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Harnessing Emerging Workforce Competencies and Talents to Attain Carbon Neutrality through Digitalization

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ABSTRACT

Aligning with Vision 2030 and SDG 13, Saudi Arabia is leveraging digital technologies and youth competencies to drive its transition toward a carbon-neutral economy. Current research often treats sustainability too broadly, limiting deep insights into its key dimensions. To bridge this gap, the present study examines how digital technologies, through their interaction with the emerging workforce, drive energy efficiency, reduce carbon emissions, and stimulate innovation in renewable energy sectors. The study collected data from 320 participants through a survey. The study is conducted in two folds. Firstly, using SPSS exploratory factor analysis discovered the underlying factor structure and confirmatory factor analysis tested and validated the factor structure. Further, structure equation modeling using AMOS was conducted to test the hypotheses. The study examined the direct link between digital technology and workforce competencies, and the moderating role of workforce competencies in the relationship between digital technology and carbon-neutral economy initiatives. The analysis demonstrated a strong positive association between digital technology and the carbon-neutral economy ($\beta = 0.580$, $p < 0.001$). Workforce competencies also exhibited a modest positive relationship with the carbon-neutral economy ($\beta = 0.239$, $p < 0.001$). In addition, the moderation effect of workforce competencies on the digital technology and carbon neutrality relationship was statistically significant but weak ($\beta = 0.029$, $p = 0.042$). These results suggest that while digital technologies and workforce skills both play important roles in advancing carbon neutrality, their interaction contributes only marginally to strengthening this relationship. The study highlights effective strategies to support Saudi Arabia's shift toward a carbon-neutral economy. Integrating digital transformation with workforce development, particularly youth empowerment and digital upskilling can drive innovation, support green startups, and enhance economic diversification, advancing the Kingdom's Vision 2030 goals for sustainable and long-term growth.

Keywords: Carbon Neutrality; Circular Carbon Economy; Digital Technology; Digital Transformation; SDG, Sustainable Development Goals; Youth Competencies

INTRODUCTION

As Saudi Arabia moves toward its ambitious carbon-neutral goals under Vision 2030, the role of digital technologies and emerging workforce competencies has become increasingly significant. Digital technologies such as smart grids (SG), artificial intelligence (AI) driven energy management, internet of things (IoT) based monitoring systems, and blockchain technology (BT) for carbon tracking offer transformative solutions for reducing carbon emissions (Bhatia et al., 2024) and restructuring industry (Negueroles et al., 2024). Simultaneously, young professionals and entrepreneurs bring innovation, technical expertise, and a sustainable driven mindset to accelerate green initiatives (Alkofahi et al., 2024). Despite these potential contributions, integrating such carbon-neutrality initiatives faces challenges, including limited digital adoption in sustainability, youth skill gaps, regulatory barriers, insufficient investment, and weak public private collaboration (Negueroles et al., 2024; Wang et al., 2022).

While Saudi Arabia is investing in digital transformation, the integration of digital technology into climate action remains fragmented. There is a lack of interoperability between digital systems in industries such as energy, transportation, and manufacturing. Though the Kingdom has a young workforce and technology advancements, many lack the specialized skills required for green technology innovation, such as expertise in renewable energy software, AI driven emissions tracking, and circular economy solutions. Despite government support for sustainability, regulatory frameworks for digital driven carbon reduction strategies remain underdeveloped (Mougayar and Buterin, 2016). While major smart city projects like NEOM and the line integrate sustainable digital solutions have begun, other sectors still lack adequate investment in digital sustainability infrastructure, such as smart grids, energy efficient cloud computing (CC), and AI powered industrial emissions monitoring. As a result, young entrepreneurs and startups often struggle to access funding and mentorship for sustainable focused digital innovations, highlighting a gap in public private partnerships for green technology development.

This study underscores the necessity of critical contribution of young workforce in advancing carbon-neutral initiatives with the help of digital technologies within Saudi Arabia. Supported by government led programs and educational reforms that prioritize STEM (Science, Technology, Engineering, and Mathematics), Saudi youth are increasingly engaged in research and innovation in renewable energy, sustainable urban development, and digital transformation. Despite these initiatives, structural challenges persist, such as the digital divide, insufficient specialized training, and regulatory constraints. To address these gaps, the study advocates for targeted policy measures that expand digital literacy, incentivize green entrepreneurship, and strengthen international collaborations to accelerate progress toward the Kingdom's carbon-neutral ambitions (Alkofahi et al., 2024).

Although prior literature offers a solid theoretical foundation in this domain, the empirical validation of the constructs particularly regarding their reliability and applicability when integrating the emerging young workforce remains unestablished. This study employs exploratory factor analysis (EFA) to uncover the underlying dimensions of the role of emerging workforce competencies (EWC) and digital technologies (DT) in promoting carbon neutrality (CN), followed by confirmatory factor analysis (CFA) to validate the proposed measurement model. Further, structural equation modeling using Amos Ver. 26 was conducted to test the hypotheses. Therefore, the present study aims to investigate the impact of DT and the EWC on the transition toward a carbon-neutral economy (CNE). Specifically, it seeks to evaluate the moderating role of EWC in strengthening the relationship between DT adoption and progress toward CN. Accordingly, the study addresses the following research questions:

1. To what extent do DT contribute to achieving a CNE?
2. How does the EWC contribute to the nation's CN efforts?
3. In what ways do the EWC moderate the effective utilization of DT in attaining a CNE?

LITERATURE REVIEW

This section presents previous studies highlighting how Saudi Arabia's Vision 2030 positions DT and the EWC as key enablers of a CNE, thereby advancing environmental sustainability.

Digital Technologies and Carbon Neutral Economy

Contemporary DT such as Big Data, AI, blockchain, IoT, and cloud computing are transforming operational systems, economies, and societies worldwide (Negueroles et al., 2024). These technologies enhance efficiency, performance, and productivity, supporting sustainable development, Industry 4.0 and the circular economy (Akarsu, 2024). Achieving a CNE aligns with UN SDG-13 and requires coordinated multi-sector efforts. Information and Communication Technologies (ICTs) provide critical infrastructure for sustainable progress, enabling energy efficiency, optimized resource management, and low-carbon innovations (Alhassan and Adam, 2021; Asongu and le Roux, 2016). Government investment in ICT infrastructure can facilitate smart energy systems and promote carbon-neutral initiatives, improving sustainable development goals (SDG) performance (Atobishi and Mansur, 2025). In Saudi Arabia, integrating digitalization with the circular carbon economy model demonstrates that IoT and AI optimize resource use and reduce carbon dioxide (CO_2) emissions, highlighting the need for organizational reforms and supportive policies to effectively monitor and manage carbon emissions (Yusuf et al., 2023). The impact of DT on achieving CN is an emerging area of research (Matos et al., 2022). Studies indicate that DT adoption particularly blockchain (BT), IoT, and cloud computing (CC) can reduce carbon emissions, manage carbon credits, and accelerate CN (Dwivedi et al., 2022; Hakovirta et al., 2023; Wang, Feng, et al., 2022; Yang et al., 2022). BT, notably, enhances security, enables transparent carbon credit tracking, improves carbon trading efficiency, and supports targeted decarbonization investments (Pan et al., 2019; Sipthorpe et al., 2022; Zhang et al., 2023).

Blockchain Technology (BT)

DT such as BT, IoT, and data analytics enhance traceability, optimization, and measurement-reporting-verification (MRV) in reuse, recycling, and carbon capture. BT based MRV strengthens the credibility and scalability of carbon accounting in both built environments and voluntary markets. Evidence shows that organizations increasingly implement integrated circular carbon economy (CCE) practices via digital tools rather than isolated measures (Ecklu and Thomas, 2025; Frank et al., 2025; Körner et al., 2025; Woo et al., 2021).

Internet of Things (IoT)

Several studies have examined the role of the IoT in advancing CN objectives. IoT integrates interconnected devices equipped with sensors to collect, transmit, and analyze data, enabling the real-time monitoring and optimization of operational and environmental parameters across dispersed locations (Akpakwu et al., 2018). This capability supports net-zero infrastructure, smart cities (Bellini et al., 2022), and climate-smart agriculture (Dibal et al., 2023) by facilitating efficient resource use and reducing emissions. In manufacturing, IoT technologies capture carbon emission data across every stage of a product life cycle, offering visibility into high impact areas and enabling precise, data driven emission reduction measures (Mishra et al., 2019). Similarly, the Internet of Vehicles (IoV), which integrates IoT technologies into transportation systems, enables accurate monitoring of vehicular emissions and generates data driven insights to inform effective emission reduction measures (Huang et al., 2024). Achieving net-zero goals requires broad deployment of such energy efficient, IoT enabled systems, which optimize resource consumption and operational efficiency, thereby accelerating the transition toward sustainable, low carbon economies (Bouckaert et al., 2021).

Cloud Computing (CC)

Infrastructure is experiencing rising demand due to its advanced computational capacity and accessible services (Da Silva et al., 2023). It supports CN by improving scheduling efficiency (Zhang et al., 2023) and has been effectively applied in sectors such as tourism, where integration with big data and 5G facilitates the development of carbon-neutral scenic destinations (Tong, 2022). Big data analytics facilitates informed decision-making processes within sustainable supply chain management and energy system operations. Additionally, advancements in CC, big data, and the IoT are driving the evolution of smart cities, creating new opportunities for intelligent energy management systems that enhance sustainability and optimize resource utilization (Zhu et al., 2022).

Artificial Intelligence and Machine Learning (AIML)

AI adoption indicate that the application of DTs can enhance the strategic orientation and performance of purchasing departments (Allal-Chérif et al., 2021; Luqman et al., 2024). Recent research by, Lee et al., 2022 further emphasizes that AI will positively contribute to energy transitions, accelerating progress toward carbon-neutral goals. Cao et al., 2022 reviews policy and technological pathways toward carbon-neutral data centers by examining major emission sources and prevailing industry practices. It highlights strategies such as renewable energy integration, enhanced energy efficiency, circular energy utilization, participation in carbon markets, and the application of digital twin driven AIML frameworks as viable means to achieve CN.

Cybersecurity (CS)

As IoT-enabled control framework for commercial buildings was presented by Pan et al., 2015, integrating smartphone interfaces with cloud infrastructure to enable energy proportional operations. Empirical testing confirms its effectiveness in achieving substantial energy savings while enhancing building intelligence.

Influence of Digital Divide on Emerging Workforce Talent

Education and Skill Development (ESD)

Access to high-speed internet and digital devices is essential for online learning, digital literacy, and skill development. The digital divide limits opportunities for underprivileged youth, leading to lower academic performance and reduced access to higher education (DiMaggio and Hargittai, 2023; Huisman, 2021). Digital literacy is also critical for the modern job market, yet unequal access exacerbates social inequalities (Helsper and van Deursen, 2017). Similarly, implementing blockchain requires expertise in IT, CS, data analytics, and supply chain management, which many firms lack due to budget constraints and limited training, resulting in slower integration, inefficiencies, and higher operational costs (Choi et al., 2020; McKinnon et al., 2017).

Employment Opportunities (EO)

The shift towards digital recruitment, online applications, and virtual networking has increased employment barriers for those without digital access (Lutz, 2019). Job seekers in underserved areas often lack the necessary digital tools to participate in remote job opportunities, online interviews, and freelancing platforms. The gig economy, which relies heavily on digital connectivity, further exacerbates employment disparities, as those with limited internet access miss out on flexible and high paying job opportunities (Gonzales, 2016).

Entrepreneurship and Innovation (EI)

Entrepreneurial success in the digital age is closely linked to access to advanced technology, including CC, AI driven business tools, and e-commerce platforms (Nambisan, 2017). DT enables startups to scale efficiently, yet entrepreneurs in digitally disconnected regions face significant hurdles in accessing global markets and securing venture capital. Without digital resources, young entrepreneurs struggle with branding, online marketing, and customer engagement, limiting their growth potential (Qureshi, 2020).

Global Competitiveness (GC)

Nations and regions with a strong digital technology proficiency tend to perform better in global competitiveness rankings, particularly in technology driven industries (Schwab and Zahidi, 2020). The digital divide not only affects individuals but also determines a country's ability to compete in the global digital economy (Castells, 2009). Advanced economies benefit from a digitally skilled workforce, while those with a persistent digital gap risk economic stagnation and a widening technological divide (Hilbert, 2016).

Social and Economic Inequality (SEI)

Digital exclusion has profound consequences on social mobility and economic equality. The digital divide reinforces income inequality by disproportionately benefiting individuals with access to high paying digital jobs while leaving others behind (Robinson et al., 2015). Studies indicate that unequal access to technology worsens existing disparities in education, employment, and economic mobility (Scheerder et al., 2017). Addressing digital inequality requires policy interventions to ensure equitable access to digital resources for all socioeconomic groups (Huisman, 2021). Based on the overall understanding effect of digital technology on youth talent, it is hypothesized

H1: DT have a positive and significant relationship with EWC in achieving a CNE.

Digital Proficiency among Saudi Arabian Emerging Workforce

Saudi Arabia's 2010 budget devoted 25% of expenditure to human resource development to enhance job-seekers' skills. However, inadequate qualifications, limited technical expertise, and weak English proficiency have constrained the employability of local workers and private section raising concerns about labor costs, employee mobility, and integration challenges that hinder Saudization (Ramady, 2010). Hence, developing digital proficiency among Saudi Arabia's emerging workforce is crucial for advancing a CNE. Despite global reliance on ICTs, digital skill gaps persist, limiting youth engagement in key sectors such as renewable energy, smart infrastructure, and green finance (Camerini et al., 2018). Saudi Arabia's emphasis on digital education and training, positions its youth to contribute significantly to sustainability initiatives. Studies indicate that policies promoting digital literacy enhance national sustainable development outcomes, economic growth, and environmental performance (Atobishi and Mansur, 2025; Chen and Li, 2022). Post Vision 2030, increased digitalization has been linked to reduced ecological footprints, highlighting the role of technologically skilled youth in implementing energy efficient and innovative solutions (Aziz et al., 2024). Overall, fostering digital skills and empowering young professionals is pivotal for accelerating the nation's transition to a CNE. Therefore, it is hypothesized that

H2: EWC has a significant positive relationship with achieving a CNE.

Carbon-Neutral Initiatives Through Digital Technologies and Youth Engagement

The rapid advancement of DT such as AI, big data, CC, and BT is transforming the energy sector and enabling carbon-neutral initiatives by improving energy production, distribution, consumption, and carbon reduction strategies (Lee et al., 2024). Leveraging these innovations alongside youth engagement can accelerate sustainable, low-carbon transitions. However, barriers such as the digital divide, CS risks, and insufficient regulatory frameworks must be addressed to ensure equitable and effective deployment of digital solutions for CN (Couldry and Mejias, 2019; Mitsilegas, 2015). Robust ICT policies and government led digital governance are essential to secure sustainable, inclusive energy transformations (Craigen et al., 2014). Addressing the digital divide and fostering continuous skills development are critical for leveraging youth talent in carbon-neutral initiatives. Equitable access to DT enables youth engagement, unlocking new pathways to achieve carbon-neutral goals and advance sustainability. Recent studies highlight the pivotal role of digital tools in supporting these objectives (Bhatia et al., 2024). Saudi Arabia's focus on digital education empowers youth with the expertise and capabilities to actively drive and implement carbon-neutral initiatives. Integrating technological innovation with human capital development is essential for realizing the Kingdom's carbon-neutral targets. Therefore, it is hypothesized

H3: EWC moderates the relationship between DT and a CNE.

DT, including AI, IoT, and blockchain, enable large-scale renewable energy integration by enhancing forecasting, grid coordination, and transactional trust (Lan, 2024). AI improves generation prediction and demand response, while IoT and BT support smart grids, distributed energy adoption, and reduced curtailment. Empirical evidence identifies digitalization as a key driver of renewable deployment (Aguilar et al., 2021). Moreover, AI and IoT enabled systems enhance energy efficiency in buildings, households, and industries through real-time monitoring, automated control, and optimized management, with studies showing that smart metering and app-based feedback reduce consumption and foster sustained conservation behavior.

Renewable Energy Adoption (REA)

Hafeez et al., 2025 investigate the role of ICT investment and human development in promoting pro-environmental behaviors in China, demonstrating that increase in ICT investment significantly enhance renewable energy consumption and reduce CO_2 emissions, whereas declines in investment exert the opposite effect. A systematic review covering the period 2010–2022 underscores that digitalization is a key driver of renewable energy adoption through technological advances such as smart grids, solid-state batteries, and digital energy systems, while also highlighting challenges related to high implementation costs and CS risks, thereby warranting further inquiry (El Zein and Gebresenbet, 2024). Complementing these findings, Yi et al., 2024, analyzed data from 65 countries between 2002 and 2019, conclude that the digital economy substantially fosters renewable energy innovation, particularly in solar, wind, and biomass sectors, with stronger effects observed in contexts characterized by higher human capital, robust policy frameworks, and substantial investments. (Bennaceur et al., 2024), applying ARDL models to Saudi Arabia (1990–2020), reveal that ICT diffusion exerts a long-term mitigating effect on CO_2 emissions, especially when coupled with renewable energy expansion, thereby moderating the environmental consequences of economic growth. Similarly, Khan et al., 2022, focusing on Germany, confirm a bidirectional causal relationship in which technological innovation drives renewable energy adoption, while progress in renewable energy further stimulates technological advancements. Within the Industry 4.0 framework, digitizing energy end-users enhances sustainability by enabling consumption pattern analysis, fostering supplier and consumer integration, supporting smart grid deployment, and facilitating renewable energy integration (Ghobakhloo and Fathi, 2021). Furthermore, (Hu et al., 2022), emphasize that ICT integration within smart grids, particularly through two-way communication mechanisms, enhances energy efficiency, reduces operational costs, and facilitates renewable energy integration, with empirical evidence across multiple regions substantiating these benefits.

Energy Efficiency and Conservation (EEC)

Zahid et al., 2025 demonstrated that ICT adoption across G20 economies enhances energy efficiency and sustainability, with governance structures playing a critical moderating role in policy effectiveness. Mirza et al., 2024, identified a dual effect of ICT use in developing nations, where technological adoption increases energy consumption and CO_2 emissions, yet rising oil prices stimulate the deployment of efficiency-oriented innovations. Soares et al., 2021 advanced this perspective through the development of ECO play, a gamified platform leveraging personalized feedback, peer comparison, and machine learning to foster energy conscious behavior among building occupants. Complementing these findings, (Dzwigol et al., 2024) highlighted that while digitalization reduces energy intensity and alters consumption structures, it also generates new demands linked to DT, with outcomes varying across contexts. Similarly, (Xu et al., 2022) confirmed that digital transformation contributes to reduced energy use and greater efficiency, mediated by factors such as technological innovation and human capital, particularly in underdeveloped regions.

Circular Carbon Economy (CCE)

Khan, 2022 emphasized that DT, including BT, big data analytics, and other Industry 4.0 applications are pivotal in facilitating circular economy practices such as recycling, refabrication, and reuse. The study argues that effective implementation of a circular economy relies on digital infrastructure, which enhances environmental performance and promotes sustainable development. Similarly, Liu et al., 2022 presents a conceptual framework demonstrating how technologies like IoT and AI support the circular economy by enabling monitoring, tracking, and detection, while emphasizing the importance of digital innovation to close the material loop, extend product lifespans, and improve end-of-life recycling processes.

Green Innovation Technology (GIT)

Digital technologies also foster green innovation and reduce carbon intensity. Firm level and panel studies demonstrate that digital tools improve the quantity and quality of green innovations, lower emissions, and facilitate efficient research and development and deployment through advanced data infrastructure, analytics, and digital platforms. At the macro level, digital platforms further support the development and diffusion of carbon-neutral technologies, although potential rebound effects should be considered (Guo et al., 2025; Hoque and Lee, 2025). Finally, digital platforms and e-governance enhance public environmental awareness and enable citizen participation in policymaking, indirectly promoting carbon-neutral transitions. Evidence suggests that social media and digital participation tools increase engagement with climate initiatives; however, their effectiveness at the city level varies, highlighting the need for carefully designed policies to ensure sustained low-carbon outcomes (Shin et al., 2024; B. Xu et al., 2025). Proactive government support in finance, infrastructure, regulation, and education can accelerate technological diffusion and strengthen stakeholder alignment across various industries. With such coordinated efforts, firms can more effectively adopt technology, fostering innovation and enhancing competitiveness (Venkatesh et al., 2003). Bocken and Short, 2021 contend that unsustainable practices cannot be solved by DT alone, requiring broader systemic change through green innovation for sustainability transitions.

Policy and Awareness Support (PAS)

E-participation initiatives (Porwol et al., 2016) serve as important mechanisms for strengthening policymaking by combining citizen involvement with innovative DT. In the era of digitalization and modern governance, collective intelligence (CI) contributes significantly to advancing both theoretical and practical discussions on e-participation and its role in shaping policies. Through the use of ICTs, e-participation enhances citizen engagement in democratic decision-making, with particular emphasis on the interaction between key stakeholders, the technologies applied, and the stages of the policymaking process (Porwol et al., 2016; Macintosh, 2004). Moreover, the effectiveness of these digital tools is closely tied to the timing and extent of citizens' involvement in the policy development process (Macintosh, 2004). Based on the theoretical foundation, this study proposed the conceptual model illustrated in figure 1, which needs empirical validation.

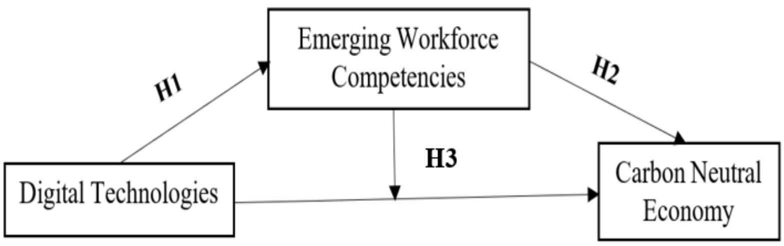

Figure 1. Conceptual Model

METHODOLOGY

The study used quantitative approach and collected research data using a survey questionnaire. The survey instrument was developed from the literature based on the identification of potential enablers of DT and EWC that will contribute for CN. The data analysis conducted EFA to examine the underlying factor's structure and CFA to statistically validate the measurement model.

Data Collection Process and Survey Instrument

The study employed stratified purposive sampling based on expert criteria, collecting data from 320 upper-management employees across Riyadh, Jeddah, and Dammam who possessed advanced knowledge of digital technology adoption and sustainability initiatives in carbon reduction. The survey captured perceptions of technology awareness, workforce capabilities, relevance to carbon reduction, and regulatory factors. Constructs were adapted from prior research and organized systematically. AIML, blockchain, cloud computing, IoT, and cyber security under digital technologies; education, skill development, employment opportunities, entrepreneurship and innovation, global competitiveness, and socio-economic inequality under workforce development; and renewable energy, energy efficiency, circular carbon practices, green innovation, and policy support under carbon-neutral initiatives. Participants were drawn from energy and utilities, manufacturing, logistics and transportation, construction, and digital service sectors, reflecting their involvement in large-scale Vision 2030 projects with sustainable design requirements.

Measurement Items

The study identified three constructs namely DT, EWC and CN. A focused literature review on these three constructs formed the basis for identified enabling factors. These constructs were further refined through consultations with industry experts from energy, utilities, manufacturing, logistics, transportation, construction, and digital services to ensure contextual relevance. A pilot test with 30 participants was then conducted to check clarity and remove redundancies. The industry experts rated their agreement with statements on the identified enablers using a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree).

(1) DT: The DT towards CN were measured by five items namely BT (Ecklu and Thomas, 2025; Frank et al., 2025; Körner et al., 2025; Woo et al., 2021); IoT integration (Akpakwu et al., 2017; Dibal et al., 2023; Mishra et al., 2019; Bouckaert et al., 2021) The use of CC (Tong, 2022; Zhang et al., 2023; Zhu et al., 2022). AIML adoption (Allal-Chérif et al., 2021; Cao et al., 2022; Lee et al., 2022; Luqman et al., 2024) and CS measures (Pan et al., 2015). Example statements used "To what extent do you agree that BT enhances transparency, efficiency, and traceability in carbon management and sustainable supply chains?"; "To what extent do you agree that IoT enables real-time monitoring and optimization of energy and resource usage, contributing to a CNE?"; "To what extent do you agree that AI and ML improve decision-making, predict energy demands, and optimize processes to reduce carbon emissions?"; "To what extent do you agree that robust CS ensures the safe implementation of DT and protects sustainability related data?"; "To what extent do you agree that CC enhances data management, collaboration, and operational efficiency, thereby supporting carbon-neutral initiatives?"

(2) EWC: This construct is measured by five items, ESD (Choi et al., 2020; DiMaggio and Hargittai, 2023; Helsper and van Deursen, 2017; Huisman, 2021); EO (Gonzales, 2016; Lutz, 2019); EI (Nambisan, 2017; Qureshi, 2020) GC (Castells, 2009; Hilbert, 2016; Schwab and Zahidi, 2020) and SEI (Huisman, 2021; Robinson et al., 2015; Scheerder et al., 2017). Example statements used "The development of youth education and digital skills enhances the effectiveness of DT in achieving carbon-neutral goals."; "Greater EO for youth strengthen the impact of DT on organizations' sustainability and carbon reduction efforts."; "Youth-driven EI amplify the contribution of DT toward a carbon-neutral economy."; "Skilled youth help organizations leverage DT to improve GC while pursuing carbon-neutral initiatives."; "Addressing SEI among youth increases the effectiveness of DT in achieving sustainable and carbon-neutral outcomes."

(3) CNE: The construct is measured by five items, REA (Bennaceur et al., 2025; Hafeez et al., 2025; Hu et al., 2022; Khan et al., 2022; Yi et al., 2024); EEC (Dzwigol et al., 2024; Mirza et al., 2024; Soares et al., 2021; Q. Xu et al., 2022; Zahid et al., 2025); CCE practices (Khan, 2022; Liu et al., 2022); GIT (Guo et al., 2025; Hoque and Lee, 2025; Shin et al., 2024; Venkatesh et al., 2003; B. Xu et al., 2025) and PAS (Macintosh, 2004; Porwol et al., 2016). Example statements used "DT (e.g., IoT, AI, blockchain) accelerate the integration and adoption of renewable energy solutions."; "Smart digital tools (such as AI, IoT, and mobile apps) help optimize energy use and promote conservation practices."; "DT enhance the effectiveness of reuse, recycling, and carbon

capture initiatives."; "Digital transformation fosters GIT that reduce carbon emissions."; "Digital platforms and e-governance increase public awareness and policy support for achieving carbon neutrality."

RESULTS AND DISCUSSION

This study utilized the Statistical Package for the Social Sciences (SPSS) version 31 for EFA and Amos 26 for CFA. Table 1 presents the demographic characteristics of the participants. The majority are non-Saudi male, predominantly within the age group of 31 to 40, and directly employed in their respective firms. Most hold a bachelor's degree, with service-based organizations placing greater emphasis on CN initiatives through the adoption of DT.

Table 1: Profile of responding firms.

Variable	Categories	Frequency	%
	Below 20	49	15.31
	21-30	61	19.06
Age	31-40	97	30.31
	41-50	72	22.50
	Above 50	41	12.81
Gender	Male	228	71.25
	Female	92	28.75
	Saudi	122	38.13
	Non-Saudi	198	61.88
Nationality	Bachelor	127	39.69
	Master	118	36.88
	Ph.D.	75	23.44
Type of the firm	Product based	118	36.88
	Service based	202	63.13
Current Occupation / Role	Employee	139	43.44
	Consultant	76	23.75
	Entrepreneur	62	19.38
	Researcher	43	13.44

Exploratory Factor Analysis

EFA is a statistical approach used to represent a large set of observed variables through a smaller number of latent constructs (Kim & Mueller, 1978). Its main purpose is to reduce dimensionality by grouping highly correlated variables into distinct factors (Tabachnick & Fidell, 2002). Among EFA techniques, Principal Component Analysis (PCA) is the most widely applied, serving as a data reduction method that identifies dominant patterns through component scores and loadings (Bryant & Yarnold, 1995; Wold et al., 1987). In this study, PCA with varimax rotation was conducted on fifteen measurement items. Item total correlations ranged from 0.300 to 0.801, with all exceeding the 0.30 validity threshold. Sampling adequacy and factorability were confirmed, with a KMO value of 0.886 (greater than 0.5 as recommended by Tabachnick & Fidell, 2002) and a significant Bartlett's test of sphericity ($\chi^2 = 6684.342$, $p < 0.001$). Scree plots, factor loadings, and total variance explained were examined to validate the factor structure. Only components with eigenvalues above 1 and items with loadings greater than 0.5 were retained. All items loaded strongly on their respective constructs, with values ranging from 0.804 to 0.939. Cross-loadings were checked to ensure construct validity and avoid measurement ambiguity. Table 2 presents the PCA results, with the scree plot shown in figure 2.

Table 2: Rotated Component Matrix.

Item	Component		
	1	2	3
BT	0.923		
IoT	0.939		
CC	0.916		
AIML	0.934		
CS	0.902		

ESD		0.854	
EO		0.896	
EI		0.904	
GC		0.907	
SEI		0.917	
REA			0.831
EEC			0.804
CCE			0.872
GIT			0.878
PAS			0.893
Initial eigenvalues	7.418	3.690	1.809
% of Variance	49.454	24.600	12.061
Cumulative %	49.454	74.054	86.115

Source: SPSS analysis of primary data.

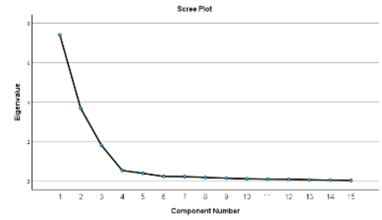

Figure 2: Factor graph for eigen values

Confirmatory Factor Analysis

CFA was conducted using AMOS version 26. The measurement model demonstrated strong construct reliability, as indicated by composite reliability values ranging from 0.940 to 0.960, exceeding the recommended threshold of 0.70 (Nunnally J.C, 1978), as presented in Table 3. The average variance extracted (AVE), which represents the proportion of variance captured by a construct relative to measurement error, ranged from 0.758 to 0.828, surpassing the 0.50 cutoff suggested by (Fornell and Larcker, 1981). Baumgartner et al., 1996; Bentler, 1980; Kline, 2023; suggested the statistically acceptable fit indices as shown in Table 4. The overall model exhibited a good fit across multiple indices: relative $\chi^2 = 2.790$ ($p < 0.001$), GFI = 0.901, CFI = 0.964, RMSEA = 0.080, and SRMR = 0.035. Construct validity was further assessed through convergent and discriminant validity tests. Convergent validity was supported, with factor loadings of the indicators on their respective constructs ranging from 0.725 to 0.981, consistent with the recommendations of (Gerbing and Anderson, 1988). Discriminant validity was confirmed by comparing the square root of the AVE for each latent variable with the correlations between constructs, ensuring that each construct was distinct from the others.

Table 3: Reliability and Convergent Validity.

Variable / Construct	Item	Standardized Factor Loading	Cronbach Alpha	C.R	AVE
	BT	0.981			
	IoT	0.972			
DT	CC	0.955	0.985	0.985	0.932
	AIML	0.972			
	CS	0.947			
	ESD	0.879			
	EO	0.905			
EWC	EI	0.935	0.972	0.970	0.867
	GC	0.964			
	SEI	0.972			
	REA	0.747			
	EEC	0.725			
CNE	CCE	0.854	0.921	0.909	0.668
	GIT	0.869			
	PAS	0.881			

Table 4: Goodness of fit indexes for the factor structure of the scale items.

Goodness of Fit Index	Acceptable Limit	Values Obtained
X2/df	<5 moderate fit <3 good fit	2.556
Goodness of fit index (GFI)	>0.90	0.903
Comparative fit index (CFI)	>0.90	0.954
Normed fit index (NFI)	>0.90	0.942
Relative Fit Index (RFI)	>0.85	0.930
Standardized Root Mean Square Residual (SRMR)	< 0.08	0.038
Root mean square error of approximation (RMSEA)	< 0.08	0.078

The CFA results indicate that BT (0.981), AIML (0.972), and IoT (0.972) exhibit very high standardized regression weights with the DT construct. Similarly, GC (0.964), SEI (0.972), and EI (0.935) revealed substantial loadings on the EWC latent construct, and PAS (0.881), GIT (0.869) are potential items of CNE. This demonstrates that these items strongly contribute and are reliable indicators of the latent construct. As seen in table 5, the correlation results among the constructs DT and EWC is 0.601, $p < 0.001$, indicating a strong and highly significant positive relationship between DT and EWC. Hence, it is inferred that use of DT is strongly associated with the development of EWC. Among EWC and CNE, it is 0.102, $p < 0.05$ which shows a weak but statistically significant positive relationship between emerging workforce talent and carbon-neutral economy. This implies that the capabilities and skills of the workforce contribute positively, though modestly, toward achieving carbon-neutral goals. The association between DT and CNE is 0.067, $p < 0.05$. The correlation between DT and CNE is weak and statistically significant.

Table 5. Correlation of the constructs.

Relationship			Coefficient
DT	<-->	EWC	0.601***
EWC	<-->	CNE	0.102*
DT	<-->	CNE	0.067

The study's findings show that digital technologies DT and EWC are central to Saudi Arabia's transition toward carbon neutrality. Advanced technologies such as BT, AI/ML, the IoT, CC, and CS are expected to improve energy efficiency and reduce carbon emissions across industries. These results are consistent with prior manufacturing research, which emphasizes digitalization as a driver of circular economy practices and economic diversification (Alshammari et al., 2025; Yusuf et al., 2023). CFA further indicates that DT alone may not directly achieve carbon neutrality; instead, their effectiveness is mediated by workforce competencies. Investing in digital education and skills development for Saudi youth can accelerate the carbon-neutral transition, strengthen sustainability, and advance Vision 2030 objectives, ultimately supporting long-term economic resilience. This observation echoes the findings of Alkofahi et al. (2024).

Hypotheses Testing

To test the formulated hypotheses, the study conducted structural equation modelling using Amos version 26 as shown in figure 3, SEM results indicated that the theoretical model demonstrated good fit, and the hypotheses were successfully tested. Hypothesis testing results confirmed that all independent factors are significantly and positively associated with the carbon-neutral economy. Table 6 presents the good fit indices of the structural model, with χ^2 /df = 1.95 ($p < 0.001$), GFI = 0.926, CFI = 0.973, RMSEA = 0.029, and SRMR = 0.037.

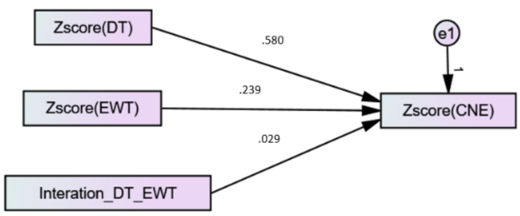

Figure 3: Structural Equation Model

Table 6: Fit Index.

Goodness of Fit Index	Acceptable Limit	Values Obtained
X2/df	<5 moderate fit <3 good fit	1.95
Goodness of fit index (GFI)	>0.90	0.926
Comparative fit index (CFI)	>0.90	0.973
Normed fit index (NFI)	>0.90	0.955
Relative Fit Index (RFI)	>0.85	0.954
Standardized Root Mean Square Residual (SRMR)	< 0.08	0.037
Root mean square error of approximation (RMSEA)	< 0.08	0.029

Table 7: Results of Direct Effect.

Hypothesis	Path	Standardized Path Coefficient	p-Value	Result
H1	DT → CNE	0.580	***	Supported
H2	EWC → CNE	0.239	***	Supported

Table 8: Results of Indirect Effect.

Hypothesis	Path	Standardized Path Coefficient	p-Value	Result
H3	DT * EWC → CNE	0.029	0.042	Supported

The direct and indirect relations are shown in Table 7 and Table 8 respectively. Hypothesis H1 was that DT has a positive significant relationship with CNE. SEM results provide empirical support for the hypothesis, with a path coefficient of 0.580 and a p-value of 0.001. H2 was that EWC has a positive significant relationship with CNE, with a path coefficient of 0.239 and a p-value of 0.001. H3 was that EWC moderates between DT and CNE, with a path coefficient of 0.056 and a p-value of 0.029. Therefore, it is evident that H1, H2 and H3 are supported. However, EWC has low moderating effect between other two constructs. This indicates, EWC exerts only a marginal moderating influence on the relationship between DT and the transition toward CNE. Although workforce competencies remain relevant, factors such as government support, regulatory frameworks, and green technological innovation appear to have a more decisive role in strengthening this linkage.

The findings of this study provide empirical evidence regarding the role of digital technologies and emerging workforce competencies in enabling Saudi Arabia's transition toward a CNE. The demographic composition reflects the labor market realities in Saudi Arabia, where expatriates play a vital role in digital and sustainability-driven sectors, consistent with labor trends observed in prior research on the Kingdom's workforce diversification (Ramady, 2010). The results of the EFA and CFA demonstrate that the constructs under study were statistically robust and valid. The high loadings of BT, AIML, and IoT on the DT construct confirm the critical role of these technologies in driving sustainable transformation. These findings resonate with prior studies emphasizing the disruptive impact of advanced digital tools in enhancing energy efficiency and facilitating low-carbon transitions (Yusuf and Lytras, 2023). Similarly, EWC indicators such as GC, SEI, and EO demonstrated strong contributions, reinforcing earlier arguments that digital skills, adaptability, and global awareness are essential in preparing workforces for green transitions (Alkofahi et al., 2024).

The structural equation modeling results offer deeper insights into the relationships among DT, EWC, and CNE. The significant positive path coefficient between DT and CNE ($\beta = 0.580$, $p < 0.001$) suggests that DT substantially contribute to carbon-neutral goals. This aligns with evidence from international studies showing that digitalization enhances renewable energy integration, resource efficiency, and green innovation (Ghobakhloo and Fathi, 2021). However, the earlier CFA correlation analysis indicated that DT alone did not show a significant direct association with CNE, highlighting a nuanced interpretation: the potential of DT may not be fully realized without complementary enablers such as skilled workforce capabilities, regulatory support, and organizational culture. This finding resonates with the argument by (Bocken and Short, 2021) that DT are necessary but not sufficient to achieve sustainability transitions. EWC demonstrated a positive direct relationship with CNE ($\beta = 0.239$, $p < 0.001$), confirming that human capital is an indispensable driver of carbon neutrality. Workforce competencies such as innovation, emotional intelligence, and sustainability-oriented decision-making enable the translation of digital adoption into meaningful environmental outcomes. This observation is in line with (Alkofahi et al., 2024), who emphasized that human competencies bridge the gap between technological potential and sustainable performance. However, the moderating role of EWC between DT and CNE was weak ($\beta = 0.029$, $p = 0.042$). This suggests that while workforce skills facilitate technological application, systemic factors such as government incentives, carbon regulation frameworks, and green research and development investments may exert stronger influences on the DT–CNE relationship. This finding is consistent with studies in the Gulf context, where national policies and institutional support have been shown to play a critical role in shaping the sustainability outcomes of digital transformation (Alshammari et al., 2025).

Moreover, the results support the premise of Saudi Vision 2030, which prioritizes digital transformation, human capital development, and sustainability as interlinked pillars of national progress. The significant role of DT in this study underscores the Kingdom's ongoing investment in smart cities, renewable energy technologies, and digital infrastructures. At the same time, the modest contribution of EWC highlights the need for strengthening higher education, vocational training, and continuous upskilling programs to align the workforce with carbon-neutral targets. The findings therefore extend the literature by demonstrating that in the Saudi context, technological progress must be coupled with human capital development and robust policy frameworks to accelerate the carbon-neutral transition. Overall, the study confirms that digital technologies and workforce competencies are essential enablers of a carbon-neutral economy, though their effects are interdependent and mediated by broader structural and institutional mechanisms. The findings both validate and extend prior empirical work, offering region specific evidence from Saudi Arabia, where economic diversification and sustainability ambitions are tightly interwoven with digitalization strategies.

LIMITATIONS AND IMPLICATIONS

The study primarily concentrated on selected industries and specific types of DT, which may limit the generalizability of its findings to other contexts or sectors. Additionally, the characteristics and capabilities of EWC can differ considerably across geographic regions, cultural settings, and organizational environments, potentially affecting the broader applicability of the results. The rapid pace of technological advancement further poses a challenge, as new digital tools and platforms may emerge, rendering current findings less relevant over time. Moreover, organizational and human factors such as resistance to change, limited digital literacy, and existing skills gaps can hinder the effective integration of digital technologies with workforce initiatives, thereby constraining their potential impact on achieving carbon-neutral objectives.

The present study holds significant value in contributing to the Kingdom's SDG goals, particularly in alignment with Vision 2030 and the Saudi Green Initiative. As Saudi Arabia commits to reaching net-zero emissions by 2060, digital technology plays a transformative role in optimizing energy efficiency, reducing carbon footprints, and fostering sustainable industries. Additionally, digital platforms facilitate remote work, paperless transactions, and e-governance, further minimizing environmental impact. As the Kingdom's youth are at the forefront of future innovation, entrepreneurship, and technological adoption, the young talent is critical driver in achieving carbon-neutral goals. Educating in emerging fields such as renewable energy, green innovation and technology, circular carbon economy and digital technology, young professionals can lead the development and implementation of nation's SDG goals. Their engagement in startups, training and development, research institutions, and corporate sustainability programs enhances the adoption of clean energy. However, for this transition to be effective, there must be a strong policy and awareness framework along with public-private collaboration. By examining the synergy between digital technologies and youth engagement, this research highlights strategic pathways to integrate sustainability into Saudi Arabia's economic transformation, ensuring a balance between technological advancement and environmental responsibility. Furthermore, the study highlights the crucial role of youth competencies in driving a green economy through entrepreneurship, research, and the implementation of sustainable practices. Future research could explore existing skill gaps, investigate technology adoptions, determine effective strategies and statistically examine the hypothetical model for promoting development in this domain.

CONCLUSION

This study examined the interconnections between DT, EWC and the CNE. It presents empirical evidence on the enablers of DT and EWC in advancing Saudi Arabia's Vision 2030 carbon-neutral goals. The results revealed that DT exerts a strong direct influence on CNE, while EWC contributes a moderate yet significant effect. The evidence highlights that technological advancement alone is insufficient for driving carbon neutrality without complementary human capital development and institutional support. The study demonstrates digital technologies like AIML, CC, IoT and BT can enhance energy efficiency, industrial sustainability, and renewable energy adoption. However, their effectiveness depends on a skilled workforce capable of integrating innovation, and global competencies into organizational practices. This supports the argument that human competencies serve as a critical bridge between technological adoption and tangible sustainability outcomes. At the same time, systemic enablers including government incentives, regulatory frameworks, and green innovation emerge as decisive factors in strengthening the linkage between DT and CNE. From a policy perspective, the results reinforce the priorities of

Saudi Vision 2030**,** where digital transformation, human capital development, and sustainability are positioned as interdependent pillars of national progress. Practical implications include investing in higher education, vocational training, and continuous upskilling initiatives to align the workforce with carbon-neutral objectives. Further, fostering green entrepreneurship, strengthening digital literacy, and embedding sustainability-oriented competencies in organizational cultures can accelerate the transition. Overall, this research provides empirical evidence that both DT and EWC are indispensable enablers of a carbon-neutral economy, though their impacts are interdependent and mediated by broader institutional frameworks.

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