoption, and governance practices.

professional networks, which may introduce self-selection bias and limit generalizability. The relatively modest survey response size (55 responses from 105 invitations) constrains statistical inference, while the interview component, involving a small number of participants, limits analytical breadth. In addition, the results are based on self-reported adoption and usage, which may be affected by recall or social desirability bias.

Future research should pursue two complementary directions. First, it should extend comparative analyses beyond the Czech context to capture cross-country regulatory diversity and to more rigorously quantify causal relationships between EA maturity, EA tool capability profiles, and measurable digital transformation outcomes, including interoperability, cybersecurity, and system reliability in DER-rich SmartGrid environments [13,15,32,33]. Second, further attention should be paid to the evolving requirements for EA tooling in regulated smart energy ecosystems. Emerging AI-enabled capabilities—such as automated model quality assurance, pattern detection, and decision support—have the potential to reduce the operational burden on lean EA teams, while the increasing adoption of digital twins reinforces the need for consistent metamodel governance across cyber-physical asset representations. At the same time, the rise of cloud-native smart energy platforms and data spaces places greater emphasis on repository collaboration, interoperability, and standardized integration interfaces. These trends indicate that EA tool evaluation frameworks should progressively move beyond baseline modeling compliance to incorporate criteria related to platform connectivity and governance automation.

Novel contribution to EA practice in a regulated environment

The article is novel because it (i) reconceptualizes EA tools as Smart Energy governance infrastructures, (ii) introduces a governance-oriented, AHP-based evaluation logic, (iii) interprets tool differences as governance risks rather than feature gaps, (iv) grounds EA research in regulated SmartGrid practice, and (v) delivers actionable, context-sensitive recommendations for energy transformation. Collectively, these contributions advance EA research beyond abstract modeling discussions toward decision-making frameworks essential for digitally enabled, sustainable, and regulated energy systems.

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