

---

# Energy Data Ecosystems Driving Sustainable Energy Mix Optimization in the EU: A 27-Country Assessment

Chinyere C. OKECHUKWU\* and Pavel BACHMANN

University of Hradec Kralove, Hradec Kralove, Czech Republic; chinyere.okechukwu@uhk.cz;  
pavel.bachmann@uhk.cz

\* Corresponding author: chinyere.okechukwu@uhk.cz

**Abstract:** The European Union's transition to climate neutrality requires not only renewable deployment but also institutional capacity to govern increasingly data-intensive electricity systems. While prior research emphasizes technological innovation, market design, and carbon pricing, limited attention has been paid to the strategic role of national energy data infrastructures. Drawing on the Resource-Based View and the Knowledge-Based View, this study conceptualizes energy data ecosystems as institutionalized public knowledge capabilities and examines their relationship with sustainable energy performance across the 27 EU Member States. To operationalize this perspective, the study develops and applies the Data-Centric Information Management Maturity Model, which evaluates national energy knowledge infrastructure along four dimensions: accuracy, timeliness, coverage, and accessibility. Using structured document analysis of Eurostat, ENTSO-E, and national regulatory sources, Member States are comparatively assessed and clustered into maturity tiers. The results reveal substantial heterogeneity in digital energy governance despite regulatory harmonization. Higher maturity scores consistently align with stronger renewable penetration and lower electricity-sector greenhouse gas intensity, supporting a structured capability performance relationship. By extending resource-based theory to national digital public infrastructure and introducing a measurable construct of institutional knowledge capability, this study advances strategic management scholarship and positions digital governance as a foundational pillar of sustainable energy transitions.

**Keywords:** energy data governance; renewable energy; Resource-Based View (RBV); Knowledge-Based View (KBV); digital public infrastructure

**JEL Classification:** Q48; O33; C43

---

## 1. Introduction

The European Union's commitment to climate neutrality by 2050 represents one of the most ambitious structural transformations in contemporary economic policy. Under the European Green Deal and REPowerEU framework, Member States must accelerate renewable deployment while strengthening market integration and energy security (European Commission, 2022). Although existing research emphasizes infrastructure

expansion, carbon pricing, and technological innovation, comparatively limited attention has been paid to the institutional maturity of national energy data systems that underpin renewable-heavy electricity markets. (Pahle et al., 2018; Sue Wing et al., 2020; Shahbaz et al., 2022),

Modern electricity systems are increasingly information-intensive and digitally coordinated (Goldfarb & Tucker, 2019; Nambisan et al., 2019). The integration of variable renewable sources such as wind and solar requires continuous monitoring, rapid coordination, and transparent market signaling (ENTSO-E, 2024; Ma et al., 2024; Santarius, T et al., 2021). Unlike fossil-based systems, renewable-heavy grids depend on reliable and timely data to balance supply and demand, manage cross-border flows, and mitigate volatility (ENTSO-E, 2024; Ma et al., 2024). In this context, energy data infrastructure is not merely administrative; it constitutes a core governance mechanism shaping system coordination and investment certainty.

Despite regulatory harmonization within the EU, Member States differ substantially in the maturity of their energy data ecosystems. These institutional differences align with broader research on digital transformation and sustainability governance (Pierli, G et al., 2023). Some countries operate advanced, interoperable platforms with real-time and machine-readable access, while others face delays, fragmentation, and limited accessibility (European Commission, 2024). These disparities raise a critical theoretical and empirical question: do differences in digital energy governance capacity influence renewable integration and carbon performance?

To address this question, this study draws on the Resource-Based View (RBV) and the Knowledge-Based View (KBV). The RBV posits that performance differences arise from heterogeneous resource endowments (Barney, 1991). Extending this logic to national systems, digital energy infrastructure can be conceptualized as a strategic public resource. The KBV further refines this argument by identifying knowledge as the most strategically significant resource in complex environments (Grant, 1996). Renewable-heavy electricity systems are inherently knowledge-intensive; their performance depends on the reliability, timeliness, comprehensiveness, and diffusion of energy-related information. National energy data ecosystems can therefore be conceptualized as institutionalized knowledge capabilities.

The study operationalizes this theoretical perspective through the Data-Centric Information Management Maturity Model (DCIM-MM), which evaluates national energy data systems across four dimensions: accuracy, timeliness, coverage, and accessibility. Applying the DCIM-MM to all 27 EU Member States provides one of the first structured cross-country assessments of digital energy governance maturity and examines its relationship with renewable share and greenhouse gas intensity. By integrating RBV and KBV with a national-level maturity operationalization, this study advances strategic management theory beyond the firm and introduces digital public infrastructure as a determinant of sustainability performance. It thus fills a theoretical and empirical gap at the intersection of energy policy and knowledge-based resource theory.

## 2. Theoretical Framework

This study conceptualizes national energy data ecosystems through the Resource-Based View (RBV) and the Knowledge-Based View (KBV) to explain cross-country variation in sustainable energy performance. The RBV argues that persistent performance differences arise from heterogeneous resource endowments (Barney, 1991). Resources generate advantage when they are valuable, rare, inimitable, and non-substitutable. This perspective builds on institutional economics emphasizing governance structures and transaction efficiency (Williamson, 1985). Although traditionally applied at the firm level, RBV logic extends to national systems. States differ in institutional capacity, regulatory design, and infrastructural sophistication, potentially producing divergent outcomes under similar policy regimes.

In renewable-heavy electricity systems, digital energy infrastructure constitutes a strategic public resource. Reducing information asymmetry and transaction costs is critical in platform-mediated and data-intensive environments (Cennamo & Santalo, 2013; van Dijck et al., 2018). Where digital infrastructures are interoperable, institutionally embedded, and difficult to replicate, they exhibit characteristics consistent with RBV. However, RBV does not specify which resources are most decisive in knowledge-intensive systems. The KBV refines this perspective by identifying knowledge as the central strategic resource (Grant, 1996).

Renewable-heavy electricity markets are inherently knowledge-intensive. System stability depends on continuous data generation, integration, and dissemination (Grant, 1996; Nambisan et al., 2019). Energy data ecosystems therefore function not merely as technical platforms but as institutionalized knowledge infrastructures. They perform four core functions: knowledge creation (data validation), knowledge integration (cross-sector aggregation), knowledge dissemination (open access and APIs), and knowledge application (market coordination and policy design). Performance differences emerge from variation in the quality of these capabilities. Countries with mature data ecosystems possess stronger institutional capacity to generate and diffuse energy knowledge, enhancing transparency, coordination, and adaptive capacity.

To operationalize this theoretical framework, the study employs the Data-Centric Information Management Maturity Model (DCIM-MM). The model evaluates national energy knowledge infrastructure across four dimensions: accuracy, timeliness, coverage, and accessibility (Fig. 1). These pillars represent reliability, responsiveness, comprehensiveness, and diffusion structural properties of institutionalized knowledge governance. Figure 2 illustrates the hierarchical pathway from resource heterogeneity (RBV) to knowledge capability (KBV), operationalized through the DCIM-MM and linked to renewable share and carbon intensity outcomes. The framework advances a structured capability performance relationship: mature knowledge infrastructures enhance coordination and transparency, thereby supporting renewable integration and emissions reduction. The model does not assume determinism but theorizes digital public infrastructure as a foundational knowledge capability shaping sustainability performance across national contexts.

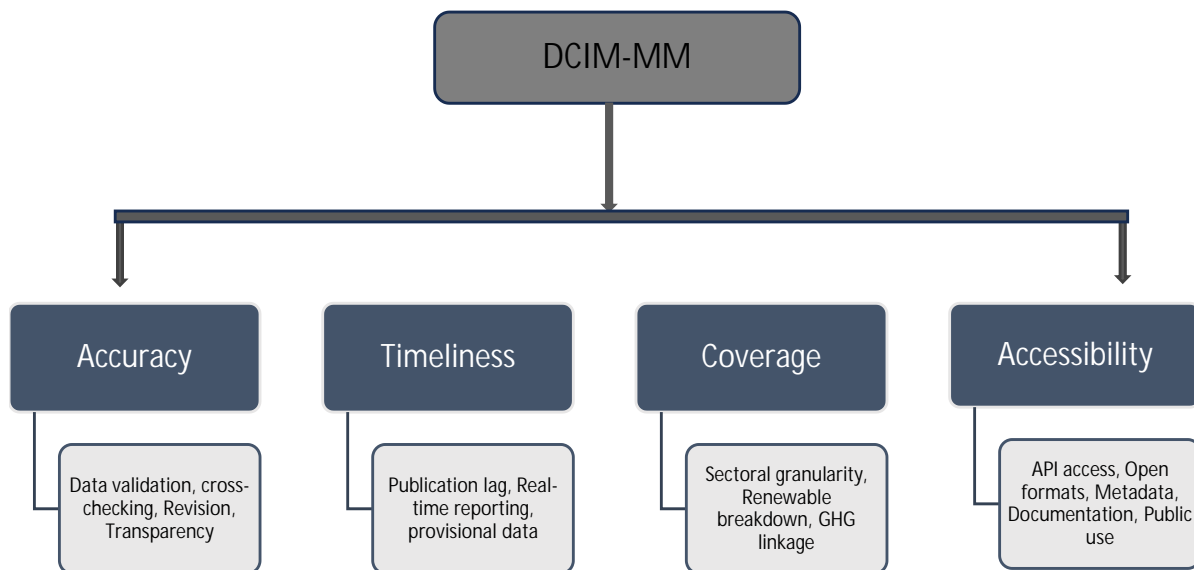


Figure 1. Structure of the DCIM-MM



Figure 2. Theoretical hierarchy and model structure

### 3. Methodology

#### 3.1. Construct Development and Research Design

This study develops and applies the Data-Centric Information Management Maturity Model (DCIM-MM) as a structured operationalization of national-level knowledge capability. While prior maturity frameworks focus primarily on firm-level IT governance and digital transformation, the DCIM-MM extends maturity modeling to public, institutionalized digital infrastructure. This extension aligns with research on digital transformation strategy and public-sector capability development (Hess et al., 2016; Pierli, G et al., 2023), thereby building a cross-level bridge between strategic management theory and national governance systems.

The research adopts a qualitative comparative design based on structured document analysis across the 27 European Union Member States. The unit of analysis is the national energy data ecosystem defined as the institutional architecture governing the production, validation, integration, and dissemination of energy information. Consistent with the Knowledge-Based View (Grant, 1996), digital energy infrastructure is conceptualized as institutionalized knowledge capability rather than a technological artifact. The DCIM-MM captures graded variation across four theoretically derived pillars: accuracy, timeliness, coverage, and accessibility representing reliability, responsiveness, comprehensiveness, and diffusion within national knowledge systems.

### *3.2. Measurement Strategy, Validation, and Analytical Procedure*

Each DCIM-MM pillar is assessed using a structured qualitative scoring rubric to ensure construct consistency across Member States. Indicators are drawn from publicly available institutional sources, including Eurostat energy statistics (Eurostat, 2024; 2025), the ENTSO-E Transparency Platform (ENTSO-E, 2024), national transmission system operator portals, National Energy and Climate Plans, and the European Commission Open Data Maturity Report (European Commission, 2024). Multi-source triangulation enhances internal validity and reduces single-source bias, consistent with best practices in data governance and transparency research.

Each pillar is scored on a standardized three-level maturity scale (low, moderate, high) based on documented evidence. The four pillars: accuracy, timeliness, coverage, and accessibility are weighted equally (25% each) to preserve theoretical neutrality and reflect the interdependence of core knowledge functions under the Knowledge-Based View. The aggregated composite index ranges from 0 to 100 and represents national energy knowledge capability within a harmonized EU regulatory environment. Uniform scoring criteria and consistent temporal reference points strengthen cross-country comparability.

Importantly, the DCIM-MM measures institutionalized knowledge governance capacity rather than technological sophistication alone. This distinction clarifies that the model captures capability maturity, not infrastructure presence. Although qualitative evaluation involves structured judgment, transparent criteria and documented decision rules enhance replicability. The composite scores are examined in relation to renewable energy share and electricity sector greenhouse gas intensity (see Table 1), providing a theoretically grounded proxy for assessing how public digital infrastructure shapes sustainability performance. A detailed replication protocol is provided in Supplementary Appendix A to ensure transparency and methodological robustness.

## 4. Results

The application of the Data-Centric Information Management Maturity Model (DCIM-MM) across the 27 EU Member States reveals substantial heterogeneity in national energy information management capabilities (Table 1). The composite scores reflect the institutional quality of energy data ecosystems as of early 2026, incorporating recent improvements in NECP reporting, TSO platform modernization, and API expansion. Despite regulatory harmonization within the Energy Union, digital maturity varies significantly, reinforcing the Resource-Based View: institutional convergence does not eliminate resource heterogeneity (Barney, 1991). This divergence aligns with broader evidence of uneven digitalization and transition pathways across Europe (Kochanek, 2021; Jonek-Kowalska, 2024).

Table 1. DCIM-MM scores and energy KPIs for 27 EU economies (Eurostat, 2025; EEA, 2024; National TSO/Market Operator Data)

Rank	Country	DCIM Score / IM Maturity	Cluster	Renewables Share (2023/24)	GHG Intensity (gCO2e/kWh)	Key IM Strength	Key IM Gap
1	Denmark	98	High	79.70%	94	World-class API (Energi Data Service)	-
2	Sweden	97.2	High	88.10%	8	Real-time hydro/wind data integration	-
3	Finland	94.5	High	54.30%	40	Datahub centralized retail data	-
4	Netherlands	92.4	High	50.50%	263	High open data maturity, TenneT API	-
5	Estonia	91.5	High	41.00%	610	Estfeed API (Openness)	Carbon Legacy
6	Portugal	90	High	65.80%	119	REN DataHub visualisations & API	Sectoral efficiency data
7	Lithuania	88.7	High	31.90%	29	Real-time Flows	Domestic Gen
8	France	88	High	22.90%	50	RTE eCO2mix app, nuclear transparency	Renewables granularity
9	Spain	87.5	High	59.70%	158	EsiOS API, real-time pricing data	Distributed generation data
10	Latvia	85.4	High	43.20%	67	Market Transparency	Interconnection
11	Germany	85	High	54.10%	329	SMARD platform coverage	Decentralized data aggregation
12	Luxembourg	84.1	High	11.70%	37	Leneda Platform (API)	Domestic RES
13	Austria	84	High	90.10%	85	APG transparency, hydro modeling	Complex federal reporting
14	Belgium	82.5	High	14.30%	145	Elia Open Data, offshore wind data	Heating/Cooling data gaps
15	Slovenia	78.6	Medium	25.10%	176	Open Data (OPSI)	Solar Granularity
16	Ireland	78	Medium	16.30%	260	SEAI "First Look" reports	Micro-generation visibility
17	Italy	75.5	Medium	20.10%	225	Terna transparency	API access barriers
18	Czechia	72.4	Medium	17.90%	440	OTE binary API transition	SME accessibility
19	Slovakia	70	Medium	24.90%	84	OKTE market data & EDC	Energy poverty data
20	Greece	68	Medium	51.20%	258	IPTO Analytics app improving	Historical data consistency

21	Hungary	65	Medium	24.10%	154	MEKH reports, regional integration	Public API availability
22	Croatia	62	Medium	58.00%	134	HOPS/CROPEX reporting	Weather-dependent forecasting
23	Romania	60.5	Low	25.30%	234	Transelectrica basic transparency	API usability (DAMAS)
24	Poland	58.3	Low	18.90%	614	PSE data available, CSIRE delayed	Significant reporting lags
25	Cyprus	55.2	Low	19.40%	585	-	Auto-Curtailment
26	Bulgaria	55	Low	22.10%	281	ESO operational data	Transparency, digitization
27	Malta	52.8	Low	13-17%	342	-	Data Granularity

It is important to distinguish digital maturity from structural energy endowment. For example, Estonia ranks among the top five in DCIM maturity due to advanced API accessibility and structured data governance, yet exhibits high carbon intensity reflecting legacy oil shale dependence. This case illustrates that institutionalized knowledge capability does not automatically eliminate historical fossil lock-in. Rather, digital maturity enhances transition capacity by improving coordination, transparency, and adaptive policy responsiveness. Similar structural effects are observable in Poland (coal dependence) and France (low carbon intensity linked to nuclear dominance). The DCIM-MM therefore captures governance capability, not energy resource structure.

Three capability tiers emerge. High-maturity systems (score  $\geq 80$ ) including Denmark, Sweden, Finland, Netherlands, Portugal, France, Spain, Germany, Austria, and Belgium operate interoperable, near real-time platforms with granular renewable reporting and structured validation. From a Knowledge-Based View perspective, these countries demonstrate advanced knowledge creation, integration, and diffusion capabilities. Many combine strong digital capacity with high renewable penetration and relatively low carbon intensity, suggesting a structured capability–performance alignment.

Medium-maturity countries (score 60–79) exhibit partial transparency and API functionality but fragmented knowledge diffusion. Low-maturity systems (score  $< 60$ ) show reporting lags and limited machine-readability, often coinciding with higher fossil dependence and carbon intensity. While causality is not inferred, the clustering pattern supports the RBV–KBV proposition that institutionalized knowledge capability shapes sustainable energy performance. Beyond ranking differences, a structural pattern emerges. Figure 3 presents the distribution of DCIM scores across Member States.

High-maturity systems consistently exhibit higher renewable penetration, lower GHG intensity, and stronger crisis responsiveness. Digital transparency facilitates efficient renewable integration and adaptive policy responses (Pata, U., et al., 2022; IEA, 2023). Platforms such as Denmark’s Energi Data Service and Germany’s SMARD enabled timely coordination during shocks, whereas lower-maturity systems faced greater institutional friction and slower interventions (Dokupilová, 2024; IEA, 2022; Ruggiero et al., 2014). These

patterns illustrate how knowledge infrastructure conditions adaptive capacity within energy systems (Figure 4).

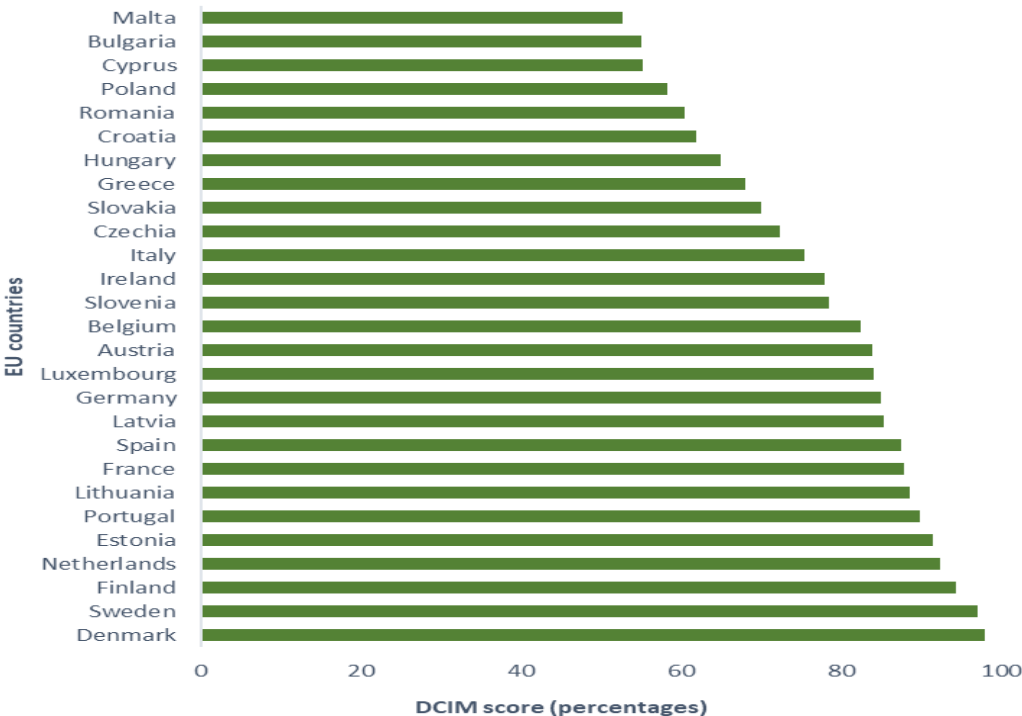


Figure 3. DCIM score (Index, 0–100)

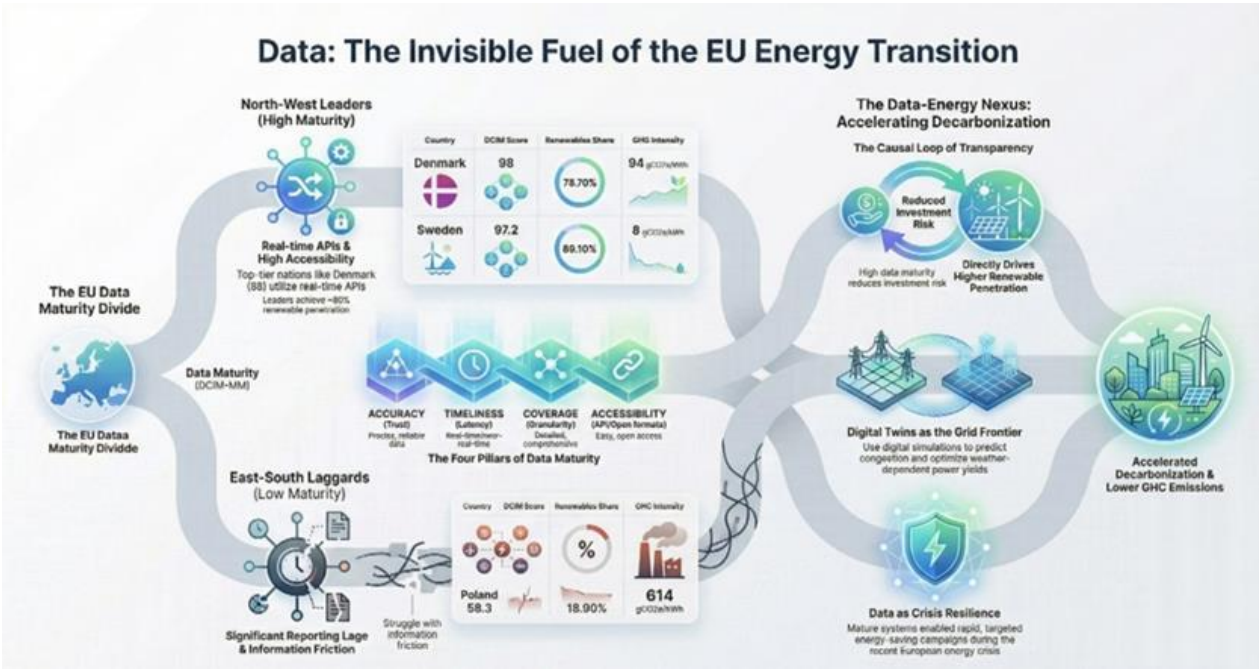


Figure 4. Data energy nexus.

This Data energy nexus loop (Fig 4) suggests that robust data governance acts as a strategic enabler of national energy transitions. The study does not claim deterministic causality but identifies a structured capability performance alignment consistent with RBV and KBV theory. Advanced data systems reduce information asymmetry, lower perceived investment risk, and facilitate renewable deployment. Greater renewable integration

improves grid flexibility and reduces carbon intensity, increasing demand for transparent, high-quality data.

Three conclusions emerge. First, digital energy governance maturity varies significantly across EU Member States despite regulatory harmonization. Second, high DCIM-MM scores reflect institutionalized knowledge infrastructures characterized by reliability, responsiveness, comprehensiveness, and diffusion capacity. Third, stronger knowledge capability systematically aligns with higher renewable penetration and lower emissions. Digital public infrastructure thus functions as a foundational strategic resource shaping sustainable energy performance.

## 5. Discussion

The findings reinforce the central proposition that national energy data ecosystems function as strategic knowledge capabilities shaping sustainable energy performance. Consistent with the Resource-Based View (Barney, 1991), substantial heterogeneity persists across EU Member States despite regulatory harmonization. Digital energy infrastructure is therefore not a uniform administrative feature but a heterogeneous strategic public resource embedded within institutional contexts. This extends RBV logic beyond the firm and aligns with research on digital platforms as coordination mechanisms in data-driven environments (Cennamo & Santalo, 2013; van Dijck et al., 2018).

Extending the Knowledge-Based View (Grant, 1996), the results show that performance differences relate not to the mere presence of digital systems but to their maturity as institutionalized knowledge infrastructures. Countries with high DCIM-MM scores demonstrate stronger reliability (accuracy), responsiveness (timeliness), comprehensiveness (coverage), and diffusion (accessibility). These properties enhance transparency, coordination, and regulatory responsiveness critical features in renewable-heavy electricity systems. The observed alignment between higher DCIM scores, stronger renewable penetration, and lower carbon intensity supports a structured capability performance relationship grounded in strategic resource theory rather than deterministic causality.

A central implication is the existence of a structural digital divide within the Energy Union. High-maturity systems benefit from lower uncertainty premiums, faster renewable integration, greater consumer empowerment, and stronger oversight. Lower-maturity systems face higher coordination costs, slower renewable scaling, and weaker transparency. This divide is institutional rather than purely technological and mirrors broader governance gaps identified in sustainability transition research (United Nations, 2023; World Economic Forum, 2024). Without interoperable standards and harmonized data architectures, cross-border electricity integration remains constrained. The Energy Union's success thus depends not only on physical interconnection but also on convergence in digital knowledge governance.

The study advances theory in three ways. First, it extends RBV to national digital public infrastructure as a strategic resource influencing sustainability outcomes. Second, it deepens KBV by framing energy data ecosystems as institutionalized public knowledge capabilities.

Third, through the DCIM-MM, it demonstrates how maturity models can operationalize cross-national capability heterogeneity in a structured manner.

Policy implications follow. Digital energy governance should be treated as strategic infrastructure. Priorities include standardized EU-wide APIs, harmonized metadata, interoperable reporting formats, and accelerated smart meter integration. Digital transparency and analytics enhance grid flexibility and optimization (Sleiti et al., 2022; Li et al., 2025). Embedding digital maturity benchmarks within EU funding mechanisms could accelerate convergence.

Limitations include the cross-sectional design, potential reverse causality, qualitative scoring subjectivity, and structural energy endowment differences (Newell et al., 1999; IEA, 2024). Future research should employ longitudinal designs, instrumental variables, and quantitative validation to further examine how institutionalized knowledge infrastructure shapes sustainable energy transitions.

## 6. Conclusions

This study set out to examine whether national energy data ecosystem maturity functions as a strategic knowledge capability influencing sustainable energy performance across the European Union. Grounded in the Resource-Based View and the Knowledge-Based View, the analysis conceptualized digital energy infrastructure not as a technical accessory, but as a strategic public resource embedded within institutional governance systems.

The findings demonstrate substantial heterogeneity in energy data maturity across EU Member States. Despite regulatory harmonization, digital knowledge infrastructures remain unevenly developed. Countries with higher DCIM-MM scores consistently exhibit stronger renewable energy penetration and lower electricity-sector greenhouse gas intensity. While structural energy endowments and policy design remain important determinants, the results suggest that knowledge infrastructure quality constitutes an independent and structurally relevant dimension of transition capacity.

From a Resource-Based View perspective, national digital energy systems represent heterogeneous strategic resources. From a Knowledge-Based View perspective, their maturity determines the reliability, responsiveness, breadth, and diffusion of institutional energy knowledge. The DCIM-MM operationalizes this theoretical construct and provides a structured empirical lens through which digital governance capacity can be evaluated. By bridging strategic management theory and energy policy analysis, this study advances understanding of how digital public infrastructure shapes sustainability outcomes. It moves beyond descriptive benchmarking by offering a theoretically grounded explanation of why differences in information management maturity matter.

The broader implication is clear: the energy transition is not solely a transformation of physical infrastructure, but also of institutional knowledge systems. Strengthening national energy data ecosystems enhances transparency, reduces uncertainty, and supports coordinated renewable integration. In this sense, digital knowledge governance constitutes a foundational pillar of Europe's climate neutrality strategy.

Future progress toward a fully integrated Energy Union will depend not only on grid interconnection and renewable capacity expansion, but also on convergence in digital maturity. Institutionalized knowledge capability is therefore not peripheral it is central to the long-term resilience and sustainability of European energy systems.

Acknowledgments: This work was supported by the internal project “SPEV 2026, University of Hradec Králové, Faculty of Informatics and Management, Czech Republic

Conflict of interest: none

## References

- Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management*, 17(1), 99–120. <https://doi.org/10.1177/014920639101700108>
- Cennamo, C., & Santalo, J. (2013). Platform competition: Strategic trade-offs in platform markets. *Strategic Management Journal*, 34(11), 1331–1350. <https://doi.org/10.1002/smj.2066>
- Dokupilová, D. (2024). *Energy poverty in Slovakia: 2024 study*. Slovak Academy of Sciences.
- ENTSO-E. (2024). *Transparency platform data availability report*. European Network of Transmission System Operators for Electricity.
- European Commission. (2022). *REPowerEU plan (COM(2022) 230 final)*.
- European Commission. (2024). *Open data maturity report 2024*. Publications Office of the European Union.
- European Environment Agency (EEA). (2024). *Trends and projections in Europe 2024*. EEA Report.
- Eurostat. (2024). *Renewable energy statistics*. European Commission.
- Eurostat. (2025). *Share of energy from renewable sources 2024 by country*. European Commission.
- Goldfarb, A., & Tucker, C. (2019). Digital economics. *Journal of Economic Literature*, 57(1), 3–43. <https://doi.org/10.1257/jel.20171452>
- Grant, R.M. (1996). Toward a knowledge-based theory of the firm. *Strategic Management Journal*, 17(S2), 109–122. <https://doi.org/10.1002/smj.4250171110>
- Hess, T., Matt, C., Benlian, A., & Wiesböck, F. (2016). Options for formulating a digital transformation strategy. *MIS Quarterly Executive*, 15(2), 123–139.
- IEA. (2022). *Energy policy review: Hungary 2022*. International Energy Agency.
- IEA. (2023). *Energy policy review: Denmark 2023*. International Energy Agency.
- IEA. (2024). *World energy outlook 2024*. International Energy Agency.
- Jonek-Kowalska, I. (2024). Effective transformation of energy resources in the Visegrad Group. *Resources*, 13(5), 64. <https://doi.org/10.3390/resources13050064>
- Kochanek, E. (2021). The energy transition in the Visegrad Group countries. *Energies*, 14(8), 2212. <https://doi.org/10.3390/en14082212>
- Li, S., Zhou, Y., Wu, J., Pan, Y., Huang, Z., & Zhou, N. (2025). A digital twin of multiple energy hub systems. *Applied Energy*, 380, Article 123456. <https://doi.org/10.1016/j.apenergy.2024.124908>
- Ma, S., Ding, W., Liu, Y., Zhang, Y., Ren, S., Kong, X., & Leng, J. (2024). Industry 4.0 and cleaner production: A comprehensive review. *Journal of Cleaner Production*, 467, 142879. <https://doi.org/10.1016/j.jclepro.2024.142879>
- Nambisan, S., Wright, M., & Feldman, M. (2019). The digital transformation of innovation and entrepreneurship. *Research Policy*, 48(8), 103773. <https://doi.org/10.1016/j.respol.2019.03.018>
- Newell, R.G., Jaffe, A.B., & Stavins, R.N. (1999). The induced innovation hypothesis and energy-saving technological change. *NBER Working Paper 6437 (1998)*, <https://doi.org/10.3386/w6437>
- Pahle, M., Burtraw, D., Flachsland, C., Kelsey, N., Biber, E., Meckling, J., Edenhofer, O., & Zysman, J. (2018). Sequencing to ratchet up climate policy stringency. *Nature Climate Change*, 8, 861–867. <https://doi.org/10.1038/s41558-018-0287-6>
- Pata, U., Kartal, M.T., & Depren, S.K. (2024). The Role of Information and Communication Technologies and Energy-Related Research and Development Investments in Energy Transition. *Energy Technology*, 12(5) <https://doi.org/10.1002/ente.202301199>

- Pierli, G., Murmura, F., Bravi, L. (2023). Digital transformation and sustainability: A systematic review. In P. Spagnoletti, M. De Marco, N. Pouloudi, D. Te'eni, J. vom Brocke, R. Winter, R. Baskerville, S. Za, A.M. Braccini (eds.), *Lecture Notes in Information Systems and Organisation* (pp. 83–99). [https://doi.org/10.1007/978-3-031-30351-7\\_8](https://doi.org/10.1007/978-3-031-30351-7_8)
- Ruggiero, S., Onkila, T., & Kuittinen, V. (2014). Realizing the social acceptance of community renewable energy: A process-outcome analysis of stakeholder influence. *Energy Research & Social Science*, 4, 53–63. <https://doi.org/10.1016/j.erss.2014.09.001>
- Santarius, T., Dencik, L., Diez, T., Ferreboeuf, H., Jankowski, P., Hankey, S., Hilbeck, A., Hilty, L.M., Höjer, M., Kleine, D., Lange, S., Pohl, J., Reisch, L., Ryghaug, M., Schwanen, T., & Staab, P. (2023) Digitalization and Sustainability: A Call for a Digital Green Deal. *Environmental Science & Policy*, 147. <https://doi.org/10.1016/j.envsci.2023.04.020>
- Shahbaz, M., Wang, J., Dong, K., & Zhao, J. (2022). The impact of digital economy on energy transition across the globe. *Renewable and Sustainable Energy Reviews*, 166, 112620. <https://doi.org/10.1016/j.rser.2022.112620>
- Sleiti, A.K., Kapat, J.S., & Vesely, L. (2022). Digital twin in the energy industry: Applications and challenges. *Energy Reports*, 8, 3704–3726. <https://dx.doi.org/10.1016/j.egy.2022.02.305>
- United Nations. (2023). *The sustainable development goals report 2023*. United Nations.
- van Dijck, J., Poell, T., & de Waal, M. (2018). *The platform society: Public values in a connective world*. Oxford University Press.
- Williamson, O.E. (1985). *The economic institutions of capitalism*. Free Press.
- Wing, S., Rose, & A.Z. (2020). Economic consequence analysis of electric power infrastructure disruptions: General equilibrium approaches. *Energy Economics*, 89, 104756. <https://doi.org/10.1016/j.eneco.2020.104756>
- World Economic Forum. (2024). *Fostering effective energy transition 2024*. World Economic Forum.

## Appendix A

The Data-Centric Information Management Maturity Model (DCIM-MM) scores are calculated using a structured quantitative framework. The total score (ranging from 0 to 100) is the sum of four equally weighted pillars, each worth a maximum of 25 points. The calculation methodology follows this step-by-step process:

Each country is evaluated against specific criteria within four pillars. Points are awarded based on the presence, quality, and performance of data attributes found in Eurostat datasets, ENTSO-E platforms, and national energy portals.

### Pillar 1: Accuracy (Verification & Consistency) - Max 25 Points

- Series Completeness (10 pts): Calculated based on the continuity of historical data series (Eurostat *nrg\_bal\_s* and *nrg\_ind\_ren*) from 2005 to 2024.
  - *Scoring*: 20 years Available = 10 pts. If a country has breaks in the time series, points are deducted proportionally.
- Cross-Validation (10 pts): Measures consistency between national aggregated data (e.g., TSO reports) and Eurostat figures.
  - *Scoring*: < 1% discrepancy = 10 pts; 1-5% discrepancy = 5 pts; > 5% discrepancy = 0 pts.
- Outlier Protocols (5 pts): Binary score (0 or 5) for the existence of public documentation regarding outlier detection and data correction methodologies.

### Pillar 2: Timeliness (Decision Relevance) - Max 25 Points

- Data Availability (10 pts): Availability of definitive annual data for T-1 (previous year) and provisional data for the current year.
  - *Scoring*: 5 pts for T-1 definitive, 5 pts for current year provisional.
- Publication Lag (10 pts): Based on the latency of monthly reporting.
  - *Scoring*: Real-time/Day-ahead = 10 pts; Monthly (lag < 30 days) = 7 pts; Monthly (lag < 90 days) = 3 pts; Lag > 90 days = 0 pts.
- Provisional Flags (5 pts): Binary score (0 or 5) for the clear labeling of "provisional" vs. "final" data to prevent policy errors based on preliminary stats.

### Pillar 3: Coverage (Holistic Assessment) - Max 25 Points

- Source Granularity (10 pts): Depth of renewable reporting.
  - *Scoring*: 2 pts for each granular category reported (e.g., Onshore Wind, Offshore Wind, Solar PV, Solar Thermal, Biogas). Max 10.
- Sectoral Breakdown (10 pts): Availability of consumption data across 4 key sectors (Industry, Transport, Households, Services).
  - *Scoring*: 2.5 pts per sector fully reported.
- Cross-Domain Linkages (5 pts): Integration of energy data with socio-economic indicators (e.g., energy poverty, prices).
  - *Scoring*: Partial integration = 2.5 pts; Full integration = 5 pts.

### Pillar 4: Accessibility (Stakeholder Reach) - Max 25 Points

- Open Formats (10 pts): Availability of machine-readable files (CSV, JSON, XML).
  - *Scoring*: Non-proprietary formats = 10 pts; PDF/Static only = 0 pts.
- API Availability (10 pts): Functional public Application Programming Interface (API) for automated retrieval.
  - *Scoring*: Full RESTful API = 10 pts; Basic/Limited API = 5 pts; No API = 0 pts.
- Documentation (5 pts): Quality of English-language metadata and user guides.
  - *Scoring*: Comprehensive = 5 pts; Basic = 2.5 pts; None/Native only = 0 pts.