An evaluation of the extent to which South African energy companies leverage Industry 4.0 technologies to improve efficiencies in comparison with China and Germany

By

NADYA BHAGWAN

9802976P

A thesis submitted to the Faculty of Science,
University of the Witwatersrand, in fulfilment
of the requirements for the degree of
DOCTOR OF PHILOSOPHY
10 APRIL 2025

School of Geography, Archaeology and Environmental Studies

DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any other degree or examination at this or any other institution.

Nadya Bhagwan

____

Signed in Johannesburg, on the 10th of APRIL 2025

ABSTRACT

Four industrial revolutions have shaped the global production of goods and services and broader economic development. These revolutions have been disruptive and transformative yet created a continuum in production processes and societal change. The disruptive capacity of these revolutions was steered by scientific and technological discoveries such as the steam engine, electricity, and magnetism as a source of energy and quantum mechanics, as well as their influence on digital technologies. At the centre of each industrial revolution is the production of different types of energy and the technologies that produced them. While most economic activity is still driven by the technologies of the second and third industrial revolutions, the world is currently experiencing the fourth industrial revolution, known as 4IR or Industry 4.0. At the same time, with the inexorable growth in global Gross Domestic Product (GDP) still heavily reliant on fossil fuel-driven energy sources, global warming progresses unabated, notwithstanding heightened investments in renewable energy.

In 2024, South Africa is the largest economy in Africa and the continent's foremost electricity producer. To sustain its economy, South Africa must enhance the efficiency, sustainability, accessibility, and reliability of its energy production. Meanwhile, Germany and China are at the forefront of transforming their own energy sectors. Given South Africa's ongoing energy crisis, assessing how its energy sector compares to those of other countries is worthwhile. This research aims to evaluate the extent to which South African energy companies are utilising Industry 4.0 technologies, compare their usage to that in China and Germany, and the extent to which a limited uptake of such technologies may exacerbate challenges facing the South African energy sector. The study focuses on South Africa, China, and Germany. It includes a literature review, an online survey of 26 energy companies, and interviews with energy companies and industry experts, yielding exciting results.

Global research on energy sector technologies predominantly focuses on the Internet of Things (IoT), Artificial Intelligence (AI), and Big, Real-Time Data (BRTD). In contrast, limited publications on Machine-Human Integration (MHI) and Robotics (ROB) exist. Part of this study

examines the application of Industry 4.0 technologies by energy companies in China, Germany, and South Africa. Overall, survey results indicate that 85% of participants reported their company being a part of the Fourth Industrial Revolution. Additionally, 50% of companies declared their usage of these technologies as “very good” or “good,” whilst a third described such usage as “fair,” although few develop these technologies in-house. The most important, efficient, reliable, and integrable technologies, facilitate access to Big, Real-Time Data and data analysis. The Internet of Things also ranks highly for data transfer. However, Artificial Intelligence, Robotics, and Machine-Human Integration are considered less important, efficient, and reliable. Notably, China rates Industry 4.0 technologies as significantly more critical than South Africa and Germany.

Interviews with energy and technology companies in South Africa, China, and Germany help determine the extent to which these companies leverage Industry 4.0 technologies and whether these contribute to efficiency in energy production. The Internet of Things and Artificial Intelligence amongst Chinese and German companies is at the forefront of their energy sectors, primarily to increase energy system efficiencies and facilitate the transition to an integrated energy sector. The development and use of Industry 4.0 technologies as an integral part of the energy system, has been spearheaded by the state through national policy, as part of a carefully constructed plan for the energy sectors of both China and Germany. Thousands of decentralised renewable energy producers and consumers in Germany are integrated into a flexible power system that produces a more stable power grid. In the case of China, the use of robots in mining, together with digitising the process of safety inspections, resulted in safer working conditions and improved worker satisfaction in its energy sector. Using a more centralised approach that incorporates the implementation and operationalisation of clear, national directives through State-Owned Entities, China is integrating Artificial Intelligence across the energy pipeline to more effectively manage demand and supply through forecasting. In South Africa, where Industry 4.0 technologies appear to be used incrementally, the constructive disruption of Artificial Intelligence on the energy sector has yet to be fully realised. For energy companies, constraints dominating the South African renewable energy sector that continue to slow down its digitalisation are high technology costs and insufficient political will. Even so, the companies in all three countries use Big, Real- Time Data and data analysis and Internet of Things platforms to flag operational and process- related concerns and perform pre-emptive maintenance, boosting plant efficiencies and increasing productivity. However, such usage within South African energy companies is limited and largely piecemeal, the result of the lack of a cohesive national policy framework for using Industry 4.0 technologies in South Africa's energy sector, particularly regarding a strategic approach to adopting Industry 4.0 technologies.

ACKNOWLEDGEMENTS

This has been a tumultuous academic journey, testing my endurance levels in every possible way, yet one of immense self-discovery and self-awareness. I enjoyed meeting interesting people in the energy space and learning about it. Thank you to all those who have nudged me gently along the way, particularly my dearest and nearest. You all know who you are! To my children, Zen and Che, my husband, Bipin, my sister, Mishal, and my parents, Ahmed and Rookaya, thank you for putting up with me and this mammoth task for so damn long! I am particularly grateful for Professor Mary Evans, my supervisor and mentor, who graciously encouraged me down this road, turning what I considered mountains into what were molehills.

RESEARCH OUTPUTS AS PART OF THIS PHD

This study is organised into six chapters, three of which are stand-alone research papers published or under peer-review. These are combined with an introduction, discussion, and conclusion chapters to present a complete PhD thesis. The three papers are:

1. Bhagwan, N., & Evans, M. 2022. A comparative analysis of the application of Fourth Industrial Revolution technologies in the energy sector: A case study of South Africa, Germany, and China. Journal of Energy in Southern Africa, 33(2), 1–14. https://doi.org/10.17159/2413-3051/2022/v33i2a9200 Journal impact factor: 0.647
   Published: May 2022

2. Bhagwan, N., & Evans, M. (2023). A review of industry 4.0 technologies used in the production of energy in China, Germany, and South Africa. Renewable and Sustainable Energy Reviews, 173, 113075. https://doi.org/10.1016/j.rser.2022.113075
   Journal impact factor: 16.799
   Published: March 2023

3. Bhagwan, N. and Evans, M. 2024. Understanding the contribution of Industry 4.0 technologies to Chinese, German, and South African energy companies. Submitted to Renewable and Sustainable Energy Reviews (under review)
   Journal impact factor: 16.799
   Submitted: 19 July 2024

Contents

LIST OF FIGURES

Chapter 2:

Chapter 3:

LIST OF TABLES

Chapter 4:

ABBREVIATIONS

1IR	First Industrial Revolution
2IR	Second Industrial Revolution
3IR	Third Industrial Revolution
4IR	Fourth Industrial Revolution
AI	Artificial Intelligence
AR	Augmented Reality
BRD/BRTD	Big, Real-Time Data
BRICS	Brazil, Russia, India, China, South Africa
CSIR	Centre for Scientific and Industrial Research
DIRP	Draft Integrated Resource Plan
DOE	Department of Energy
EIA	Environmental Impact Assessment
EMSEZ	Energy and Metallurgical Special Economic Zone
EWSETA	Energy and Water Sector Education and Training Authority
FBE	Free Basic Electricity
GDP	Gross Domestic Product
GES	Global Economic System
GT CO^2	One Billion Tonnes of Carbon Dioxide
ICT	Information and Communications Technology
IEA	International Energy Agency
IoT	Internet of Things
IPP	Independent Power Producer
M&G	Mail and Guardian
MHI	Machine Human Integration
MTOE	Million / Mega Tonnes of Oil Equivalent

NDP	National Development Plan
OECD	Organisation for Economic Cooperation and Development
OFO	Organising Framework for Occupations
PPP	Public Private Partnership
PwC	PricewaterhouseCoopers
R&D	Research and Development
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
ROB	Robotics
SANEDA	South African Energy Development Agency
SAREM	South African Renewable Energy Masterplan
SAWEA	South Africa Wind Energy Association
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SEASSA	Sustainable Energy Society of Southern Africa
SoE	State-owned Entity
SSS	Specialised Solar System
STASA	Solar Thermal Association of Southern Africa
UN	United Nations
UNDP	United Nations Development Programme
UNIDO	United Nations Industrial Development Organisation
UNSDG	United Nations Sustainable Development Goal
USAID	United Nations Agency for International Development
USEIA	United States Environmental Impact Assessment
WB	World Bank
WB NACI	World Bank National Advisory Council on Innovation

CHAPTER 1: INTRODUCTION

1.1. Introduction

1.1.1. Global energy systems amidst rampant digitalisation and global warming

United Nations' Sustainable Development Goal 7 (SDG 7) aims for full access to "affordable, reliable, sustainable and modern energy for all" (United Nations, 2016). This comes when more than 600 million people live without electricity, 80% of whom live in Sub-Saharan Africa (United Nations, 2016). While SDG 7 is specific to global energy security, securing energy provision for citizens is relevant to all SDGs. At the same time, with the inexorable growth in global GDP, global energy demand continues to escalate, despite a short-lived, 6% reduction in energy demand caused by worldwide lockdowns and economic decline during the Covid-19 pandemic (International Energy Agency, 2020). This happens at a stage when two conditions are shaping the energy sector. The first is the unabated progression of global warming (Ganopolski, 2019; Fletcher & Smith, 2020; Xie, 2024). Notwithstanding heightened investments in renewable energy, growing the global installed capacity of renewable energy from 849 Gigawatts (GW) in 2000 to 3,258 Gigawatts (GW) in 2021 (South African Department of Mineral Resources & Energy, 2024), reliance on fossil fuels remains unacceptably high. The second is the modernisation of energy production using the technologies of the fourth industrial revolution, or Industry 4.0 (Lyu & Liu, 2021; Ghenai et al., 2022; Wang et al., 2022). SDG 7 is crucially linked with all other SDGs, particularly SDG 13, Climate Action, as sustainable energy is fundamental to sustainable development. Achieving this requires transitioning from fossil fuel-based energy production to renewable energy sources. By 2040, 60% of global energy is projected to be renewable (International Energy Agency, 2018). The 2015 Paris Agreement (United Nations Framework Convention on Climate Change, 2015) aims to reduce carbon emissions to zero by 2050. Addressing these challenges involves reducing energy consumption, especially in the global north.

According to the International Energy Agency (2018), over $2 trillion per year in new energy supply investments will be necessary to meet global energy demand over the next two decades, if global economic growth continues at the current rate. In 2022, the global economy was valued at $102.4 trillion (International Monetary Fund, 2022). Therefore, at current prices, total global energy investments by 2040 are projected to be under two percent of the 2022 global Gross Domestic Product. To address this, national development policies must prioritise facilitating access to and optimising the benefits of technologies in energy production, transmission, and management (Ahmad et al., 2021). If existing energy policies remain unchanged, total energy demand is expected to rise from 14,000 million tonnes of oil equivalent (Mtoe) in 2019 to 17,500 Mtoe in 2040, and carbon dioxide or CO_2 emissions will increase from 32.5 Gigatonnes (Gt) CO_2 to 42.5 Gt CO_2, further threatening economic and environmental sustainability (International Energy Agency, 2018).

Between 1973 and 2017, the global output of production of energy grew from 5,982 Mtoe to 13,950 Mtoe (International Energy Agency, 2020), more than a doubling in less than 50 years (Ritchie & Rosado, 2020). During this time, the share of fossil fuels (coal, oil and gas) fell only marginally (Ritchie & Rosado, 2020) from 88% to 82% (International Energy Agency, 2020), despite the accelerated investments in renewable energy (Li & Han, 2023; Harlan & Baka, 2024). In addition to the growth in production, there are also some shifts in the geographical spread of production, notably a leap in energy production in the developed world led by the United States, Australia and Europe, but also in newly industrialised and emerging economies including the United Arab Emirates, Russia, Brazil, India, South Africa, and various countries in Asia, most noticeably, China (International Energy Agency, 2020). In 2022, China produced more than twice the energy of the USA (International Energy Agency, 2020), reflecting the seismic shifts in manufacturing from the West to China (and other Asian nations).

The increase in energy production, propelled by technology (Rifkin, 2013; Boudet, 2019; Bamati & Raoofi, 2020) is evident in short and long-term economic, as well as social and environmental benefits (Holmberg and Sandbrook, 1992, cited in Spalding-Fecher and Williams, 2000, He & Ni, 2022). The race towards providing efficient and sustainable energy is essentially a global one – increasingly driven by new, revolutionised technologies (Yuen et al., 2011; Zhang, 2018; Zeng et al., 2022; Hao et al., 2019; Oláh et al., 2020; Wang et al., 2020 and Brown at al., 2020). The reality is that every country is their own participant in such a race. Countries in the race to transform the energy system, are using various technologies to drive their progress. China, Germany, and South Africa are notable examples. China is leveraging advancements in solar and wind energy, which has created simultaneous growth in battery storage technologies batteries (World Intellectual Property Organization, 2021; International Energy Agency, 2022). Germany leads in renewable energy integration and smart grid modernization (South African Department of Mineral Resources & Energy, 2024). In June of 2024, South Africa approved the South African Renewable Energy Masterplan (SAREM) in which it sets out its plan to actively capitalize on the growing demand for renewable energy and storage technologies—particularly in solar and wind energy, as well as lithium-ion and vanadium-based battery systems—to foster the industrial development and inclusive growth of related value chains within the country (South African Department of Mineral Resources & Energy, 2024). Such technological adoptions are crucial for advancing a sustainable energy future and must be advocated alongside the management of other factors impacting South Africa's energy sector, for instance, an aging infrastructure and poor governance.

1.1.2. Industry 4.0 as a pathway for change

The emergence of Industry 4.0 or Fourth Industrial Revolution (4IR) technologies plays a vital role in the transformation of energy sectors. Technologies such as smart grids, the Internet of Things (IoT), and Artificial Intelligence (AI) are essential for optimising energy efficiency, integrating renewable energy sources, and managing energy consumption more effectively (Lyu & Liu, 2021; Ghenai et al., 2022; Wang et al., 2022). These innovations are key to meeting global energy and climate goals, ensuring a sustainable and equitable energy future (Beier, 2017).

Economic development globally has been categorised into four seamless industrial revolutions – the first, second, third, and fourth (Mokyr, 2009; Pinheiro, 2019). These revolutions, recognised as radical and groundbreaking for society, have been led by industrial, scientific and technological developments (Morrar et al., 2017; Liao et al., 2017; Pinheiro, 2019, p. 831). A central construct of each industrial revolution has been the production of different types of energy via various technologies - energy resources that would drive the economy of the time. We are presently experiencing the fourth industrial revolution, familiarly known as 4IR or

Industry 4.0. The term *Industry 4.0* was constructed as early as 2011 by a German association of academics, policymakers and industries (Ardito et al., 2019; Yang et al., S, 2021). Globally, other countries worldwide have followed suit, aligning industrial policies to Industry 4.0 aims and principles (Ardito et al., 2019).

Conceptualising Industry 4.0 (4IR) must be preceded by understanding the first, second and third industrial revolutions (1IR, 2IR and 3IR). The first industrial revolution (1IR) began in Britain and extended over the end of the eighteenth and beginning of the nineteenth centuries (Mokyr, 2009; Bruland, 2004). There was a shift away from agricultural production and craft industries resulting in the beginning of mechanisation within manufacturing industries. Manual production was replaced by factory production (Kravchenko, 2019). This period was marked by the invention of the steam engine and the building of an extensive railway system that promoted the exchange of goods (Deane, 1965; Craft, 1996; Zmolek, 2013). Central to the first industrial revolution was the use of coal to fire the boilers to produce steam that drove the engines of the machinery. The second industrial revolution (2IR) occurred towards the end of the nineteenth century (Craft, 1996) and was built on the exploitation of natural gas and oil resources that provided additional sources of energy (Mokyr, 1999). Electricity generation emerged from earlier scientific work by Faraday and Maxwell, who brought magnetism and electricity together (Forbes & Mahon, 2013). During the third industrial revolution (3IR), information technologies became a much bigger part of industry production processes in about the middle of the twentieth century. This included energy technologies used in renewables, smart grids and hybrid engines (Kravchenko & Kyzymenko, 2019). The proliferation of nuclear power stations added nuclear energy to the global mix. The world began to prioritise creating a sustainable environment, reducing pollution and global warming caused by burning fossil fuels (Mokyr, 1999; Kander et al., 2014; Rifkin, 2013). Sustainable energy using the sun, wind, water, geothermal heat, biomass, waves and tides were offered as alternatives to fossil fuels – as cleaner and environmentally friendly sources. Rifkin (2013) referred to 3IR as instilling confidence in a post-carbon world.

The fourth industrial revolution, or Industry 4.0, was described as major and impending, on a global scale, (HSRC, 2018) and unique from its predecessors. (Schwab, 2017). Integrating disruptive digital technologies, like Artificial Intelligence (AI), Machine Learning, Big, Real-Time

Data and data analytics (BRD), the Internet of Things (IoT), cloud technologies, and so on, into production processes, has transformed the workplace and how services and goods are traded. It is a moment when machines and humans are intertwined and work together to produce goods (Pinheiro, 2019). The value of integrating advanced technologies, using AI systems that draw on BRD in production processes, as Dentici (2018) explains, is its contribution to increased productivity. Interest in Industry 4.0 has expanded, driven by business leaders including Klaus Schwab, Founder and Executive Chairman of the World Economic Forum, and Emmanuel D. Hatzakis, Chief Investment Strategist at the Bank of America Merrill Lynch. Since the COVID-19 pandemic, the European Union has published a White Paper on Industry 5.0 (European Commission, 2022), which extends the Industry 4.0 conceptual framework by including human-centricity and sustainability. Presently, Industry 5.0 is still a developing framework.

Kravchenko & Kyzymenko (2019) define Industry 4.0 as a period marked by collaboration between advanced technology, Artificial Intelligence systems, and humanity, whereas Ghobakhloo (2020, 3) describes it as the digital transformation and intelligent optimisation of factories, distribution channels, and value chain participants, more broadly, shifts in the structure of the economy. For Ardito et al., (2019), Industry 4.0 involves integrating digital technologies to enable firms to connect their machinery, supply systems, production facilities, final products, and customers. This connectivity facilitates the collection and sharing of real-time market and operational information. Ardito et al., (2019) identify IoT, BRD, AI and cloud computing as facilitating technologies that start operating jointly to help to digitise supply-chain-management (SCM) systems across industries. However, accessibility to Industry 4.0 and the technologies that have emerged, is dependent on collaboration across borders, sectors, and disciplines (Schwab, 2017).

The global technological landscape is undergoing rapid transformation, with Industry 4.0 emerging as a key driver of this change. (Ng & Ghobakhloo, 2020; Pfeiffer, 2017). In the energy sector, the rise of an increasingly interconnected world, powered by advanced digital technologies such as IoT, is driving the integration of electricity grids with other digital systems. This interconnectedness allows for improved monitoring, control, and optimisation of energy systems, enabling smarter grids that can seamlessly incorporate renewable energy sources, enhance efficiency, and respond dynamically to changes in demand. IoT-enabled systems facilitate real-time data exchange, predictive maintenance, and energy management, creating opportunities for more resilient and adaptive energy infrastructure (Chen et al., 2016; ESI Africa, 2018; Shapsough et al., 2020). Advanced technologies have inspired innovation in energy production, distribution, and storage. Industry 4.0 builds on the digital revolution, spearheading novel ways in which technologies are woven into the very fabric of society (Human Sciences Research Council, 2018). These *Cyber-Physical Systems* include connected machines that collect massive amounts of data through smart sensors and interact with each other and humans to make decisions (Wübbeke et al., 2016, 13). There has been a move towards smart energy globally to better manage the demand and supply of electricity. This shift consists of a two-way energy exchange in which consumers can access electricity directly from the grid and produce or supply electricity to the grid (Lund, 2017). The Presidential Commission on the Fourth Industrial Revolution (4IR) in South Africa was created to help the nation address the challenges and harness the opportunities associated with Industry 4.0. Its main goal is to offer strategic advice to the government on utilising Industry 4.0 technologies to foster inclusive growth and development across different sectors of the economy. The Presidential Commission on 4IR (2020, 132) is instrumental in driving transformation in this sector by advocating for and enabling the adoption of smart grids that use IoT and AI to optimise energy distribution, reduce losses, and improve efficiency, and the integration of renewable energy sources (solar, wind) with traditional grids to create hybrid energy systems. The Commission has presented linkages between Industry 4.0 technologies and the South African energy sector. Some of these linkages include using big data and data analytics to reduce maintenance outages and costs, integrating AI and machine learning to improve operational planning in the energy system, as well as advanced remote sensing for plant operations and control (2020, 132).

1.1.3. An overview of the energy sector in South Africa, China, and Germany

In 2024, South Africa is regarded as the largest economy in Africa (International Monetary Fund, 2024) and the continent's foremost electricity producer. To sustain its economy, South Africa must enhance the efficiency, sustainability, accessibility, and reliability of its electrical energy production – approximately 95% of which is the responsibility of the state-owned parastatal, Eskom (Baker and Phillips, 2019). Presently, South Africa's electricity generation portfolio includes 38 Gigawatts of coal capacity, 1.8 Gigawatts from nuclear power, 2.7

Gigawatts from pumped storage, 1.7 Gigawatts from hydropower, 3.8 Gigawatts from diesel, and 3.7 Gigawatts sourced from renewable energy technologies (SA Integrated Resource Plan, 2019). The generated electricity is transported via a network of high-voltage transmission lines that link the load centres. Distribution to various end users is managed by Eskom and municipal entities (SA Integrated Resource Plan, 2019). Over the past few decades, an energy crisis originating from a fragile energy infrastructure, inadequate planning and a lack of political will, leading to long-term damage, has caused havoc on the South African energy system and its economy (Cotterill, 2023; Cohen, 2023; Rose, 2024). Criminal elements such as in-transit coal swapping and copper wire theft have further robbed an already delicate system (Wired, 2024; IoT.nxt, 2024). Load-shedding, both planned and unplanned, has in recent decades defined much of South Africa’s energy calamity (SA Integrated Resource Plan, 2019).

The underproduction of electrical power in South Africa and the ever-rising cost of imported oil have given impetus to a range of public and private sector interventions that provide hope for a more balanced energy future. South Africa is making major investments in the maintenance of its ageing fleet of coal-fired power stations to extend its lifespan, creating new coal-fired capacity at Kusile and Medupi, and exploring further opportunities to invest in cleaner and more efficient coal technologies, including Carbon Capture Utilisation and Storage technologies (2023 Draft Integrated Resource Plan, 2024). Unit 1 of the Koeberg nuclear energy plant has also undergone extensive maintenance and upgrades, leading to the successful extension of its operations for a further twenty years until 2044 (Eskom, 2024). Further exploring natural gas resources and developing gas-to-power technologies, provide alternatives to large-scale and expensive diesel-run power plants. Regarding renewables, the recent Draft Integrated Resource Plan (2023) (currently out for public comment) proposes accelerating the transition to renewable sources, for example solar PV, wind, hydro, and Concentrated Solar Power with storage, through investments in large-scale solar plants as well as small-scale, embedded generation installations and run-off river hydro projects (2023 Draft Integrated Resource Plan, 2024).

Nevertheless, the renewable energy sector remains entangled in other political and financial challenges within Eskom (Bhorat et al., 2017; Baker and Phillips, 2019; Cotterill, 2023). Efforts have primarily been concentrated on addressing issues stemming from years of mismanagement, insufficient maintenance, corruption, and a lack of accountability among

Eskom executives (Bhorat et al., 2017; Baker and Phillips, 2019; Lawrence, 2020). In 2021, 91% of South Africa's total energy supply came from burning fossil fuels, the rest being produced through nuclear, hydro and renewable installations (IEA, 2023). The World Energy Outlook Report for 2023 report also indicates that between 2000 and 2021, while electrical energy production increased by 16%, this was considerably lower than was required (IEA, 2023). While the dependence on coal-fired power stations will persist for decades, there are important signs of growth in renewables in the new energy mix. The Ember Report of May 2024 highlights significant growth in South Africa's renewable energy sector, with installed solar and wind capacity increasing from 2% in 2015 to 12% in 2023 (Ember Report, 2024). According to South Africa's Draft Integrated Resource Plan (2024), 19 out of 29.3 Gigawatts of new installed capacity will be from renewable sources. Post-covid, installed renewable capacity has rapidly accelerated, partly as the result of expanding the commercial and residential role of the private sector via small-scale embedded generation installations, with the share of electricity generated from renewable energy technologies rising from under 1% in 2000 to nearly 7% by 2022 (South African Renewable Energy Masterplan, 2024). The implementation of South Africa's Renewable Energy Masterplan is pivotal to unlocking renewable energy capacity in the country, in a manner that is both sustainable and inclusive.

Understanding the energy sector in South Africa, existing challenges and future possibilities must incorporate the role of digitalisation in the sector and its effect on the status quo of the energy system. To date, literature on using Industry 4.0 technologies in the South African Energy sector exists in pockets and is essentially project-based at a micro level. The recently published report of the Presidential Commission on 4IR refers extensively to the possible uses of Industry 4.0 technologies in the energy sector (2023). For instance, Gayoor et al. (2021) used AI modelling to identify the optimal size of a hybrid renewable energy system for a residential area in Durban. Potts and Walwyn (2020) conducted an exploratory study of Concentrated Solar Power technology in South Africa, concluding that this technology is still only used at a very niche level, with limited financial and policy support. The Centre for Scientific and Industrial Research (CSIR) conducts projects on variable renewable energy forecasting using meteorology and machine learning as part of helping Eskom to make better informed, short-term energy generation decisions (www.csir.co.za, 2025). The CSIR is also involved in developing a variable renewable energy forecasting system on behalf of Eskom (www.csir.co.za, 2025). Large-scale studies on the use of Industry 4.0 technologies remain scant, especially an understanding of the extent to which South Africa has optimised using the digital technologies of the fourth industrial revolution, and if not, whether such non-usage is contributing to the challenges facing the energy sector. Yet, there are indications that Eskom is committed towards growing its integration of Industry 4.0 technologies, some of which involve partnerships with technology stakeholders. For instance, Eskom, earlier this year, entered an IoT agreement with Vodacom (the mobile telecoms company) and its partner company called IoT.nxt, set to provide real-time data monitoring and analysis of the coal supply system, one outcome of which was for it to help it address the criminal issue of coal swapping in which better quality coal is swapped out for poorer quality coal (www.iotnxt.com). Also, in August 2023, Eskom entered into its first ever virtual wheeling agreement with Vodacom (Eskom, 2023). Although traditional third-party wheeling agreements have existed since 2008, whereby large-scale, private, renewable energy producers sold energy to large-scale buyers of power connected at medium to high voltages, using the transmission and distribution networks of Eskom and local municipalities, this process needs to be scaled up to include smaller sellers and buyers of medium to low power voltages. Eskom's partnership with Vodacom is a first step in integrating smaller providers of renewable (Eskom, 2023) energy into the energy system, adopting a more inclusive way of generating additional power supplies, using Industry 4.0 technologies. The agreement utilises sophisticated energy analytics and monitoring technologies to efficiently manage energy distribution across Vodacom's extensive network of over 15,000 low-voltage sites linked to multiple municipal grids. This approach facilitates accurate tracking and allocation of renewable energy sources (Mybroadband, 2023; Energize, 2023). Blockchain technology could streamline the tracking and reconciliation of energy transactions between independent power producers (IPPs) and consumers, promoting transparency and enhancing reliability in the process (Energize, 2023; Engineering News, 2023). AI and data analytics tools are utilised to enhance energy efficiency by optimising usage patterns and forecasting demand, enabling smarter energy allocation and decreasing reliance on fossil fuels (Engineering News, 2023). Vodacom's subsidiary, Mezzanine, leveraged cloud-based platforms to create the virtual wheeling platform, enabling scalable solutions for reconciling energy across multiple sites (Energize, 2023, Engineering News, 2023). This platform facilitates the dynamic management of renewable energy credits and streamlines wheeling processes. This partnership highlights the application of Industry 4.0 innovations to address South Africa's energy challenges while advancing corporate sustainability objectives. It establishes a model for private sector engagement in expanding renewable energy infrastructure and capacity (Energize, 2023, Engineering News, 2023).

Meanwhile, outside of South Africa, China and Germany are at the forefront of transforming the energy sector. China is the largest consumer of energy and producer of CO_2 in the world (Ahmed & Khan, 2024). This is largely due to the size of its population and its rapid industrialisation over the last 4-5 decades (Zhou et al., 2020). China is also the second-largest economy in the world, with a GDP in 2023 of about US$18 trillion (Statista, 2024). The IEA Report (2023b) indicates that while its reliance on fossil fuels remains high, accounting for 61% of China's total energy supply in 2021, China has made considerable progress in giving effect to a transition to Carbon Zero. Between 2019 and 2024, China accounted for 40% of global renewable capacity expansion, driven by improved system integration, lower curtailment rates and enhanced competitiveness of both solar PV and onshore wind. China is advancing its share of global renewable energy technology development, holding numerous patents in wind turbines, photovoltaic modules, light-emitting diode packages, and lithium-ion batteries (World Intellectual Property Organization, 2021; International Energy Agency, 2022). During the same period, China is forecast to account for almost half of global distributed PV growth, overtaking the EU to become the world leader in installed capacity (IEA, 2023b). The pressure to grow the production of energy will continue. China's commitment to digitising its energy sector and significantly reducing its carbon footprint is demonstrated by initiatives such as establishing a highly automated virtual power plant (VPP) management centre in Shenzhen, which has enhanced grid reliability with over 1.5 million kilowatts of capacity by mid-2023 (Shenzhen Municipality, 2023). According to China's 14th Five-Year Plan (2021-2025), renewable energy production is expected to increase by 50% (from 1 trillion kWh in 2020 to 3.3 trillion kWh in 2025), leading to an annual reduction of carbon emissions by 2.6 gigatons, with the long-term goal of achieving carbon neutrality by 2060 (Energy Foundation China, 2022). China's power sector is largely centralised. Power generation is controlled by five State-Owned Entities (SOEs), Huaneng, Datang, Guodian, Huadian, and the State Power Investment Corporation. The distribution and supply of power through the grid is operated by two other SOEs, the State Grid Corporation of China and the China Southern Power Grid (Lo & Mah, 2024). Using a "developmental state" model, the Chinese government has been able to rapidly transform its energy sector to not only catch up but exceed developed nations in terms of renewable energy production (Lees & Chen, 2016). By 2021, the renewable energy capacity of China equated to almost a third of global renewable energy capacity (Yan et al., 2024).

As a champion of Industry 4.0 and a formidable player in renewable energy, Germany is committed to prioritising Industry 4.0 in national policy, specifically through initiatives like Energiewende and the Roadmap for Energy Efficiency Strategy 2050, to achieve total climate neutrality by 2050 (Kuittinen et al., 2018). In the context that Germany has transitioned out of nuclear energy, following the nuclear disaster at Fukushima, Japan in 2011 (Kramm, 2012), this will be a remarkable achievement if met. To achieve this, Germany is adopting a two-pronged approach: rapidly expanding renewable energy sources to reach a 65% share by 2030 and promoting energy efficiency by drastically reducing primary energy consumption to 30% below its 2008 level (German Federal Ministry for Economic Affairs and Energy, 2016). Germany's Energiewende (or Energy Turnaround), that began in the nineties, involved considerable decentralisation of its energy market, giving customers the opportunity to choose their own, local renewable energy suppliers, and to supply energy themselves, independently or as part of larger local or regional cooperatives (Burger, & Weinmann, 2013). The decentralising of renewable energy is what enabled tremendous growth in renewables (Beermann & Tews, 2017). Additionally, energy efficiency, for Germany, has involved consuming less energy, lowering energy costs for companies, and enhancing their competitive advantage (German Federal Ministry for Economic Affairs and Energy, 2016). Regarding technology, Germany is increasingly focusing on the use of AI as a lens through which it considers its energy and climate issues. (Deutsche Energie-Agentur, 2019). The German Federal Ministry for Economic Affairs and Energy has prioritised the development of an Artificial Intelligence Standardisation Roadmap and the establishment of a Specialist Unit for Artificial Intelligence. Germany and China collaborate through the Sino-German Energy Partnership, focusing on climate policy and energy issues. Established in 2016, this bilateral initiative promotes dialogue, business-to-government exchanges, and the sharing of technological and regulatory solutions for sustainable energy transitions (Deutsche Energie- Agentur, 2019).

1.2. Problem Statement

Globally, there has been a shift towards using Industry 4.0 technologies across most sectors: Artificial Intelligence, Robotics, Machine-Human Integration, the Internet of Things, and access to and analysis of Big, Real-Time Data. The energy sector is no different. As an industrial powerhouse in Africa, South Africa depends on energy efficiency for economic development, and to make energy more sustainable by being accessible, reliable and of minimal detriment to the natural environment. However, South Africa struggles to keep up with the country's energy demand, facing persistent blackouts, and sluggish performance in expanding its share of renewables. Reasons for this have been attributed to South Africa's broader energy landscape, some of which comprises an aging infrastructure, difficult socio-economic conditions, and poor governance of the energy sector. The contribution of limited Industry 4.0 technology adoption to an already challenged energy sector is less obvious. Specifically, what is not known is whether the energy sector in South Africa is adequately leveraging these technologies, compared to countries which are rapidly transforming their energy sectors, specifically China and Germany, and the effects of such usage on efficiency in energy production in these countries.

1.3. Aim and Objectives

This research aims to determine the uptake of Industry 4.0 technologies by the South African energy sector, how such usage compares to China and Germany, and the extent to which the level of uptake of such technologies could exacerbate challenges facing the sector.

To achieve this aim, the study was guided by the following objectives:

1. To identify research gaps relating to the uptake of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa by technology type and impact.
2. To compare the importance and use of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa.
3. To determine the extent to which the level of uptake of such technologies could exacerbate challenges facing the South African energy sector.

1.4. Rationale

The continuing energy crisis in South Africa is the backdrop to this study. There are multiple reasons for this crisis including the lack of investment, poor management and leadership, the lack of foresight, and corruption. The rationale for this study is to determine the extent to which Industry 4.0 technologies have been adopted by South Africa's energy sector, as a means to improve efficiency and sustainability, and whether this has been effective in addressing challenges. Emerging, sophisticated technologies may be used to address the energy crisis, but to do so, one needs to understand if and where these technologies are being adopted in the energy value chain, and the extent to which they contribute to more efficient energy production. The South African Presidential Commission on 4IR (2020, 132) recommends that technologies of "the 4IR can and should play a fundamental role for South Africa to realise the National Development Plan (NDP) Vision 2030 in energy." Given their commitment to integrating Industry 4.0 technologies within their respective energy sectors, this is worth exploring. Additionally, South Africa's growing bilateral relations with these countries, within the energy space, makes a comparative study of this nature valuable (Yan et al., 2024; South African German Energy Partnership, 2024). As such, given the fragile state of South Africa's energy sector, and the potential for Industry 4.0 technologies to improve efficiencies in energy production, it is important to determine how South Africa's adoption of such technologies compares to that of these countries.

1.4.1. Selection of countries

South Africa is presented with many major challenges, such as dealing with the severe shortfall in electricity generation to prevent the debilitating impact of load shedding, extending the accessibility of electricity to all its citizens, improving the efficiency of production and consumption, and ensuring that South Africa meets its climate change targets and commitments. Perhaps the most important difference between Germany and China, on the one hand, and South Africa, on the other, is the instability of the energy sector facing the latter (Mabunda, 2023).

The use of China and Germany as comparatives, does not underestimate the achievements made by other global leaders in using Industry 4.0 technologies in energy production. The literature review provides data for global publications on using Industry 4.0 technologies in energy production for newly industrialised countries such as India, developed countries such as the United States of America, as well as the emerging economies of Mexico, Brazil, and Nigeria (Bhagwan & Evans, 2023). Germany, China, Australia, Netherlands, and Japan have made systemic changes by decentralising energy systems. They achieved this by installing computer chips in individual households, enabling residents to manage their energy grids and distribution through the internet (Burger et al., 2020; Viétor et al, 2015; Kafle et al, 2016). Finland is leveraging IoT, AI, and blockchain technology to facilitate cross-commodity energy sharing within local, decentralized energy systems. This includes establishing energy-sharing communities, known as "smart cities," to mitigate the cost challenges associated with the lack of economies of scale in decentralized energy models (Paiho et al., 2021). India has recognised the potential of using remotely piloted aircraft equipped with infrared imaging, to monitor and analyse photovoltaic energy systems in hard-to-reach areas (Rahaman et al., 2020). Nigeria is exploring the integration of AI into regression analyses for solar energy estimation studies, and the application of artificial neural networks to develop time-series data (Ozoegwu, 2018).

However, China and Germany were ultimately chosen as the countries of comparison for reasons tied to their respective accomplishments in the energy sector, as well as each one's unique relationship with South Africa. China was included in this study because of its status as a newly industrialised global manufacturing powerhouse, driven by its Made in China 2025 initiative (Made in China, 2025). This initiative underscores China's commitment to accelerating Industry 4.0 advancements across sectors by financing research, development, and the implementation of related technologies, particularly in the renewable energy domain. Notably, China is currently recognised as a global leader in renewable energy installations (World Intellectual Property Organization, 2021; International Energy Agency, 2022). Both Chinese and German companies are adopting 4IR technologies and expanding digital renewable energy solutions. Germany was included in the study due to its status as a European economic power, its recognition as a conceptual pioneer of Industry 4.0, its leadership in renewable energy, and its strong emphasis on integrating Industry 4.0 into national policy, exemplified by initiatives like Energiewende and the Energy Efficiency Strategy 2050 (German Federal Ministry for Energy and Economic Affairs, 2016).

The three countries selected for this study are at significantly different stages of development regarding the scale of their energy sectors and the progress of their energy transition, shaped by factors such as infrastructure availability, socio-economic conditions, and energy-related policies. These factors collectively influence the degree to which Industry 4.0 technologies are adopted. Despite these differences, notable commonalities exist between South Africa and

China, and South Africa and Germany. Like South Africa, China's energy system is rooted in in its rich supply of natural coal reserves, with the 90% of energy generation, transmission, and distribution being jointly controlled by the Chinese state, provincially and nationally. In South Africa, Eskom which is a state-owned enterprise controls 90% of all energy production, distribution, and transmission. South Africa, since democracy, has grown its bilateral relations with China, across multiple economic sectors, one of which includes energy. China is involved in the Kusile and Medupi coal-powered stations, wind energy projects in the Northern Cape, Chinese company involvements in large-scale solar farms, several hydropower feasibility studies, and continuing dialogue on collaboration in nuclear energy. Joint technology transfer initiatives, such as the Forum on China-Africa Cooperation (Forum on China-Africa Cooperation, 2024), as well as green energy financing partnerships created via the China-Africa Development Fund (United Nations Industrial Development Organization, 2025), reflect a growing, strategic relationship between South Africa and China in the energy space. Also, about a third of the populations of each live in rural areas (https://data.worldbank.org/, 2025), and China has made progress in reaching its rural populations using centralised, digital platforms (Energy Foundation China, 2022; Shenzhen Municipality, 2023). There are also important connections between South Africa and Germany based on overlaps in socio-economic ideology, and partnerships within the energy sector. While Germany has benefitted from a stable economy and a longer history of implementation of social welfare policies and unionisation, South Africa faces unique challenges as a developing country recovering from apartheid's legacy. However, the shared emphasis on welfare, labour rights, education, and energy, reflects their mutual commitment to addressing socio-economic issues (Patel, L, 2015; Seeleib-Kaiser, M, 2016). Whilst it is noted that the German energy sector is structured differently to both China and South Africa, being liberalised and highly competitive, there are ideological and policy-based parallels between the participatory approach of Germany's Energiewende, and the social compact envisioned for South Africa in its National Development Plan. Furthermore, the South African German Energy Partnership Secretariat highlights South Africa's interest in Germany's model of energy decentralization, particularly due to its strong reliance on local municipalities (https://energypartnership.org.za/, 2025).

1.5. Methodology

For the research aim stated, a mixed-methods methodology framework, also referred to as blended or multi-method research (Johnson et al., 2007) was most appropriate because the study involves exploring both quantitative and qualitative aspects of Industry 4.0 technology adoption, its impact on efficiency in the South African energy sector and international comparisons. The research design adopted was an Explanatory Mixed-Methods Approach (Creswell and Plano Clark, 2018; Creswell, 2014) that combined quantitative data to assess adoption levels and efficiencies with qualitative insights to understand challenges and underlying reasons for limited uptake. The approach drew on quantitative and qualitative research methods, extending the breadth and depth of the research and enhancing corroboration within the study (Johnson et al., 2007; Doyle et al., 2009). Using mixed methods provided a more complete picture of the research in that it facilitated the inclusion of different types of questions (quantitative and qualitative) used to collect different types of data, that would not be possible to collect through only quantitative or qualitative questioning (Doyle et al., 2009). The quantitative component of the Explanatory Mixed-Methods Approach (Creswell and Plano Clark, 2018, Creswell, 2014) provided objective measures of technology adoption and efficiency. The qualitative component offered deeper insights into contextual challenges and drivers, enriching the understanding of the data. The two methods complemented each other, allowing for a more comprehensive analysis of the issue. This methodology ensured a robust approach to answering the research questions by combining data-driven insights with context-rich qualitative exploration. Following the Leech & Onwuegbuzie (2007, cited in Doyle et al., 2009) typology of mixed methods, quantitative and qualitative components were carried out sequentially, each method carrying equal status in the data analysis, but in a complementary manner. The results collected from the quantitative survey were used to inform or complement the interview questions to gain further clarity and detail (Creswell and Plano Clark, 2018). By treating both methods with equal status, neither approach dominated, and numerical and contextual factors were equally considered, making the findings more holistic and representative. Moreover, applying the quantitative and qualitative methods sequentially strengthened the rigour of the study, by providing multiple lenses to examine the same phenomenon (Leech & Onwuegbuzie, 2007, cited in Doyle et al., 2009).

1.5.1. Data collection methods

Data for the study was collected in four parts, two of which were produced as published articles and one as a manuscript submitted for review. Part 1 was an online survey that sought to determine the level of participation of South African, Chinese and German energy companies in Industry 4.0, the main categories of Industry 4.0 technologies within the energy sector, the extent to which such technologies are being used, and their level of impact on efficiency, sustainability and reliability across the energy sector (Bhagwan & Evans, 2022). Part 2 of the study was a review of existing literature on Industry 4.0 technologies in these three countries' energy sectors to identify industry leaders and research gaps (Bhagwan & Evans, 2023). Part 3 presented the results of interviews with energy companies in South Africa, China, and Germany and experts in the South African energy sector. Here, the subsequent paper has been submitted and is under review. Part 4 comprised a desktop review of the most important policy documents, national and global, that inform the energy sectors in South Africa, China, and Germany.

1.5.1.1. Online survey and sampling

An online survey, drawing on purposive sampling, was used. The identified target group was selective and included local (South African) and international (specifically Chinese and German) energy companies that use Industry 4.0 technologies to produce and/ or distribute either renewable or non-renewable energy. The names of these companies were sourced via an internet search. Chinese companies partnering with South Africa on projects in the South African energy sector were also surveyed.

The survey was administered using Google Forms to 30 global and 20 local energy companies among individuals involved in technology and innovation, research and development, and strategic development. The names of these individuals were sourced via company websites, phone calls, and emails. Companies choosing not to participate, believing they were not suited to the study's objectives, were asked to recommend other companies.

1.5.1.2. Interviews and sampling

Table 1 lists the company participants and experts interviewed for this study. Given the small sample size of sixteen participants, purposive and expert sampling was used to identify company representatives and experts to be interviewed, to obtain rich, targeted, and meaningful data while addressing the constraints of limited participants. Focused, in-depth interviews were held with executives, process engineers and technology specialists at three South African companies (a chemicals company operating its own power plant, an international energy plant consortia with a South African partner and an IT and digital solutions company providing IoT and other digital services to Eskom), and four Chinese companies, including two electricity utilities, and two ICT companies, one of which is a large global player. Attempts to interview employees responsible for technology development and implementation at Eskom, and to visit Eskom plants were denied, for reasons relating to the sensitivity of data pertaining to Eskom's assets and their accessibility given their status as national, strategic assets. To address Eskom's non-participation, two South African companies were selected for interviews based on their roles in supplying energy resources to the national grid and providing IoT and other digital services in collaboration with Eskom. Difficulties experienced in setting up online interviews with German energy companies, meant that relevant information had to be acquired online using a desktop search of three companies (all ICT and digital solutions companies, one of which operates a large virtual power plant). Company interview participants included engineers, Chief Executive Officers, Chief Operations Officers, and company representatives selected for their expertise in digital technologies in energy production. This diverse group offered insights into developing and utilising Industry 4.0 technologies within energy producers, utilities, and technology firms. In addition to interviewing companies, six experts were also interviewed. These experts included prominent academics from two South African universities, the director of an international agency of the German government, the head of a national energy institute in South Africa, and an Industry 4.0 research centre director, enriching the study with historical nuances and varied strategic perspectives.

The main objectives of the interviews were to validate and supplement the data obtained through the online survey, better understand the energy sector in South Africa from the perspective of private companies and industry experts and establish the extent to which the uptake of Industry 4.0 technologies is influencing efficiencies in energy production and, as such, contributing to the challenges facing the South African energy sector. A snowballing technique was useful for identifying additional interviewee respondents and companies of interest and value to the study (Sharma, 2017).

Table 1: Table 1: Company participant identifier, participant designation, company type and location. SAC=South African Company; CHC=Chinese Company; GEC=German Company, EXP= Expert

Participant identifier	Participant Designation	Company Type/ institution	Location
SAC1	Plant Engineer	Large chemicals manufacturer in South Africa, producing energy to self-sustain its plant	South Africa
SAC2	Chief Executive Officer	IT and digital solutions company, providing IoT and other digital services to Eskom	South Africa
SAC3	Chief Operations Officer	International energy plant consortia with a local partner, providing energy to the national grid	South Africa
CHC4	Company Representative	ICT and digital solutions	China
CHC5	Company Representative	Electric Utilities	China
CHC6	Company Representative	ICT and digital solutions	China
CHC7	Company representative	Electric utilities	China
GEC8	Company website	IT, operating a virtual power plant	Germany
GEC9	Company website	IT and digital solutions	Germany
GEC10	Company website	IT and digital solutions	Germany
EXP11	Academic	University	South Africa
EXP12	Director	International development agency of German Government	South Africa
EXP13	Academic	University	South Africa
EXP14	Centre Head	4IR research centre	South Africa
EXP15	Unit Head	National Energy Development Institute	South Africa
EXP16	Academic	University	South Africa

1.5.1.3. Desktop review

The desktop review comprised an appraisal of data accessed through industry reports and strategic plans of South African, German and Chinese energy companies on integrating 4IR technologies into their production and or distribution systems. Industry reports were reviewed to identify Industry 4.0 technologies that energy companies are already using. Company-specific and sector-wide strategic plans provided data on such technologies' intended or planned use. The appraisal determined patterns and consistencies in the types of Industry 4.0 technologies integrated as part of the energy production and distribution process pipeline. The choice of using rapid appraisal for this study was influenced by the "iterative" nature of the method, in the sense that it allowed for the flexibility to change the instrument as the research process unfolded and additional data was collected through the survey and interviews (Beebe, 1995, p. 48).

National policies and strategies were reviewed for countries integrating 4IR technologies to advance their energy sectors by making them more efficient, reliable and integrated. For South Africa, the main policy documents were the 2012 National Development Plan (South African Presidency, 2012), the 2019 Integrated Resource Plan (SA Department of Mineral Affairs and Energy, 2019), the 2019 South African Energy Sector Report (SA Department of Mineral Affairs and Energy, 2019), and, most recently, the Integrated Resource Plan of 2023 (SA Department of Mineral Resources and Energy, 2024). The Made in China 2025 strategy (Wübbeke et al., 2016; Institute for Security and Development Policy, 2015) and China's 14th Five-Year Plan on Renewable Energy Development (2021–2025) provided key information on the strategic plans of the Chinese government to promote the design, manufacturing, distribution, and export of renewable energy technologies (Sino-German Energy Transition Project, 2020). The German energy transition programme, Energiewende, informed the study on the strategies developed by Germany as part of its efforts to promote energy sustainability (German Federal Ministry for Energy and Economic Affairs, 2016). These documents were used to compare the energy sector in South Africa with that of China and Germany. Reports produced by the current Sino-German Energy Partnership provided interesting comparisons between the Chinese and German energy sectors and details of their bilateral cooperation partnership (Sino-German Energy Transition Project, 2020).

Global reports on energy, including reports commissioned by the International Energy Agency (IEA Country Reports, 2023a, 2023b, 2023c; IEA World Energy Outlook, 2021), the United Nations (United Nations Industrial Development Organisation Impact LCCR Report, 2018; UN

Sustainable Development Report, 2020), Statista (Country GDP Reports, 2024), and the World Bank (WB Climate Change Action Plan 2021-2025, 2021), playing an active role in the energy sector as well as addressing climate change through a reduction in energy emissions, were sourced. This assisted in understanding global initiatives surrounding the need to reduce energy emissions, improve energy efficiencies and grow renewables, and the technologies being used to facilitate these processes. The objective of the desktop analysis was to understand the status quo in energy production and distribution in different countries and the policy commitments and strategic objectives that have influenced and guided their energy sector towards more sustainable approaches. The desktop analysis contributed significantly to identifying 4IR technologies characterising energy production and distribution processes.

1.5.2. Data analysis

For the survey, Cronbach Alpha, Kruskal-Wallis, and Mann-Whitney tests were carried out using the Statistical Package for the Social Sciences (SPSS). First, the collected data was validated and assessed using Cronbach's Alpha to test for internal consistency. This analysis determined whether the variables (different Industry 4.0 technologies) consistently measured the same underlying construct identified in each question. The constructs included the importance of these technologies to the Global Economic Sector (GES), the significance of using Industry 4.0 technologies within individual companies, and the levels of efficiency, reliability, and integration of Industry 4.0 technologies within companies. The data analysis process began with a descriptive statistical analysis, to summarize the levels of Industry 4.0 technology adoption. This initial step involved exploring the nature of the variables used in the survey by assessing the response frequencies, percentages, and means. This provided insights into respondents' perceptions of different Industry 4.0 technologies and the average overall view concerning these technologies. A clear set of descriptors for Industry 4.0 technology was utilised throughout this analysis. Next, comparative statistical analysis, applying the Kruskal-Wallis test was employed, to examine country-specific similarities and differences regarding the perceived importance of utilising Industry 4.0 technologies within the Global Energy System (GES) and individual companies.

For the interview data, after immersing in the data and familiarizing myself with the data by reading and re-reading transcripts, a process recommended by Braun & Clarke (2006), a less formal thematic analysis was conducted based on a set of predetermined themes, covering differing perceptions of the novelty of Industry 4.0 technologies and their impact on energy production.

Thematic analysis helped to identify recurring themes in interview responses related to barriers, opportunities, and impacts of Industry 4.0 adoption. There were notable differences in the types of 4IR technologies used and their perceived value. Additionally, through Cross-Case Comparison, qualitative findings from South Africa were compared with insights from China and Germany to highlight differences and best practices in the adoption of these technologies in the energy sectors of the three countries. Although no formal coding techniques were developed to analyse the qualitative data, an Excel spreadsheet was used to map out the responses of interview participants (Miles et al., 2014), to identify recurring themes and trends across participants (Noble & Smith, 2015). To reduce biases, strategies that enhance credibility, trustworthiness, and transparency of the research process were incorporated, for example, triangulation, maintaining a clear audit trail, and using direct quotes from respondents (Nowell et al., 2017; Noble & Smith, 2015; Lincoln & Guba, 1985). Triangulation comprised the use of multiple data sources and methods. In the case of the former, data was collected from different participant groups (e.g., energy executives, company employees, energy sector experts, and academics). Combining different qualitative methods (e.g., interviews and document analysis) in addition to both quantitative and qualitative methods (e.g., survey and interviews) helped to strengthen insights. By validating findings through multiple sources or methods, triangulation ensures that the results are not influenced by the limitations of a single approach. Furthermore, all raw data (both quantitative and qualitative) has been retained for future reference. Thirdly, the research findings are grounded in participants' actual words to reduce subjective interpretation.

1.6. Ethical considerations

This research was covered by ethical clearance from the University of the Witwatersrand Human Research Ethics Committee (HREC) (non-medical). All participants were 18 years and older and did not fall into the high-risk, vulnerable categories. All participants were informed about the research, its purpose, and its output before they formally consented to participate. The names of survey respondents, companies and interviewees remained confidential, and pseudonyms were used where necessary. Participants did not receive any remuneration for participating, and there were no penalties for non-participation. All information was kept anonymous, and no identifying features were recorded on the questionnaires. All data were kept strictly confidential, and participants' identities were protected. The ethics clearance number for this research is H190706. The participant information sheet, survey questionnaire, and interview schedules are attached in Appendix A. The ethics certificate is attached in Appendix B.

1.7. Structure of Thesis

The thesis comprises six chapters and is structured as follows:

Chapter 1 introduces the concept of Industry 4.0, specifically how it is being used as a pathway for change, sets the scene for global energy systems amidst rampant digitalisation and unacceptably high levels of fossil fuel emissions and provides an overview of the energy sector globally and in South Africa, China, and Germany. The problem statement was identified, followed by the research's aim, objectives, and rationale. An overview of the study's methodology and details on how the countries, companies, and expert samples were selected is outlined. The thesis structure and the ethical considerations follow this. Chapter 2 is a published manuscript that reviews Industry 4.0 technologies used in energy production in South Africa and compares them to China and Germany. Chapter 3, also a published paper, compares the application of Industry 4.0 technologies in the energy sectors of South Africa, Germany, and China. Chapter 4 is a submitted manuscript, currently under review, that demonstrates an understanding of the extent to which energy companies in Germany, China, and South Africa are using Industry 4.0 technologies and the contribution of these technologies to rising efficiency in energy production. Chapter 5 synthesises the data and discusses the significance of the findings. Chapter 6 concludes the discussion, establishes the limitations of the research, and recommends further research regarding the data's implications, analysis, and findings. Each chapter adheres to journal-specific formatting, spelling, and referencing style requirements as determined by the associated journal to which the papers were submitted.

CHAPTER 2: A REVIEW OF INDUSTRY 4.0 TECHNOLOGIES USED IN THE PRODUCTION OF ENERGY IN CHINA, GERMANY, AND SOUTH AFRICA

2.1. Brief synopsis

Industry 4.0 technologies can be distinguished according to their type, effect, and impact on industries. Using a Scopus search, this review identifies research gaps related to the deployment of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa. Globally, research on the type of technology in the energy sector is skewed toward the Internet of Things, Artificial Intelligence, and Big, Real-Time Data. In contrast, publications on Machine-Human-Integration and Robotics are limited. In this area of research China outnumbers Germany in research publications, and South Africa produces the least. While there may not be a direct correlation between these frequency counts and the use of the Industry 4.0 technologies in the energy sectors, it does provide the basis for the assumption that such technologies are less deployed in energy production in South Africa. Firm-specific, empirical research on South Africa, although valuable, is scarce regarding if, where, and how Industry 4.0 technologies affect energy production, increased plant productivity and revenue. The review encourages implementing firm-based, empirical studies using actual data on Industry 4.0 technologies in energy production in South Africa. Empirical studies provide an improved understanding of a South African energy sector facing Industry 4.0 and in crisis, identifying how Industry 4.0 technologies may be leveraged to increase energy productivity and efficiency. Such studies will contribute to evidence-based policy on expanding Industry 4.0 technologies to create an efficient and sustainable South African energy sector.

Publication details:

Bhagwan, N., & Evans, M. (2023). A review of Industry 4.0 technologies used in the production of energy in China, Germany, and South Africa. *Renewable and Sustainable Energy Reviews*, 173, 113075. Journal impact factor: 16.79

Renewable and Sustainable Energy Reviews 173 (2023) 113075

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of industry 4.0 technologies used in the production of energy in China, Germany, and South Africa

N. Bhagwan [a,*], M. Evans [a,b]

[a] The University of the Witwatersrand, School of Geography, Archaeology and Environmental Studies, Faculty of Science, Johannesburg, South Africa

[b] The University of the Witwatersrand, School of Geography, Archaeology and Environmental Studies, Faculty of Science, Johannesburg, South Africa

A R T I C L E I N F O

Keywords:
Industry 4.0 energy sector technologies
Energy value chain
Internet of things
Artificial intelligence
Robotics
Human-machine integration
Big Real-time data

A B S T R A C T

Industry 4.0 technologies are reconfiguring energy value chains and changing how we understand efficiency in energy production. Using Scopus, this review identifies research gaps in Industry 4.0 technologies in the energy sectors of Germany, China and South Africa, by technology type, effect and impact. Globally, research on the energy sector is skewed toward the Internet of things, Artificial Intelligence, and Big, Real-Time Data. Publications on Machine-Human-Integration and Robotics are limited. China outnumbers Germany in research publications and, South Africa produces the least, leading to the assumption is that such technologies are missing in energy production in South Africa. The literature presents clear content foci: i. using Industry 4.0 technologies to reduce energy intensity through better process-related materials, thereby shrinking the carbon footprint; ii. growing efficiencies through smart energy systems; iii. rethinking energy policy to incentivise research in Industry 4.0 technologies, and iv. managing network securities in within energy systems. Firm-specific, empirical research on South Africa, although valuable, is scarce regarding if, where and how Industry 4.0 technologies affect energy production, increased plant productivity and revenue. The review encourages implementing firm-based, empirical studies, using actual data on Industry 4.0 technologies in energy production in South Africa. Such studies provide improved understanding of a South African energy sector facing a Fourth Industrial Revolution and in crisis, identifying how Industry 4.0 technologies may be leveraged to increase energy productivity and efficiency. Such studies will contribute to evidence-based policy on expanding Industry 4.0 technologies to create an efficient and sustainable South African energy sector.

1. Introduction

Global dialogue on the impact of changes in the demand and supply of energy resources is significant, specifically, the implications for reducing harmful energy emissions and promoting responsible economic growth and sustainability. According to the International Energy Agency (IEA), in 2019, global energy production was 617 Exajoules, out of which China contributed 113847.9 Terajoules, Germany 4022.7 Terajoules, and South Africa 6689.3 Terajoules [1]. Total energy consumption for the same year was 412.8 Exajoules [2]. “Getting the world on track for 1.5 ˚C requires a surge in annual investment in clean energy projects and infrastructure to nearly USD 4 trillion by 2030" [2]. The global technological landscape is evolving swiftly, and Industry 4.0 provides the pathway to this change [3,4]. Specifically, a hyper-connected world enabled by complex digital interfaces, such as the Internet of things (IoT), connects multiple digital systems [5]. New and better technologies characterising Industry 4.0 are driven by the “genuinely disruptive innovations” that Kazca has “world-changing consequences” for society and its environment [6]. Economic value chains are reconfiguring, bolstering efficiency and productivity across the energy and other sectors [7,8]. Increased digitalisation in energy production, as part of a hybrid biomass-solar-wind energy system, create more flexible power systems, reduce carbon dioxide emissions, help grow renewables and promote economic growth [9].

Industry 4.0, as applied to the energy sector, has been marked by multiple technology-specific developments, including the Internet of things (IoT), Robotics (ROB), Artificial Intelligence (AI), and big, real-time data (BRD), located in a cyber-physical space, that blend global, physical, digital, and biological systems [6,10]. In addition, human-machine partnerships have brought together the best minds (human and artificial) in what has become an augmented reality [11], a reality that is redefining energy sectors. However, are energy producers leveraging technological efficiencies created by Industry 4.0 across the

* Corresponding author.
E-mail addresses: 9802976p@students.wits.ac.za (N. Bhagwan), Mary.Evans@wits.ac.za (M. Evans).

https://doi.org/10.1016/j.rser.2022.113075
Received 8 June 2022; Received in revised form 18 November 2022; Accepted 19 November 2022
Available online 1 December 2022

Abbreviations

AI	Artificial Intelligence
BRD	Big Real-Time Data
BRICS	Brazil, Russia, India, China, and South Africa
EWSETA	Energy and Water Sector Education and Training Authority
GDP	Gross Domestic Product
IoT	Internet of Things
IEA	International Energy Agency
IPPs	Independent Power Producers
HMI	Human Machine Integration
OECD	Organisation for Economic Co-operation and Development
OFO	Organising Framework for Occupations
PPP	Public-Private Partnership
ROB	Robotics
SOE	State-Owned Entity
SCADA	Supervisory Control and Data Acquisition
UNIDO	United Nations Industrial Development Organisation
WEO	World Economic Outlook

value chain, particularly at the production stage and, as a result, benefiting from doing so? This review aims to identify and appraise what has been published on the use and impact of Industry 4.0 technologies in energy production. This review is focused on China, Germany and South Africa and contributes to an earlier study by Ref. [12] on the importance and application of Fourth Industrial Revolution technologies in the energy sector. The paper provides perspective on the use of Industry 4.0 technologies in Chinese and German energy companies and the opportunities these technologies create for enhancing energy productivity, efficiency and sustainability. For South Africa, in a time of an energy crisis, the review begins to fill a knowledge gap on the value of Industry 4.0 technologies in energy production and the opportunities created by such technologies to navigate better the challenges it faces in energy demand and supply. The review suggests conducting firm-based studies, drawing on actual productivity data at energy plants, on the usage and impact, current and potential, of Industry 4.0 technologies in energy production and the value-add created.

Using the number of publications as our reference point for 2018 to 2022, we identify critical types of technologies used in the energy sector, the location of such technologies in the energy value chain and disparities between developed, newly industrialised, and emerging economies. Next, we provide perspective on the thematic foci of global literature published on Industry 4.0 technologies in the energy sector, first through a scan of global literature and then in China, Germany, and South Africa. The perspective highlights a gap in the literature on the Chinese, German and South African energy sectors.

South Africa was chosen as a developing African country supplying almost 40% of all energy across the continent [13]. Domestically, almost 90% of all energy production and distribution is controlled and carried out by the state-owned entity: Eskom [13]. As a country with access to the fifth-biggest supply globally, its primary energy source is still coal (69%) [11,13]. The country is currently facing an energy crisis, under immense pressure to expand energy supply, firstly by optimising efficiency levels at coal-fired plants through proper maintenance and infrastructure upgrades, and secondly, by growing production of renewable energy resources that are more sustainable and less environmentally damaging, both requiring huge investments in existing and new energy plant build [11,13].

Through its Made in China 2025 initiative, China was selected as part of this review as a newly industrialised, global manufacturing powerhouse [14] that continues to display its dedication towards fast-tracking Industry 4.0 initiatives, sector-wide, in providing finance for research, development, and implementation of associated Industry 4.0 technologies, in this case, relating to renewables [15,16]. “China is currently a global leader in renewable energy installations” [2]. A component of the Made in China 2025 initiative is “Internet Plus,” which focuses on improving quality in manufacturing and quantity using Industry 4.0 technologies [15]. However, regarding the energy sector, the generated power is predominantly thermal based using coal, although forecasted scenarios by the IEA expect this to drop substantially by 2015 [2]. The sector in China has undergone a process of deregulation to de-monopolise a market that was 70% owned by the Chinese central government. Via its State Power Corporation, many Independent Power Producers (IPPs) that entered the energy market were subsidiaries of the State Power Corporation [17]. Five state-owned generating companies currently own 45% of all energy generation [18]. In addition, the central and local governments own another 45% of energy-generating plants [18]. In other words, 90% of all energy generation is controlled by the Chinese State (central and local), and these institutions are responsible for 100% of all energy transmission and distribution [18]. In South Africa, although Eskom controls 90% of energy production, distribution and transmission, there are plans to create SOE subsidiaries of Eskom (as is the case in China) according to their role in the energy value chain. China, like South Africa, is under pressure to expand cleaner and more sustainable energy production to reduce carbon dioxide emissions, a goal that necessitates substantial capital investments by the government and the private sector through creating Public-Private Partnerships (PPPs) [19]. However, joint ownership and control by central and local levels of government of the Chinese energy sector have led to local level governments “undermining the implementation of central government policies” “despite the efforts of the top leadership to centralise control [18]." Sharing lessons like these are essential for South Africa to strategise around an increasingly decentralised energy system.

Germany was included in the study based on its dominance as a European economic power, its reputation as the conceptual champion of Industry 4.0 and leader in renewable energy, and its commitment to prioritising Industry 4.0 in national policy, particularly Germany Energiewende [20,21] and its Energy Efficiency Strategy 2050 [22]. Germany has implemented a phase-out plan for coal plants producing energy by 2038 [22]. Also, the German energy market is liberalised and competitive, with energy consumers buying energy from a producer of their choice, generating their own energy and selling it in the energy market [23]. Hence, the German energy market is structured differently from South Africa and China. However, “there are ideological, policy-based similarities between the participatory nature of Germany’s Energiewende and the social compact envisaged for South Africa in its National Development Plan” [12]. The South African-German Energy Partnership Secretariat illustrates South Africa’s interest in the German model of energy decentralisation, mainly as this is primarily driven by local municipalities [12].

A discussion of publications on Industry 4.0 technologies in energy companies and their overall impact on energy production is then presented. The aim is to identify and understand how these studies applied different approaches to formulating an overview of the use and impact of varied Industry 4.0 technologies in these energy companies, the strengths and gaps in these publications, and, more importantly, the opportunities they create to understand the South African energy sector better.

2. Methods

This review comprises a Scopus search to broadly investigate the types of Industry 4.0 technologies used in the energy sector and then exclusively for energy production. The timeframe covered by the search was 2018–2022, which draws on the most recent publications on the latest technologies in energy and accommodates the rapidity of the speed of digitalisation, characterising Industry 4.0. The search was initially limited to three subjects, engineering, computer science, and energy, based on their relevance to the study. However, this was later restricted to just the subject of energy.

Five steps were followed in the review. First, Scopus was used to conduct an initial diagnostic scan of the global literature using publication titles on digitalisation and Industry 4.0 in the energy sector and then in energy production. The number of publications across relevant subject specialisations, engineering, computer science, and energy, were recorded (Fig. 1a and b).

Next, the search was condensed to just energy as the subject specialisation. Country-specific data were collected for nine countries (China, Germany, South Africa, The United States, Brazil, Russia, India, Mexico, and Nigeria), grouped according to their economic status, these being developed, newly industrialised and developing (Fig. 2a and b).

The third step involved pinning categories of Industry 4.0 technologies used across the energy value chain (Fig. 3a) and then tightening to just energy production (Fig. 3b) globally. Here, the search was subjective in that it drew on our interpretation of Industry 4.0 technologies applied in the energy sector and research conducted by various authors. Categories of Industry 4.0 technologies in the energy sector comprised the Internet of Things, Artificial Intelligence, Big Real-Time Data, Robotics, and Machine Human Integration. Despite overlaps in how Industry 4.0 technologies were categorised, certain hierarchies emerged through the data.

In step 4, the review focused on the five categories of Industry 4.0 technologies, only for the three countries making up this research – China, Germany, and South Africa (Fig. 4a–i).

Step 5 was a thematic assessment that aimed to identify and discuss dominant themes emerging through the literature on the use of Industry 4.0 technologies within the energy value chain in the three countries, as well as selected methodologies used to measure the impact of Industry 4.0 technologies on energy production. Selected publications were specific to China, Germany, and South Africa and based on the relevance of their titles and abstracts to this study.

3. Results

In a search of publications on the energy sector focusing on "Industry 4.0 and technology," "Digitalisation technology", and "Industry 4.0 energy technology," across the subject domains of engineering, computer science, and energy, a total of 17,104 publications emerged (Fig. 1a). These publications were identified using the keywords "Industry 4.0 technology" (52%) and "Digitalisation technology" (44%). Reference to "Industry 4.0 energy technology" was just 4%. However, narrowing the search to the use of Industry 4.0 technologies in production (Fig. 1b), the number of publications was reduced to 4398. Industry 4.0 production technology accounted for 63% of the publications, followed by digitalisation production technology at 31% and Industry 4.0 energy production technology at 6%. Engineering publications focussed on applying specific Industry 4.0 technologies across industries such as aircraft, shipping, and education, or the implications these have on business processes within supply chains regarding their efficiency and sustainability. Computer Science included publications that dealt with technologies, and although associated with Industry 4.0 (such as blockchain, real-time sensors, digital analysis models, and predictive maintenance programmes), these were not related to energy or its production.

A search of publications by country reveals disparities in the number of publications on Industry 4.0 technologies in energy overall and just energy production (Fig. 2). A total of 60 publications across nine countries were identified on energy technology. In contrast, only 35 were found in energy production. China produced the most significant percentage of articles, 27% on energy technology and 29% on energy production technology. An apparent disparity exists when comparing newly industrialised (India and China), developed countries (United States, Germany, and Russia) and the emerging economies of Brazil, Mexico, Nigeria, and South Africa (Fig. 2a and b). Germany produced the second largest number of publications in both categories (20% and 23%), whereas South Africa only produced 7% of articles in energy technology but none in energy production technology.

The Industry 4.0 technologies which are dominant in the research on the global energy sector are IoT (43%), AI (22%) and BRD (21%) (Fig. 3a). ROB comprises only 5% of the total publications and HMI, only 1%. Similarly, of the total publications on Industry 4.0 technologies in energy production, ROB comprised 7% and HMI 1%, whereas IoT, AI and BRD contributed an equal share at 24% (Fig. 3b).

The total number of publications in each technology category for China, Germany and South Africa in energy overall and energy production is presented in Fig. 4 a-i. China produces the most significant number of publications in all technology categories in energy and energy production. South Africa has zero publications in IoT (Fig. 4a and b), AI (Fig. 4d), ROB (Fig. 4f) and BRD (4 h). The most significant number of publications for South Africa is on ROB (20%) (Fig. 4e). Germany produces the same number of publications as China in IoT (Fig. 4b) and ROB (Fig. 4f) in production technology. Germany also produces the same number of publications as South Africa in ROB

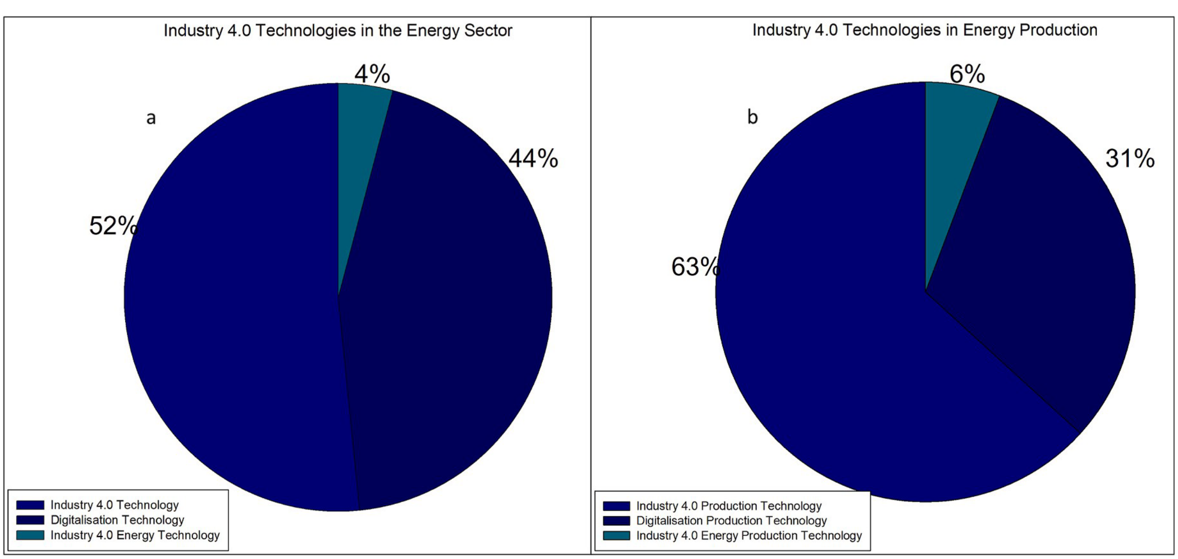

Fig. 1. The number of publications focussed on Industry 4.0 technologies in (a) the global energy sector and (b) energy production only.

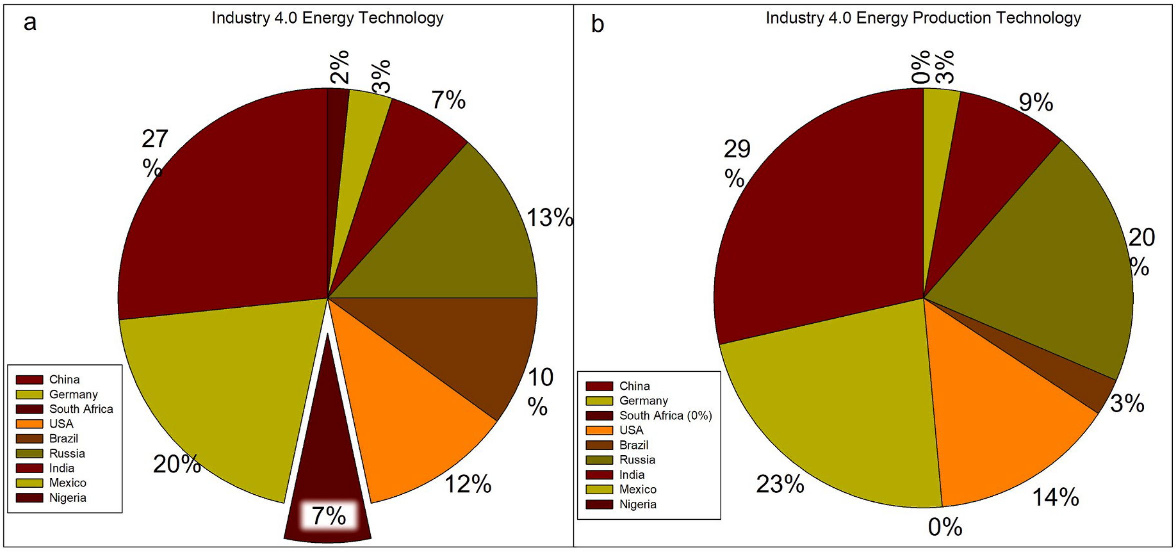

Fig. 2. The number of publications produced per country in (a) energy technology and (b) energy production technology. South Africa accounts for 7% of publications on energy technologies.

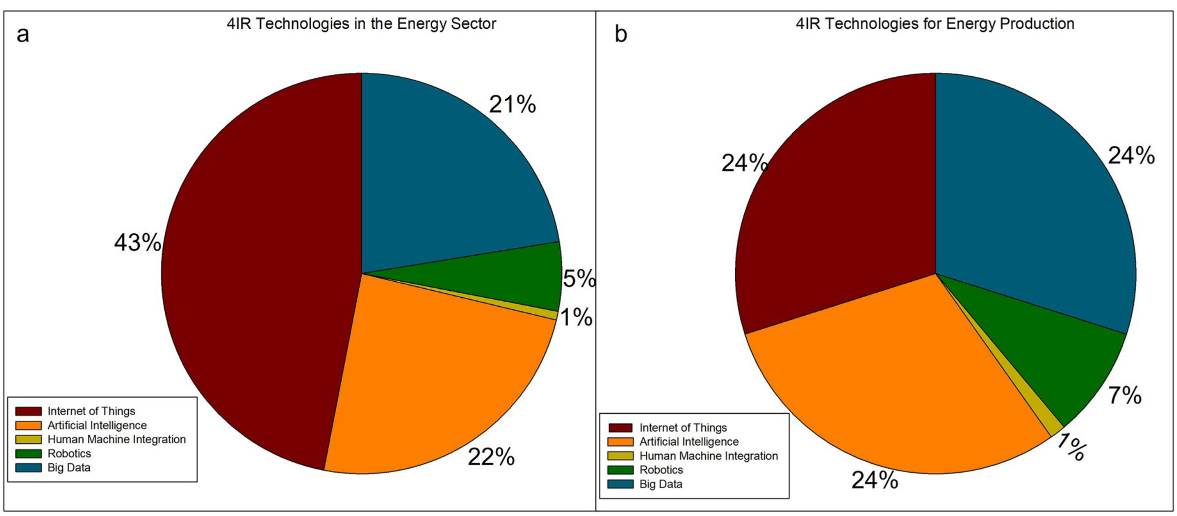

Fig. 3. The number of global publications globally per Industry 4.0 technology category in a) the overall energy sector and (b) energy production only.

energy technology (Fig. 4e).

4. Discussion

Of the publications on China, Germany and South Africa, four key themes emerged on using Industry 4.0 technologies within the energy value chain. Firstly, increasing energy efficiency and sustainability were emphasised. Secondly, the energy policy and regulatory environment were explored. Thirdly, a proof-of-concept approach to lower energy costs in the industry was presented. Finally, different methodologies for measuring the impact of Industry 4.0 technologies on energy production were described.

Literature on Industry 4.0 technologies used in the energy sector, most notably in energy production, is limited (Fig. 1). This lacuna exists, despite global initiatives by the United Nations Industrial Development Organisation (UNIDO), the World Bank Group and the IEA; to promote digitalisation in energy, improve efficiencies, reduce harmful emissions and promote environmental sustainability [24–26], and national, strategic initiatives and policies with similar aims. In Germany, these include the Energiewende Strategy [21] and its Energy Efficiency Strategy 2050 [22]. In China, the Made in China 2025 strategy [14,15] and the IEA Energy Sector Roadmap to Carbon Neutrality in China [27] exist. South Africa is guided by its Integrated Resource Plan [28] and the National Development Plan [29], which encourage evidence-based policy.

4.1. Developed, newly industrialised and emerging economy disparities in publication numbers

In Fig. 2b, China produced more publications than its Indian, newly industrialised counterpart and the developed nations of Germany, Russia, and the United States. The higher publication number is despite Germany and the United States making significant strides in tran- sitioning to renewables. The combined contribution of Brazil and Mexico, leading emerging economies in South America, is 23%, whilst their African counterparts are 3% for Nigeria and zero for South Africa. A comparison of the BRICS nations, again, placed South Africa the lowest. This review agrees with [16], “although South Africa likes to present itself as one of the BRICS, comparisons with Brazil, Russia, India, and China can seem unconvincing,” with the government “struggling to

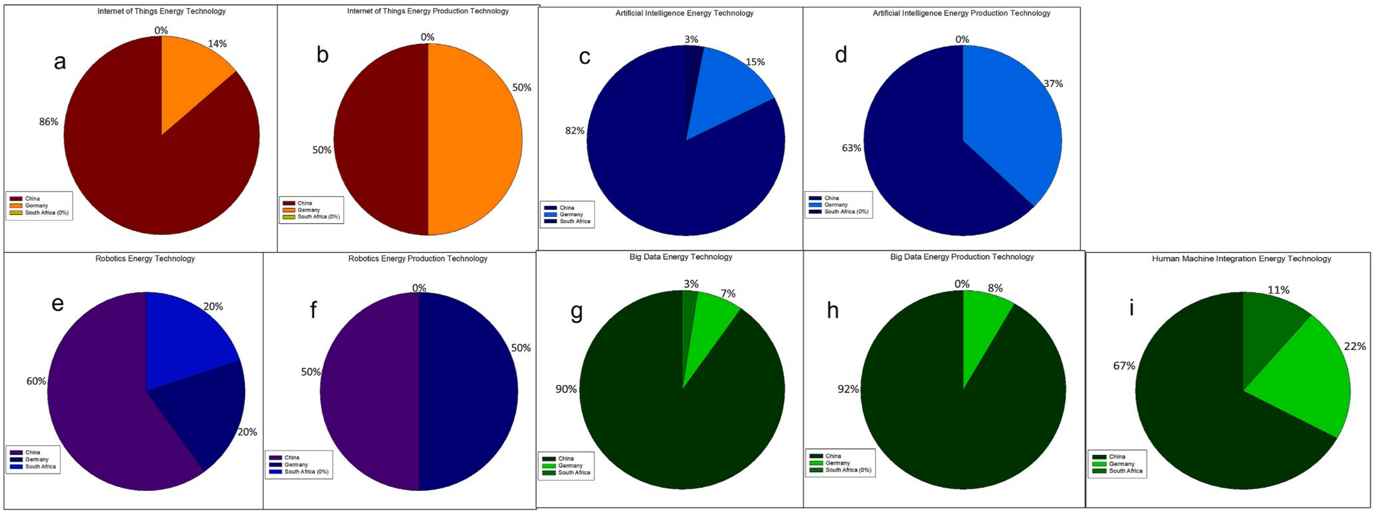

Fig. 4. Total number of publications in each technology category for China, Germany and South Africa in energy overall and energy production.

hold a consistent position on the roles and limits of the private sector."

China's lead in the number of publications (Fig. 2a and b) is supported by the survey results in Ref. [12]. The survey found that Chinese energy companies valued the importance of Industry 4.0 technologies to the global energy sector more than those from Germany and South Africa. In addition, Chinese companies placed more importance on using Industry 4.0 technologies. However, this was despite 85% of the Chinese, German and South African companies believing themselves to be a part of Industry 4.0 [12].

Global research highlights the benefits of integrating Industry 4.0 technologies across industries for economic growth and rising competitiveness. Furthermore, these studies have necessitated and provided a comparative baseline for conducting similar studies in South Africa and other developing countries by implementing various approaches to measuring the impact of Industry 4.0 technologies in the energy sector.

A hierarchy is evident in the types of Industry 4.0 technologies used across the energy sector and in energy production. IoT, AI and BRD are the most prominent technologies researched, whereas research on ROB and HMI is limited. The outcome is despite ROB and HMI contributing to foregrounding energy sector efficiencies and sustainability [6,10,11]. [30] estimated that for Organisation for Economic Cooperation and Development countries (OEDC), as much as 10% of GDP growth between 1993 and 2016 was because of raised investments in robots. The slow implementation of Industry 4.0 technologies in the energy sector is related to high technology costs, a lack of buy-in by IPPs to invest in the technologies, insufficient government support and incentives, unclear policy direction and the lack of political will to do so [12]. Further research is required to identify and understand obstacles to implementing Industry 4.0 technologies in the energy sector.

Stark differences appear in the number of publications produced by China, Germany, and South Africa (Fig. 4). China is the leading country in all Industry 4.0 technologies, attributed to more government support to develop and implement these technologies. Research and innovation in the Chinese energy sector are encouraged and incentivised to reduce coal-based energy generation, grow renewables, and minimise technology costs by producing these technologies locally.

Fewer publications on Industry 4.0 technologies in Germany are cause for concern, mainly as Germany was the first country to develop the concept of Industry 4.0 through Energiewende, and a large proportion of digital technologies relevant within the energy sector are produced in Germany [12]. On the other hand, in the case of South Africa, the focus has centred on energy security and expanding access to energy resources due to failures in proper planning and investment on the part of the state, financial challenges, and a poor maintenance programme for existing power plants [12].

4.2. Increasing energy efficiency and sustainability

Alekseev [8], in citing [31,32], looked at the advantages of integrating AI systems and ROB to reduce the energy intensity, carbon footprint, and energy efficiency of energy-intensive manufacturing industries. Measuring firm-specific production data and how AI and ROB impact energy productivity at energy plants is not an area in the research. Using digitalisation to promote energy efficiency and sustainability is a concern in the global and national dialogue on implementing renewable and sustainable energy sources. However, it provides a broad, top-level view of the impact of such digitalisation [8]. "Reaching the critical but formidable goal of net zero emissions by 2050 will require major efforts from across society – but it also offers major advantages in terms of human health and economic development. What comes through clearly in the World Energy Outlook are the huge opportunities that come with clean energy transitions – for manufacturers of wind turbines, batteries, electrolysers, and a host of other technologies" [2]. [33] share similar sentiments and develop a set of scenarios to pave the way for a more sustainable Industry 4.0 that emphasises environmental protection. The studies [2,32,33] are interested in using Industry 4.0 technology to address climate change and promote environmental sustainability. Part of this is about creating efficiencies to reduce production costs through optimising the energy resources needed to drive production processes [7]. However, emphasis is on environmental impact rather than an impact assessment of how and the extent to which the technologies shape processes across the energy production chain, creating a gap in the literature reviewed.

In Alsaleh & Adul-Rahim [34], there was a focus on how economic determinants, including capital and labour input costs, actual interest rates and real Gross Domestic Product rates, have affected cost efficiencies in the bioenergy industry in parts of the European Union, concluding that better cost efficiencies promoted the growth of the bioenergy sector. In Ref. [9], the authors showed how cost efficiencies linked to improved information and communication technology contributed positively to rising competitiveness in the bioenergy sector and the overall growth and sustainability of the sector in the same region and assisted in addressing increasing environmental pollution and climate change. In addition, the cost-efficiency forecasting models highlighted the importance of improved technology in bioenergy production. However, the study provides a comprehensive, overarching evaluation of 'information and communication technologies and does not specify technology type (especially those tied to Industry 4.0), where these are used in energy production chains and the impact of identified technologies on firm-based energy production by measuring real productivity at energy plants.

4.3. The energy policy and regulatory environment

Other studies [35,36], as one author indicated [8], identify how reforming the national policy and regulatory environment may incentivise private energy companies to research and implement Industry 4.0 technologies. A review [17] states that "energy reforms play an essential role in technological change as they aim to contribute to an open market", reducing costs, raising firm competitiveness, and promoting developments in sector-based technologies. For [37], implementing IoT using 5G results in various challenges, such as "including practical implementation, cost of implementation, and stakeholder and citizen commitment among others, the benefits that smart cities offer for the South African context, like smart resource management, energy efficiency, long term cost-saving, improved services, etcetera. will outweigh the challenges." In Ref. [23], the authors review the energy sectors in Germany and Finland and how IoT, AI, and blockchains can support the realisation of cross-commodity energy sharing in local, decentralised energy systems. The authors explain how creating energy-sharing communities, called "smart cities," can address costs associated with a lack of economies of scale in a decentralised energy model [23]. propose that policy and regulations be reconceptualised to enable and incentivise technologies deployed locally rather than na- tionally [23]. suggest that this involves sharing cross-commodity and energy solutions across countries to promote learning. These policy suggestions are helpful for South Africa. After all, a decentralised and integrated energy system driven by municipalities through collaboration with private and public stakeholders (for example, the South African-German Energy Partnership Secretariat) is being encouraged in South Africa, although this needs to be expedited [13]. This review agrees with [23], using Industry 4.0 technologies to promote energy sharing across a more integrated and decentralised energy sector - a view that makes more sense given that Industry 4.0 technologies are being developed and implemented globally, in both large and smaller companies, meaning that "sector delineation is more relevant than national markets for Industry 4.0 technology diffusion" [38]. However, unlike Germany, this becomes difficult in a country such as South Africa, where the energy sector is still heavily regulated, with policy providing unclear direction for municipalities and IPPs [22]. Furthermore, the authors of this paper believe that the literature on rethinking policy interventions and implementation must be based on accurate, empirical data that supports the integration of Industry 4.0 technologies at energy plants through productivity-based impact studies, both current and forecasted. The need for empirical data is foregrounded in sector-based policy and planning documents [29,39,40].

[23] identify gaps in the literature on the use of AI for cross-commodity energy sharing in that it is concentrated on data emerging from simulated environments rather than actual, practical implementation. Although this may be the case, other studies have shown that the simulation of operational environments in the power system using AI enables better training on the grid and safety measures, the virtual maintenance of plants and therefore reduced costs linked to plant testing equipment. In support of these studies [12], cites [41] and explains that "machines are being developed to carry out what is referred to as 'deep learning' to help discern patterns and anomalies across huge datasets – both on the power demand and power supply sides – that otherwise would be nearly impossible to achieve." The authors in Ref. [23] also propose that the real-time periods over which data is collected and later analysed using AI be reduced from hourly to every 15 min to model better and control energy consumption and generation. Faster and more accurate collection and analysis of real-time data that leads to AI being able to better model energy trends and solutions cannot be disputed [3–5]. These processes should be part of the natural progression of technologies as these become more sophisticated through big data accessibility, ROB and improved materials development, and quicker and more accurate data analysis using machine learning.

Industry 4.0 has increased research on the changes that technologies will bring, both good and bad, in the development and well-being of human capital and socio-economic architecture [42]. Despite the extent of the topics within the reviewed literature [8], agrees with [43] that a thorough assessment of all parts of the energy value chain based on empirical evidence must precede any policy and regulatory change. This assessment should include where and how these technologies may be implemented and measure existing or potential impact using a consistent methodology. As cited by Ref. [8], the implementation of smart meters [3,44] and enhancements in cyber-physical network security systems [45–47] was another area of interest represented in the research. However, the publications prioritised the latter part of the energy value chain, involving power distributors and the energy customer. Although essential, there was no mention of technologies' role in energy production lower down in the value chain.

4.4. Proof-of-concept approach to materials processing technology

Scholars [48,49] look at specific technologies in energy and how to improve these using advanced, process-related materials that are more flexible, stretchable, agile, and capable of withstanding harsh environmental conditions. In Refs. [50–53], the authors explore energy efficiency in wireless sensors, such as triboelectric sensors and nanogenerators in wearable devices and self-powered nano-systems, to promote hu man-machine interfaces. Dielectric elastomer actuators are technologies not relevant to energy production, used in soft robots and wearable devices to harvest and store ambient energy to make such devices self-powered [54–57]. These are *proof of concept articles* in which new, often improved technologies were conceptualised, developed, and tested to the point of implementation. Being materials-orientated, although still necessary, does not contribute to interpreting and measuring the impact of Industry 4.0 technologies on energy production and other parts of the energy value chain [7]. share similar sentiments concerning the Russian energy sector in describing that "scientific and technological limitations are in the shortage of scientific research and experimental development in the field of digital energy, an insufficient number of digital devices at power facilities, the lack of development of a unified methodology for assessing the effect of introducing elements of digital energy etcetera." This review supports the view by Ref. [43], [cited by Ref. [8], on a lack of scientific research because of limited and inconsistent data collection on digitisation in energy. Unless there is baseline data to illustrate the positive impact of Industry 4.0 technologies in energy production, energy companies will be cautious about investing in Industry 4.0 technologies.

4.5. Measuring the impact of industry 4.0 technologies across the energy value chain

Research has been carried out on the impact of Industry 4.0 technology on the energy value chain, highlighting how such technologies impact the extraction of better-quality raw materials such as coal using intelligent robots [58]. [16] refers to how, in South Africa, "automation might sustain its economic output by replacing people with smart machines. Again, the interest is in the initial part of the energy value chain and not energy production. Moving further along the value chain, a large part of the literature deals with energy distribution via smart grids, enabling better planning and communication between the grid and energy users [59,60]. Here, critical issues explored are more sophisticated ways of managing energy demand and supply through the improved processing of energy information [61,62], monitoring and controlling these grids in real-time using systems such as Supervisory Control and Data Acquisition [63], digital twin drive technology [64], 'source--network-load-storage' coordination optimisation technology [65], simulation technology and, energy forecasting systems [66,67]. The apparent void in research targeting the middle parts of the energy value chain deserves further attention to unpack whether such imbalances in applying Industry 4.0 technologies are consistent globally and across different energy sectors.

In [10], the authors looked at the link between AI technologies, workforce productivity and wages in large energy companies leading in Industry 4.0 technology implementation in the United States. Although not related directly to energy production at these plants, rising workforce productivity means rising plant productivity [42]. One of the findings that emerged [8] was the positive correlation between hiring employees with AI-related skills and their wages, the more developed AI skills, the higher the employee wage. Skills in Robotics contributed the second most to wage increases. The study further concluded that AI is the most valued Industry 4.0 technology in the US energy sector as it is associated with a higher revenue generated per job [9]. The study presented an exciting angle to measure the impact of emerging Industry 4.0 technologies on energy producers as it outlines how skills demands are changing using actual empirical data on the labour market.

The Energy and Water Sector Education and Training Authority (EWSETA) in South Africa is responsible for planning and implementing skills and training programmes for employers in its sector. One of the change factors in the energy sector it has identified is Industry 4.0 and the need to reskill and rethink skills development in the sector [39]. The involved skills development processes have not proven to be easy. To quote [39], "as it becomes increasingly difficult to accurately determine future skill needs because of the pace at which technology is rapidly advancing (i.e., Industry 4.0), it equally becomes increasingly difficult to plan for skills required in future. This further complicates skills development efforts." The review supports [10] as one way to measure energy companies' changing skills needs. Energy productivity studies on the South African energy sector, whether centred on the types of skills employed and their associated wages, in the case of [10] or plant productivity indicators, would be helpful in better measuring and understanding the impact or potential impact of Industry 4.0 technologies in the local energy sector. It would also provide essential data on how the skill-set required by energy companies is changing at energy plants because of Industry 4.0 [40]. explains that the current process that the Sector Education and Training Authorities use to collect data on skills needs of various economic sectors, here energy, is cumbersome and is based on an outdated job classification system called the Organising Framework for Occupations (OFO). Thus, employer data on skills and training needs are often inaccurate and do not reflect the impact of technological changes on skills, training and development needs [40]. Impact studies on the current and forecasted role of Industry 4.0 technologies on productivity in the energy sector offer a different approach to evaluating fundamental skills needs based on empirical labour and plant productivity data. Such an evaluation will contribute to better planning for skills development and training amongst energy sector stakeholders, including employers and government (EWSETA), focusing on enhancing labour and, subsequently, energy plant productivity.

[7] reviewed ten publications that provide an overview of Industry 4.0 digital applications in the German energy sector. A structured overview of categories of grouped digital applications across the energy value chain is presented, and the benefits for affected stakeholders impacted the most. Three categories of digital applications were put forward: i) system balance, ii) process optimisation, and iii) customer orientation [7]. System balance ensures the grid's stability by optimally managing energy demand and supply using technologies such as digital sensors, demand and supply forecasting algorithms, remotely controlled systems, and smart grids. The second category of digital applications is process optimisation which is about improving internal and process efficiency at energy plants and relates to energy production. Customer Orientation is the third category. The focus herein is on technologies such as smart metres and intelligent home systems that create more transparency and cost efficiencies in consumption, enabling customers to measure and control their energy usage and costs in real-time, down to the actual appliance that consumes energy [7].

[7] used the following criteria to evaluate the expected benefits of digitalisation in the German energy sector: i. stability, ii. environmental protection, iii. energy demand reduction, iv. revenue increase, v. cost reduction, and vi. customer expectations. This literature review also identified each of these criteria in the discussion above. Environmental protection addresses climate change, which is linked to reduced energy demand [33,34]. Reducing energy demand is enabled by improved efficiencies in the materials used in production processes [50–53] and better management of energy demand and supply through AI modelling and forecasting [3–5,23]. The result is lower production costs [7,17]. Customer expectations are better met by providing more efficient, reliable, and sustainable energy resources and through energy-sharing communities [23] and smart grids [3,44]. The authors sought to illustrate the amount of research conducted on these expected benefits using the formula: number of publications referring to the benefits of technologies divided by the number of publications referring to the application of these technologies. Cost reductions were the expected benefit most referred to in the literature review [7]. This review agrees with the findings in Ref. [7]. In this review, cost reductions were also referred to the most as a benefit of Industry 4.0 technologies in energy across the value chain. However, these were based on cost savings that are not necessarily the result of process efficiencies in the production part of the value chain but due to efficiencies created in the distribution and consumption of energy further down [7,23,60,61].

The second most mentioned benefit in Ref. [7] is balancing the energy system. Again, this emphasised optimising the stability of the energy system at the distribution and consumption parts of the energy value chain by incorporating smart grids and smart technologies [7,23,60,61]. Improved efficiencies in the distribution and supply of energy meant cost reductions through reduced demand because of flexibly managing the energy system and improved the meeting of customer expectations within the energy sector. Publications identified in Ref. [7] on the benefits of digitisation are linked to process optimisation mechanisms at energy plants using advanced data analytics. These studies were concerned with cost reductions linked to using technology for predictive maintenance to reduce maintenance costs. However, other Industry 4.0 technologies, such as AI, ROB and HMI, were not considered. Hence, the benefits of using sophisticated Industry 4.0 technologies such as AI for productivity forecasting, adaptation, and optimisation, such as via the establishment of digital twins, scenario setting and simulations, were not unpacked. Similar results emerged in Ref. [12] through a survey of Chinese, German and South African energy companies. AI, ROB and MHI were identified as of least importance to the surveyed companies and were considered less reliable, efficient, and integrated within the surveyed firms. Such company views emerged, even though literature has shown massive potential for AI, ROB and MHI to advance the energy sector, and there is much to learn from China and Germany, who are already using these technologies [12]. This review agrees with both studies [7,12]. Of the 8826 global publications in this review on Industry 4.0 technologies, publications relating to ROB and MHI were the lowest at 119 and 4, respectively. Research on ROB and HMI in the energy sector appears comparatively limited despite a country's economic status and technological advancement and is recommended.

[7] recognised these shortcomings and developed a model that could be used to measure the impact of Industry 4.0 technologies more accurately across the energy value chain, drawing on empirical firm data. Their findings reaffirm the results emerging through this review, noting a lack of research on how digitisation in production processes may lead to increased productivity and rising revenues. Also, and like the study conducted by Ref. [10], the review could be strengthened by drawing on literature, possibly available in other countries, containing actual productivity data, data analyses and trends to forecast expected benefits as well as determine the location, nature, and scale of such benefits more

accurately within energy production processes.

Nevertheless, quantifying the benefits of Industry 4.0 technologies in production using other studies [7,10,12] as a point of reference would be invaluable to the South African energy sector to evaluate its integration of such technologies. For example, it remains to be investigated why the impact of Industry 4.0 technologies in the energy sector and why energy producers are not leveraging ROB and HMI. Is this attributed to overlaps in the classifications of ROB and MHI with AI and a consolidated method to measure these technologies' impact, as suggested in Refs. [7,8,12]? Is this tied to reduced access to Industry 4.0 technologies because of high costs, found to be the case in Ref. [12], or the lack of state support to help materialise such benefits as identified in Refs. [5,8,35,36]? Either way, Industry 4.0 technologies for the energy sector need to be explored across the entire value chain to avoid a missed opportunity for advancing productivity, efficiency, reliability, interconnectedness, and sustainability. The findings of the studies referred to in this review [7,8,10,12,16] and the data emerging through the Scopus search conducted here may offer a starting point for expanding research on the impact of Industry 4.0 technologies in the South African energy sector. This research may help to conceptualise better what Industry 4.0 means in the context of energy production and how it has been implemented and driven successfully within countries including Germany, the United States and China. Also, if and how countries experiencing challenges and limitations in applying Industry 4.0 technologies in their energy sectors are navigating these difficulties. This review highlights different ways in which to measure the impact of Industry 4.0 technologies on the overall energy sector, especially energy production -— helpful for developing a more reliable, accurate and consistent approach to collecting, analysing, and forecasting data required for monitoring and evaluating the present and future impact of Industry 4.0 technologies in the South African energy sector, including energy production.

5. Conclusion and recommendations

Several conclusions emerged from this review. First, although there is research on Industry 4.0 technologies across various sectors to improve industry efficiencies and promote sustainable development, there is limited research on whether and how these technologies are used in the energy sector, specifically, energy production. Second, there are differences in the number of publications spanning the various Industry 4.0 categories of technology at a global level. Third, there are far more publications on IoT, AI and BRD than ROB and MHI, a finding supported by a survey of energy companies [12]. Fourth, there are disparities in the number of publications on Industry 4.0 technologies used in energy sectors, based on economic development status, with emerging economies (South Africa, Nigeria, Brazil, and Mexico) lagging both developed (Germany, Russia, and the United States) and newly industrialised countries (China and India). South Africa is the worst performing compared to the number of publications produced by other BRICS countries. Germany is driving Industry 4.0 technology integration across the industry through "Energiewende," yet remains behind China in publication numbers. Through its "Made in China 2025" initiative, the Chinese government has promoted and incentivised research and innovation in energy and supports local production of Industry 4.0 technologies. As South Africa lags China and Germany in the number of publications, the review highlights a gap in research on the energy sector in South Africa.

There is limited empirical data on Industry 4.0 technologies in energy production and how these technologies contribute to rising productivity and revenue at energy plants. The collection of empirical data could involve a range of other indicators, such as those measuring costs (other than maintenance); the time taken to implement new technologies; productivity changes based on the optimal quantity and quality of production; ability to use Industry 4.0 technologies to simulate and forecast changing conditions and then use technologies to adjust and adapt; and returns on technology investment.

For example, the methodologies for measuring the impact of Industry 4.0 technologies in Germany and the United States were varied. Some used the rising workforce productivity to measure rising plant productivity. Other studies measured cost savings emerging via efficiencies created in the distribution and consumption of energy further down the energy value chain and not those linked to process efficiencies in the production part of the value chain. One review measured the impact of Industry 4.0 technologies on energy by calculating the number of publications referring to the benefits of technologies divided by the number of publications referring to the application of these technologies. A more reliable, accurate and consistent approach to collecting, analysing, and forecasting data is suggested for monitoring and evaluating the present and future impact of Industry 4.0 technologies in the South African energy sector, including energy production.

The value created by using Industry 4.0 technologies, increasing efficiency and productivity in energy companies, cannot be disputed, as is the contribution of these technologies to a cleaner, safer and more sustainable environment. The ability to quantify the benefits of Industry 4.0 technologies in energy production, using other global studies as a point of reference, is invaluable for a South African energy sector in crisis. However, despite studies highlighting the benefits of developing and implementing Industry 4.0 technologies within the energy sector, there remains a void in the number of publications regarding the South African energy sector. Evidence-based policy is crucial for addressing energy security and sustainability in South Africa, but this relies on the availability of accurate, firm-level productivity data on how and where Industry 4.0 technologies across the energy production value chain. The review recommends a commitment from multiple stakeholders in energy, driven by the State, to facilitate and expand in-depth, firm-level research to determine the positive impact of Industry 4.0 technologies on energy production and guide the leveraging of these technologies to boost energy productivity, efficiency and sustainability.

CrediT author contributions

Nadya Bhagwan: conceptualisation, data curation, formal analysis, funding acquisition, methodology, resources, writing and addressing supervisor comments, Evans, M: conceptualisation, supervision, visualisation, methodology, review, and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

Nadya Bhagwan acknowledges the University of Johannesburg's Capacity Development Programme for funding support.

References

[1] International Energy Agency. Key energy statistics [Internet]. 2019 [cited 2022 Sep 27]. Available from: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics.
[2] Energy Agency I. World Energy Outlook 2021 [Internet]. 2021. Available from: www.iea.org/weo.
[3] Ng TC, Ghobakhloo M. Energy sustainability and industry 4.0. In: IOP conference series: Earth and environmental science. Institute of Physics Publishing; 2020.
[4] Pfeiffer S. The vision of "industrie 4.0" in the making—a case of future told, tamed, and traded. Nanoethics 2017 Apr 1;11(1):107–21.

[5] Shapsough S, Takrouri M, Dhaouadi R, Zualkernan I. An IoT-based remote IV tracing system for analysis of city-wide solar power facilities. Sustain Cities Soc 2020 Jun 1:57.
[6] Kasza J. Forth industrial revolution (4 IR): Digital disruption of cyber-physical systems. World Sci News [Internet] 2019;134(2):118–47. Available from: www.worldscientificnews.com.
[7] Weigel P, Fischedick M. Review and categorization of digital applications in the energy sector, vol. 9. Switzerland): Applied Sciences; 2019. MDPI AG.
[8] Alekseev AN, Lobova Sv, Bogoviz Av, Ragulina Yv. Digitalization of the Russian energy sector: state-of-the-art and potential for future research. Int J Energy Econ Pol 2019;9(5):274–80.
[9] Alsaleh M, Abdul-Rahim AS. The pathway toward bioenergy growth: does information and communication technology development make a difference in EU economies? Biomass Convers Biorefin 2021. https://doi.org/10.1007/s13399-021-01933-9.
[10] Lyu W, Liu J. Artificial Intelligence and emerging digital technologies in the energy sector. Appl Energy 2021 Dec 1:303.
[11] Govender D, Moodley J, Balmahoon R. Augmented and mixed reality based decision support tool for the integrated resource plan. In: IECON proceedings (industrial electronics conference). IEEE Computer Society; 2021.
[12] Bhagwan N, Evans M. A comparative analysis of the application of Fourth Industrial Revolution technologies in the energy sector: a case study of South Africa, Germany and China. J Energy South Afr 2022 May 1;33(2).
[13] South Africa Department of Energy. The South African energy sector. Report 2019 [Internet]. 2019 [cited 2022 Jul 26]. Available from: http://www.energy.gov.
[14] Liu S. Innovation design: made in China 2025. DMI [Internet]. 2016 [cited 2022 May 27];27(1):51–8. Available from: https://www.researchgate.net/publication/323869484.
[15] Wübbeke J, Meissner M, Zenglein MJ, Ives J. Made in China 2025. MERICS PAP 2016:1–74. 2.
[16] Sutherland E. The Fourth industrial revolution–the case of South Africa. Politik 2020 Apr 2;47(2):233–52.
[17] Necoechea-Porras PD, Lo´pez A, Salazar-Elena JC. Deregulation in the energy sector and its economic effects on the power sector: a literature review. Sustainability 2021 Mar 2;13(6).
[18] Zhang S, Andrews-Speed P. State versus market in China's low-carbon energy transition: an institutional perspective. Energy Res Social Sci 2020 Aug 1:66.
[19] Cheng G, Zhao C, Iqbal N, Gülmez O¨, Is¸ik H, Kirikkaleli D. Does energy productivity and public-private investment in energy achieve carbon neutrality target of China? J Environ Manag 2021 Nov 15:298.
[20] Roth L, Lowitzsch J, Yildiz O¨, Hashani A. Does (Co-)ownership in renewables matter for an electricity consumer's demand flexibility? Empirical evidence from Germany. Energy Res Social Sci 2018 Dec 1;46:169–82.
[21] Kuittinen H, Velte D. Case study report Energiewende. 2018. Available from: http://europa.eu.
[22] Federal Ministry for Economic Affairs and Energy. Germany's Energy Efficiency Strategy 2050 [Internet]. Berlin [cited 2022 Jul 26]. Available from: www.bmwi.de; 2020.
[23] Paiho S, Kiljander J, Sarala R, Siikavirta H, Kilkki O, Bajpai A, et al., Towards cross-commodity energy-sharing communities – a review of the market, regulatory, and technical situation. Renew Sustain Energy Rev Elsevier Ltd 2021;151.
[24] United Nations Industrial Development Organisation. Low-Carbon and Climate Resilient Industrial Development in Africa. Impact LCCR Report. https://www.unido.org/sites/default/files/files/2018-12/LCCR-Impact-Report.pdf. [Accessed 18 July 2022].
[25] World Bank Group. Climate Change Action Plan 2021-2025. www.worldbank.org. [Accessed 16 July 2022].
[26] International Energy Agency. Special report on clean energy innovation energy technology perspectives [Internet]. Paris. 2020 [cited 2022 Jul 26]. Available from: https://iea.blob.core.windows.net/assets/04dc5d08-4e45-447d-a0c1-d76b5ac43987/Energy_Technology_Perspectives_2020_-_Special_Report_on_Clean_Energy_Innovation.pdf.
[27] International Energy Agency. Energy sector Roadmap to carbon neutrality in China: IEA country report [Internet]. Paris. 2021 [cited 2022 Jul 15]. Available from: https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china.
[28] South Africa - Integrated Resource Plan - 2019 [Internet]. Pretoria South African department of mineral resources and energy. 2019 [cited 2022 Apr 28]. Available from: http://www.energy.gov.za/IRP/2019/IRP-2019.pdf.
[29] South Africa Presidency. South Africa - national development plan. 2030 [Internet]. Pretoria. 2012 [cited 2022 Feb 15]. Available from: https://www.gov.za/sites/default/files/gcis_document/201409/ndp-2030-our-future-make-it-workr.pdf.
[30] Centre for Economics and Business Research. Impact of Automation: a report for Redwood Software [Internet]. Melbourne; 2017 [cited 2022 Feb 15]. Available from: https://apo.org.au/node/218266.
[31] Holkin DVCI. Digital transition in Russian power engineering: in search of meaning. Energy Pol 2018;5:7–16.
[32] Zhang Y MSYHLJLY. A big data driven analytical framework for energy-intensive manufacturing industries. J Clean Prod 2018 Aug;197(1):57–72.
[33] Ola´h J ANPJKMHHKN. Impact of Industry 4.0 on environmental sustainability. Sustainability 2020 Jun;12(11):4674.
[34] Alsaleh M, Rahim ASA. Cost efficiency of bioenergy industry and its economic determinants in EU-28: a tobit model based on DEA efficiency scores. Int J Manag Sustain 2019;8(2):79–87.
[35] Ahmad T, Zhang D, Huang C, Zhang H, Dai N, Song Y, et al,. Artificial intelligence in sustainable energy industry: status Quo, challenges and opportunities. In: Journal of cleaner production, vol. 289. Elsevier Ltd; 2021.
[36] Grabchak EP MEVI. How to make digitalization successful. Energy Pol 2018;5:25–9.
[37] Jordaan CG MNMR. Internet of things and 5G solutions for development of smart cities and connected systems. Commun CCISA 2019 May 1;25(2):1–6.
[38] Meceda AMVN. The singular economy: end of the digital/physical divide. STI Pol Rev 2018;9(1):133–57.
[39] Energy and Water Sector Education and Training Authority. Sector skills plan. 2021. 2022-2023.
[40] South African Qualifications Authority. The South African national qualifications Framework and the Fourth industrial revolution. Johannesburg. 2021.
[41] Makala B, Bakovic T. Artificial intelligence in the power sector [Internet]. International Finance Corporation, World Bank; 2020. pp. 1–8. Available from: https://www.researchgate.net/publication/343624277.
[42] Sima V, Gheorghe IG, Subi´c J, Nancu D. Influences of the industry 4.0 revolution on the human capital development and consumer behavior: a systematic review. Sustainability 2020 May 1;12(10).
[43] Massel LV. Methods and intelligent technologies for scientific substantiation of strategic solutions on the digital transformation of the energy industry. Energeticheskaya Polit 2018;5:30–42.
[44] Lund H, OPA CD, MB v. Smart energy and smart energy systems. Energy 2017 Oct;173:556.
[45] Zhou R FRZXTYWQ. Research on situational sensing method of grid cyber-physical system under network attack. In: 2019 IEEE sustainable power and energy conference (iSPEC). Beijing: IEEE; 2019. p. 454–8.
[46] Cui YYYXG. Research of ubiquitous power Internet of Things security authentication method based on CPK and RIFD. In: 2020 IEEE 4th information technology, networking, electronic and automation control conference (ITNEC). Chongqing: IEEE; 2020.
[47] Voropai N KIKEOA. Problems of vulnerability and survivability of cyber-physical and electric power systems. Energy Pol 2018;5:53–61.
[48] Sun C SQHDYMZMMYDBLYLC. Self-powered multifunctional monitoring system using hybrid integrated triboelectric nanogenerators and piezoelectric microsensors. Nano Energy 2019;58:612–23.
[49] Castro-Hermosa S LGTMFMFJBT. Perovskite photovoltaics on roll-to-roll coated ultra-thin glass as flexible high-efficiency indoor power generators. Cell Rep Phys Sci 2020 May;1(5).
[50] ZFXWWMYTHJCY Choy TH. Enhanced output power of a freestanding ball-based triboelectric generator through the electrophorus effect. J Mater Chem A Mater 2018;6(38):18518–24.
[51] Chen JWZL. Reviving vibration energy harvesting and self-powered sensing by a triboelectric nanogenerator. Joule 2017;6(38):480–521.
[52] Fan X HJMJQJZNYCHXGWWXCX. Triboelectric-electromagnetic hybrid nanogenerator driven by wind for self-powered wireless transmission in Internet of Things and self-powered wind speed sensor. Nano Energy 2020 Feb;68:104319.
[53] Go¨tz M. Energy management concepts for wireless sensor nodes. Energy harvesting for wireless sensor networks: technology, components, and system design. DeGruyter 2018:65–100.
[54] Neu J CSHJRGSGSS. Design and characterization of polymeric domes as biasing elements for dielectric elastomer membrane actuators. In: ACTUATOR: international conference and exhibition on new actuator systems and applications. VDE; 2021. p. 1–4.
[55] Ma C WRTHGSWMTZLDDDWW. Hybrid nanomanufacturing of mixed-dimensional manganese oxide/graphene aerogel macroporous hierarchy for ultralight efficient supercapacitor electrodes in self-powered ubiquitous nanosystems. Nano Energy 2019 Dec 1;66:104124.
[56] Dong B SQYYWFZZLC. Technology evolution from self-powered sensors to AIoT enabled smart homes. Nano Energy 2021 Jan;79:105414.
[57] Gao M WPJLWBYYLSCDCWLY. Power generation for wearable systems. Energy Environ Sci 2021;14(4):2114–57.
[58] Ge SHEPW. Classification system and key technology of coal mine robot. China Coal Soc 2020;45:455–63.
[59] Jiang A YHLDTJ. Key technologies of ubiquitous power Internet of Things-aided smart grid. J Renew Sustain Energy 2019 Nov 12;11(6):062702.
[60] Hao et al.. IoT-G: a low-latency and high-reliability private power wireless communication architecture for smart grid. In: 2019 IEEE international conference on communications, control, and computing technologies for smart grids. IEEE; 2019. p. 1–6.
[61] Wang et al.. Congestion management of urban power grid considering demand response of data centre. Power Syst Technol 2020 Mar;44:3129–38.
[62] Brown et al.. A software defined approach for improving resilience in smart distribution grids. In: 2020 international SAUPEC/RobMech/PRASA conference. IEEE; 2020. p. 1–6.
[63] Narayan A KCGABDHMWBLALS. Towards future SCADA systems for ICT-reliant energy systems. In: International ETG-congress 2019; ETG symposium. VDE; 2019. p. 1–7.
[64] Gao YHXAQ. Multi agent coordinated optimal control strategy for smart microgrid based on digital twin drive. Power Syst Technol 2021;45:2483–91.
[65] Lu W SYLBCL. Research and application of 'source-network-load-storage' coordination optimisation technology based on cloud platform. In: 2021 4th

international conference on energy, electrical and power engineering (CEEPE). IEEE; 2021. p. 813–8.
[66] Wang et al. A review of wind speed and wind power forecasting with deep neural networks. Appl Energy 2021 Dec 15;304:117766.
[67] Wu ZCW. Sampling strategy analysis of machine learning models for energy consumption prediction. In: 2021 IEEE 9th international conference on smart energy grid engineering (SEGE). IEEE; 2021. p. 77–81.

CHAPTER 3: A COMPARATIVE ANALYSIS OF THE APPLICATION OF FOURTH INDUSTRIAL TECHNOLOGIES IN THE ENERGY SECTOR: A CASE STUDY OF SOUTH AFRICA, GERMANY, AND CHINA

3.1. Brief synopsis

Industry 4.0 technologies have boosted possibilities for enhanced efficiencies within the energy sector. In this paper, the application of Industry 4.0 technologies is examined for the energy sectors of China, Germany, and South Africa via a survey of 26 energy companies. Cronbach Alpha, Kruskal-Wallis and Mann-Whitney tests inform the data analysis. According to the survey results, 85% of companies acknowledge good levels of participation in Industry 4.0 and are cognisant of the types of Industry 4.0 technologies considered important for the energy sector, although few companies develop these themselves. The most valued technologies in terms of measured importance, efficiency, reliability, and ability to be integrated across the energy system enable access to and analysis of Big, Real-Time Data. Also ranked highly is the transfer of data using the Internet of Things. Contrary to these technologies, Artificial Intelligence, Robotics and Machine-Human Integration (also called Machine-Human Interaction) are considered far less important, efficient, and reliable. China rates Industry 4.0 technologies far more important than South Africa and Germany. For South Africa to be competitive in the global energy sector, it needs to engage with and embrace Industry 4.0 technologies to a greater extent.

Publication details: Bhagwan, N., & Evans, M. 2022. A comparative analysis of the application of Fourth Industrial Revolution technologies in the energy sector: A case study of South Africa, Germany, and China. Journal of Energy in Southern Africa,33(2), 1–14. https://doi.org/10.17159/2413-3051/2022/v33i2a9200

Journal impact factor: 0.647

Journal of Energy in Southern Africa

Volume 33 Number 2
May 2022

A comparative analysis of the application of Fourth Industrial Revolution technologies in the energy sector: A case study of South Africa, Germany and China

N. Bhagwan[1,2*], **M. Evans**[1]

1. *Department of Geography, Faculty of Science, University of the Witwatersrand, Johannesburg, South Africa*

2. *Department of Education and Curriculum Studies, Faculty of Education, University of Johannesburg, Johannesburg, South Africa*

Abstract

Fourth Industrial Revolution (4IR) technologies have elevated the capabilities and possibilities of improvement and efficiency in the energy sector. This paper interrogates how energy companies in South Africa, Germany and China apply 4IR technologies. A total of 26 energy companies in those countries were surveyed. An analysis was carried out using the Cronbach Alpha, Kruskal-Wallis and Mann-Whitney tests. Survey results indicate that 85% of companies acknowledge good levels of participation in the 4IR, and were clear about which 4IR technologies are important, although few companies develop these themselves. Technologies enabling access to big, real-time data (BRTD) and BRTD analysis software, are valued the most in measured importance, efficiency, reliability and ability to be integrated across the energy system. The transfer of data using the Internet of things ranked highly as a 4IR technology, whereas artificial intelligence, robotics and machine-human integration (also referred to as machine-human interaction) are considered less important, efficient, and reliable. China rates 4IR technologies as more important than South Africa and Germany do. For South Africa to be competitive in the global energy sector it needs to engage with and embrace 4IR technologies to a greater extent.

Keywords: *4IR technologies; energy sector; Internet of things; big, real-time data; artificial intelligence; robotics; machine-human integration*

Highlights:

- *4IR technologies are applied within the energy sector.*
- *China rates 4IR technologies higher in importance than South Africa and Germany.*
- *The Internet of things is a highly ranked 4IR technology.*
- *South Africa needs to embrace 4IR technologies within the energy sector.*

Journal of Energy in Southern Africa 33(2): 1–14

DOI: https://dx.doi.org/10.17159/2413-3051/2022/v33i2a8362

Published by the University of Cape Town ISSN: 2413-3051 https://journals.assaf.org.za/jesa

Sponsored by the Department of Science and Innovation

Corresponding author: Email: nadyab@uj.ac.za

1. Introduction

The global technological landscape is flourishing, and the Fourth Industrial Revolution (4IR) is providing a pathway to this change (Ng et al, 2020; Pfeiffe, 2017). A 'hyper-connected' world enabled by 5G and complex digital interfaces are connecting electricity grids with multiple digital devices and systems (Shapsough et al., 2020; ESI Africa, 2018; Chen et al., 2016) and improving their resilience. Figure 1 illustrates the advanced 4IR technologies leading innovation in the production and distribution of renewable energy. New build for energy production plants is more efficient and cost- effective, and 4IR technologies have created conditions under which these plants may be man- aged and maintained remotely, in real time, using devices such as unmanned aerial vehicles (UAVs), remotely operated underwater vehicles (ROUVs), autonomous underwater vehicles (AUVs), and drones to collect live data on environmental conditions. The ability to access and analyse big, real-time data (BRTD), which according to Sigwadi (2020) may be presented as data science, is applied in energy plant operations.

There has been a move towards expanding smart energy (Knieps, 2017). Smart devices, sensors and microgrids, connected to multiple mobile and other technical devices, enable consumers and producers to interact in real time to better manage their demand and supply of electricity, improving resource efficiency and sustainability (Ng et al., 2020; United States Department of Energy, 2015). A 'bi-directional flow of power' has emerged with consumers accessing electricity from the grid and supplying electricity to the grid (Lund et al., 2017).

Artificial intelligence (AI) presents a huge opportunity for developing smart solutions for energy production and distribution. Dong et al (2021: 2) define AI as 'the science of simulating a series of human intelligent behaviors, such as autonomous learning, decision making, and judgments. AI is incorporated into the design, production and distribution of wind, solar, geothermal, hydro, ocean, bio, hydrogen, and hybrid energy (Jha et al, 2017). Voyant et al (2017) speak of machine learning (or AI) techniques that may be used to better forecast solar radiation, which allows solar plants to optimise productivity. Yunfeng and Mingming (2019) and Liao et al., (2019) explain how AI (or virtual reality) is being used to reproduce various operational environments in the power system for power grid simulation teaching and training, safety and rescue training, and virtual maintenance testing of power system equipment, as well as addressing training-related challenges such as lack of personnel and the need for expensive testing equipment. Machines are being developed to carry out what Makala and Bakovic (2020, 2) refer to as 'deep learning' to 'help discern patterns and anomalies across very large datasets – both on the power demand and power supply sides – that otherwise would be nearly impossible to achieve.'

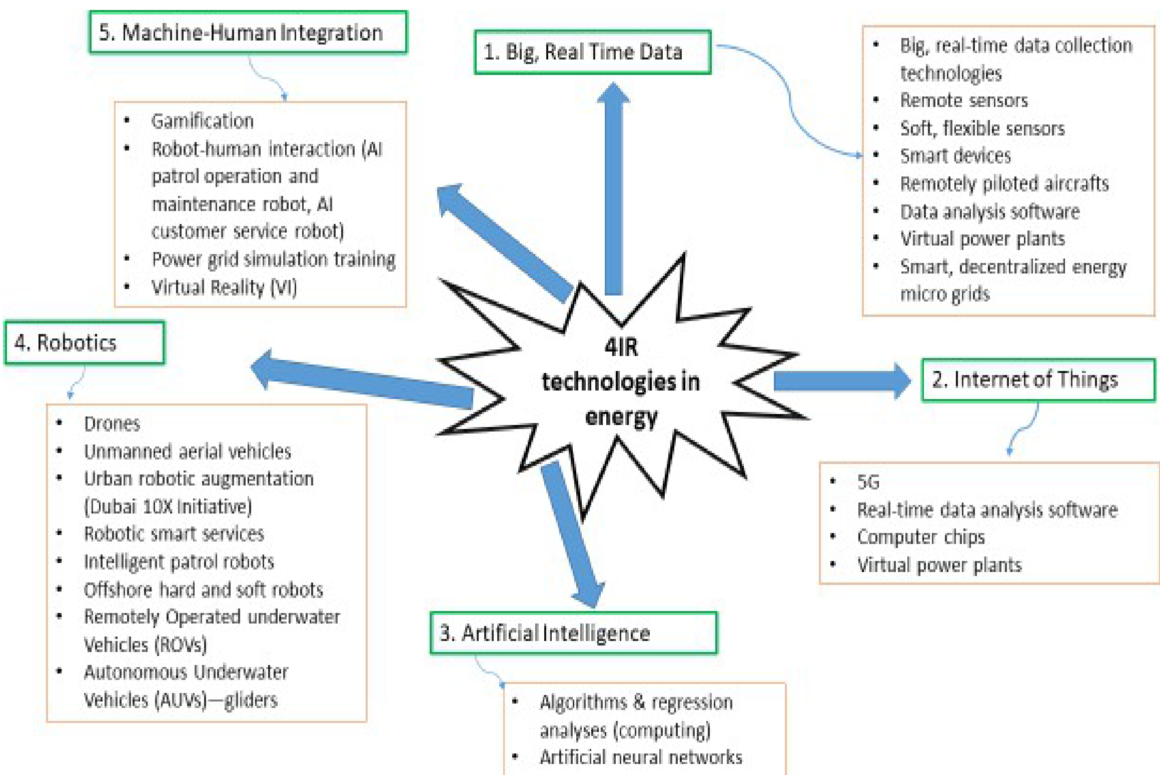

Figure 1: 4IR technologies in the energy sector

Robotics, according to Lyu and Liu (2021: 2) 'is at the intersection of computer science and engineering, involving design, construction, oper-ation, and use of robots, increasingly adopted in the energy sector to reduce set-up time and cost and improve quality and productivity'. Intelligent patrol robots are used to patrol outdoor power substations remotely, detecting defects in equipment and machinery in real time (Yunfeng and Mingming, 2019).

Machine-human integration (MHI), referred to by Yunfeng and Mingming (2019) as machine-human interaction, has developed from simple switches that used analogue systems to using computer systems to collect and analyse data at power terminals to dispatch this power within the grid, and to the use of voice to promote knowledge learning and transmission of data. Today, fifth generation MHI technology facilitates the friendly interaction between users and various systems with information tasks being exchanged between humans and various systems, such as computers and mechanical systems (Yunfeng and Mingming, 2019). Here, multi-sensor fusion technology is used as the interface for more intelligent interaction between staff and robots, initiated by robots themselves. The fifth generation of MHI, although still in the early stages of implementation, includes robot-human interaction, such as the AI power supply service robot, to integrate the 'basic abilities of speech recognition, dialogue management, real-time communication, image recognition, process automation and professional knowledge aggregation to 'understand customer demands, understand grid indicators, control power system business processes, issue command orders, transfer service information and remind abnormal behaviour' (Liu et al., 2018 and Yin et al., 2015, as cited by Yunfeng and Mingming, 2019: 3). MHI in energy may also be applied to gamification. Here, energy users interact with the energy system, through games such as Energy battle, that encourage households to take cogniscence of their behaviour towards energy consumption and in turn change such behaviour to reduce their energy usage and associated costs as well as their carbon footprint (AlSkaif et al., 2018).

Germany, China, Australia, the Netherlands and Japan have implemented systemic changes, choosing to decentralise energy, using computer chips installed in individual households allowing these households to control their energy grid and distribution via the internet (Burger et al., 2020; Viétor et al., 2015; Kafle et al., 2016). Nigeria is researching how to integrate AI into the regression analyses of solar energy estimation studies and to apply artificial neural networks to develop time-series data (Ozoegwu, 2018). India has identified the use of remotely piloted aircraft-based infrared imaging for monitoring and analysing photovoltaic energy systems in less accessible locations (Rahaman et al., 2020). The German Energiewende policy is driving the expansion of renewable and decentralised energy systems (Kuittinen and Velte, 2018; German Federal Ministry of Economic Affairs and Energy, 2019). The co-ownership of German energy production facilities, enabled by a decentralised energy sector and rising demand-side management of energy resources by consumers, has promoted the development and use of renewable energy (Roth et al, 2018). China continues to drive Renewable Energy Technologies particularly in industrial regions, such as Jiangsu Province, facing bigger climate change challenges (Lin and Zhu, 2019). Through nationwide policy initiatives such as the Made in China 2025 strategy, the Chinese government is driving Renewable Energy Technologies through investments in 'smart manufacturing' (Wübbeke et al, 2016, 15). China is using virtual power plants that combine gas turbines, renewable energy units and flexible loads using advanced technologies and software (Liu et al, 2018).

Globally, there has been a shift towards using new technologies across most sectors. The energy sector is no different. Fourth Industrial Revolution technology in South Africa likewise offers opportunities for improving the production and distribution of renewables, whilst at the same time enabling the achievement of the United Nations Sustainable Development Goal 7 – referring to expanding access to 'modern' and 'sustainable' forms of energy (United Nations, 2020). The focus of research in energy over the past decade has predominantly been on expanding the capacity of the South African electricity public utility, Eskom, and not private sector partnerships. The result has been increased power failures and load-shedding (Joffe, 2012). The United States Energy Information Administration (cited by Urban, 2018) has calculated the economic loss of income in South Africa due to the energy crisis to be between USD 253 and USD 282 million. A centralised and highly monopolised energy industry, driven by Eskom, has concentrated risks and challenges incurred relating to energy production and distribution, especially for renewables. South Africa, as an industrial powerhouse in Africa, depends on energy efficiency for economic development and on making energy more sustainable in terms of being efficient, more reliable and integrated across the system with minimal detriment to the natural environment. What is not known is the extent to which the energy sector in the country has leveraged these 4IR technologies and whether technologies applied are improving levels of efficiency, reliability and sustainability in the South African context.

In South Africa, industry leaders have studied the wider impacts of the 4IR on employment and society at large (O'Reilly et al, 2018; Aspen Institute, 2019). Central to this research was achieving a clearer understanding of whether countries are ready for the 4IR and what its socio-economic impact will be on society as we know it (Deloitte Insights, 2018; World Economic Forum, 2017). In addition to the effects of 4IR on the production and distribution of goods, research includes how curricula, as well as teaching and learning, need to change to incorporate the skills and knowledge needs of industry within the 4IR (Penprase, 2018; Stewart and Stanford, 2017; Chinese University of Hong Kong, 2020). To reiterate, this review does not focus on the education sector but on manufacturing in the energy industry. In addition to academic research, there have also been a number of studies conducted by institutions, such as the World Bank (2019), on how to harness the digital revolution to eradicate poverty in Africa. The argument presented is that digital technologies 'offer a chance to unlock new pathways for rapid economic growth, innovation, job creation, and access to services in Africa' (World Bank, 2019, 81).

A Scopus search for the years 2019-2021 yielded interesting results. A search on '4IR+ South+ Africa' brought up a total of 58 publications, but none referred to 4IR and the energy sector. A search on '4IR+technologies+South+Africa' presented 33 publications. These referred to the impact of 4IR on certain sectors including education (Pretorius and Kotze, 2021) and the future of the workplace (Scopus, 2021); O'Reilly et al, 2018; Aspen Institute, 2019). A refined search on '4IR+energy+South+ Africa yielded zero results. By searching for 'renewable+energy+technology', a total of 220 publications, from the past three years, were displayed. At a quick glance, these publications are centred on developments in particular types of renewable energy such as tidal (Sewnarain et al., 2020), solar (Obiora et al., 2020) and wind (Neshat et al., 2021); the creation of hybrid energy systems; access to energy (Monyei and Akpeji, 2020); decentralisation of the energy system in the country and using individual technologies such as solarvoltaics in specific sectors such as agriculture (Obiora et al., 2020). This Scopus search, then, suggests that there is little research on using a range of 4IR technologies across the energy sector in South Africa.

As the global energy sector steers its way through 4IR, it is critical to examine how renewable energy companies apply 4IR technologies. Research behind this paper examined this relationship by exploring the applicability of 4IR technologies in the energy sector in Germany, China and South Africa. It investigated what renewable energy companies understand by 4IR, and the contribution that the application of such technologies makes towards their companies becoming more efficient, reliable, and integrated.

2. Methodology

A quantitative research design was applied, surveying 26 German, Chinese and South African energy companies, online. The analysis was carried out through the Statistical Package for the Social Sciences, using the Cronbach Alpha test, frequencies and descriptives, and the Kruskal-Wallis test. The data collected was all validated. It was Cronbach Alpha tested for internal consistency – in other words, whether the variables (different 4IR technologies) are all measuring the same underlying construct identified in each question, these being, the importance of these technologies to the global economic sector (GES), the importance of using 4IR technologies within individual companies, and the levels of efficiency, reliablility and integration of 4IR technologies within companies. An ordinal, Likert scale was used to test respondents' perceptions of the different sections – with 1 being the most important and 7 the least important. A descriptive statistical analysis was the first step in the data analysis process. The nature of the variables used in the survey was explored through an assessment of the response frequencies, percentages and means. This provided details on how respondents perceived different 4IR technologies and what the average, overall view was concerning these technologies. A clear set of descriptors of 4IR technology was used. The 4IR descriptors were: the interactions between human and machines (MHI) to improve productivity in industry; creating technology to connect globally; developing and using AI in industry; developing other, new technologies to improve efficiencies; all of these; and none of these. Respondents ticked the appropriate descriptor box based on the one which was best aligned with their understanding of 4IR. The Kruskal-Wallis test was used to test for country-specific similarities and differences in the measured importance of using 4IR technologies within the GES and companies themselves. The test was based on the country in which each company was located.

2.1 Sampling techniques

Using purposive sampling, of the 26 companies surveyed and compared, nine were Chinese (five of them based in South Africa and the other four in China), eight German (all based in Germany), and the remaining nine South African, situated across the country. The German and Chinese companies were selected based on their leading role in using 4IR technologies and their prioritisation of expanding digital renewable energy solutions in their countries. South Africa was chosen because of the gap in the literature on whether and how 4IR technologies are being applied across the energy sector and the impact of these technologies on enhancing efficiency in the energy system.

Germany has been a 'highly industrialised, pioneer of Industry 4.0' (Beier et al., 2017, 227). Industry 4.0 has affirmed its commitment, at all levels of society, business, unions and government, toward promoting digitisation as a socio-economic growth discourse that is driven nationally. Its strong participatory and cooperative links with business, civil society and unions, a defining feature of the German industrial model, make it very different from most other leading and emerging economies such as the United States and China (Schroeder, 2016). Germany was selected as a research subject for several reasons. There are ideological, policy-based, similarities between the participatory nature of Industry 4.0 and the social compact envisaged for South Africa in its National Development Plan (Presidency of South Africa, 2012); historical ties exist (South African-German Energy Partnership Secretariat, 2018); and interest has grown in the way the German energy sector is constituted – highly decentralised, driven by local municipalities, displaying a mix of private and public sustainable energy provision (Viétor et al., 2015; Beerman and Tews, 2017; Burger et al., 2020; South African Local Government Association, 2018; all priorities highlighted in the 2019 Integrated Resource Plan (South African Department of Mineral Resources and Energy, 2019). Local firms and leaders are driving renewable energy developments through 'regional spillovers' (Horbach et al., 2018: 404).

The selection of China in this study was also carefully considered. The Made in China 2025 strategy (Wübbeke et al, 2016) exemplifies China's remarkable strides in becoming a leader of the 4IR in sectors including new and renewable energy, with expanded efforts to develop 'intelligent manufacturing' (Institute for Security & Development Policy, 2018, 1). Already China is a leading, global manufacturer, exporter and installer of renewable, clean energy technologies, with plans to produce 80% of these technologies in China by 2025 (Wübbeke et al, 2016). There are valuable lessons to be learnt from China. Bilateral relations between South Africa and China are expanding through developments such as coal-fired energy plants in the Waterberg (Limpopo Economic Development Agency, 2019). Such relations may provide future spill-overs for renewable energy relations.

2.2 Data collection methods

The next part of the data collection process was the online sourcing of company names, again using the Google search engine to find company websites. Environmental conditions brought about by the COVID-19 global pandemic meant that the most efficient way to compile a list of companies and their details was via the internet, telephone calls to these companies, and word of mouth referrals. There were challenges experienced in communicating with the companies in Germany and China including communication challenges because of language differences. Access-related challenges emerged with these countries being identified as COVID-19 hotspots, resulting in an extensive economic shutdown. These circumstances all contributed to delays in the collection of survey data. As part of addressing these challenges, the offices of both the German and Chinese High Commissions in Johannesburg were contacted for assistance in providing the names of German and Chinese companies and for facilitating participation in the survey. Once translated into Chinese and German, the survey was sent to 56 energy companies, of which 26 responded.

3. Results and discussion

The findings are based on an overall positive submission rate of 47%, with 26 out of 55 companies responding positively to the survey. Again, the main reason for the sample size was the onset of the Covid-19 pandemic and the resultant poor response rate. Despite the smaller sample size, the data was considered reliable and statistically significant findings did emerge.

The reliability of the data was tested using the Cronbach alpha coefficient for each construct (Table 1), of which all are above the recommended value of 0.7 (Pallant, 2007), indicating the reliability of the data constructs.

Table 1: Cronbach's alpha values of the data constructs (importance, efficiency, reliability, and integration).

Constructs	*Cronbach's alpha coefficient*
The importance of 4IR technologies to the GES	0.73
The importance of using 4IR technologies for companies	0.80
The efficiency of 4IR technologies within companies	0.70
The reliability of 4IR technologies within companies	0.78
The integration of 4IR technologies within companies	0.80

3.1 Descriptive statistical analysis

Almost 65% of all respondents described the 4IR to be a combination of the above survey descriptors (all of these). No respondent ticked 'none,' implying the legitimacy of descriptors. Participants were then asked to indicate the level of importance of 4IR technologies, collectively, for the GES. The data was coded using a tick-box rating. Respondent percentages were used to break down the levels of importance of 4IR technologies in the GES (Figure 2). The degrees of importance varied, yet all respondents agreed that 4IR technologies were important. 73% ticked very important, 23% ticked important and only 4% selected somewhat important. There were no respondents who believed that 4IR technologies were not important, indicating the high value placed on the importance of technology in the GES.

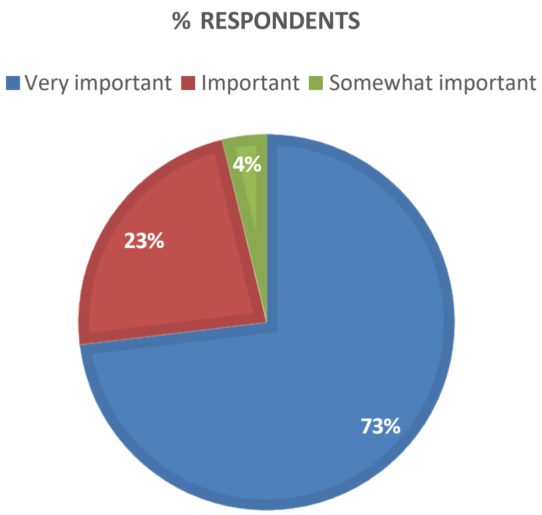

Figure 2: The importance of Fourth Industrial Revolution technologies to the global energy sector.

Technology categories were broken down into seven variables (Table 3). Three of the seven variables were tied to data access and usage. The remaining four comprised AI, ROB, MHI and the IoT. Participants were requested to rank each technology variable on a Likert scale of 1-7, with 1 being the most and 7 the least important to the GES. The results showed that, instead of ranking technologies, respondents chose to rate each one. As such, the analysis of the ranking questions drew on calculated means and standard deviations. In Table 2, mean ranks all fell below 4, implying that, using the 1–7 ranking scale, all described technologies were considered important to the GES. RTD was ranked as most important to the GES. The survey results pointed to fundamental influencers of this result as being the development of drones and UAVs, rapid advancements of faster and more reliable mobile networks, and the creation of huge data storage facilities in the cloud. The importance of ROB and MHI was considered far less important, with means of 3.96 and 3.65, respectively. Further research needs to establish why this may be the case.

There were two, key high-level conclusions linked to the global energy sector. The first was consistency in how respondents interpreted 4IR, with all describing it as one or a combination of interactions between machines and humans to improve productivity in industry; creating technology to connect globally; developing and using AI in the industry; developing other, new technologies to improve efficiencies. The global importance of 4IR technologies was clearly articulated. Secondly, leading in importance were the technologies providing access to real-time data (RTD), possibly influenced by the expansive use of drones, AUVs and ROVs in the sector. ROB and MHI fared the least in their importance to the GES. Interviews with experts in the sector will be important for determining why this may be the case.

The survey then referred to individual companies and their involvement with 4IR technologies. Respondents rated their company's involvement in the 4IR, in totality (Figure 3). Interestingly, most companies (85%) were confident about such participation, suggesting that the majority felt connected to the 4IR. 8% were unsure, whilst 8% believed that they were not participating at all in 4IR. If 85% of companies felt that they were a part of the 4IR, what were the reasons provided for the remaining companies that considered themselves to not be part of the 4IR? Data collected showed that the reasons were not that these companies had not heard of 4IR technologies but, rather, that the technologies were too expensive.

Table 2: Ranking the importance of each Fourth Industrial Revolution technology in the global energy sector

Importance to the GES of:	*Big data*	*Real-time data*	*Big real-time data analysis*	*Artificial intelligence*	*Robotics*	*Machine-human integration*	*Internet of things*
Mean rank	2.50	2.00	2.12	2.81	3.96	3.65	2.42
Std deviation	1.273	1.575	1.306	1.575	2.236	1.896	1.501

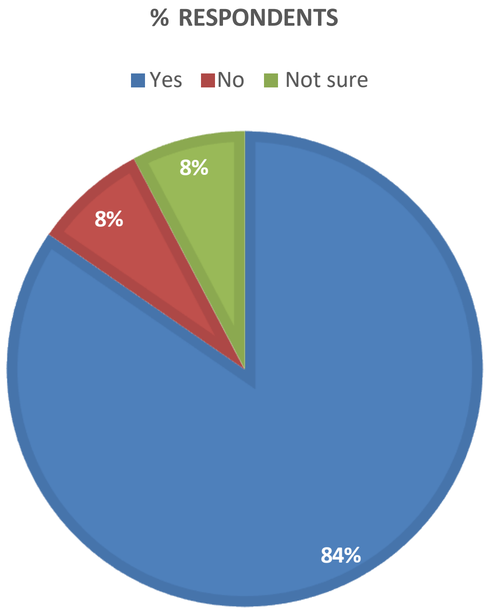

Figure 3: Company participation in the Fourth Industrial Revolution.

Once the respondents had rated their company's involvement in 4IR, they went on to describe their company's usage of these technologies. Descriptors ranged from no use of 4IR technologies, partial use, good use, very good use, and pioneer or leader of 4IR technologies development. Half (50%) of the respondents described their company usage as 'very good' or 'good,' whilst a third were more modest, with a rating of 'fair or partial.' Only one company believed they were a 'pioneer' or 'leader' in the development of 4IR technologies, despite their country of origin. The pioneer identified was a South African energy company.

Respondents were asked to name specific 4IR technologies they used. Some referred to distinct names. Others were non-specific, broadly categorising the technologies into whether they could best be described as tools enabling the collection of BRTD, the analysis of BRTD, the IoT, AI, ROB and MHI. All responses, specific and non-specific, were then clustered according to these category descriptives. Specific technologies referred to included: remote-controlled drones, uncrewed aerial vehicle (UAV) inspection technology, smart thermal and infrared sensors, microcontrollers (MCUs), digital signal controllers (DSCs) and advanced computer chip technology. Drones for thermal capturing use special, thermal and infrared sensors to capture invisible temperature and other climate data. UAVs also use drones equipped with infrared and thermal sensors to inspect energy infrastructure and capture various geographical information. The latter comprises relief data of land and climatic conditions such as temperature, wind speed, rainfall, etc. The data are then used to create 3D models and maps that provide important information for new, energy production site planning and current site management. It is accepted that technologies such as UAVs and robots are not new, but the way in which they are being used is different and they offer a greater range of capabilities than general purpose technologies. UAVs and robots have been repurposed to collect large amounts of RTD that are transferred rapidly using 5G networks, to mobile devices and sophisticated computers that use complex algorithms to analyse the data in ways that are more accurate and therefore reliable.

The IoT is about connecting and integrating multiple smart devices and users across the globe through the internet. Examples of IoT identified by the survey respondents were 5th generation mobile networking technology (5G) to transfer bigger quantities of data to a range of smart, digital devices (mobile phones, smart meters, smart grids, virtual power plants and smart, remote environmental sensors). It must be noted that access to 5G is still limited, particularly in rural areas of South Africa, and this presents an imbalance in terms of who benefits from 4IR technologies such as the IoT (facilitated by 5G). That said, Jordaan et al. (2019: 12) indicate that, although 5G 'applications pose a series of challenges including practical implementation, cost of implementation, and stakeholder and citizen commitment among others, the benefits that smart cities offer for the South African context, like smart resource management, energy efficiency, long term cost saving, improved services, etc. will definitely out-weigh the challenges.'

Devices such as smart meters transmit data between consumers and suppliers in real time. Consumers themselves can measure their consumption of energy in real time. Energy suppliers can also use smart meters to monitor energy consumption patterns, adjust supply accordingly and subsequently draw an energy billing system that is more accurate and efficient. Smart sensors that are connected through the IoT are used to collect operational data relating to a particular energy plant to monitor operations and where necessary carry out maintenance remotely.

BRTD analysis incorporates implementing intelligent information control and management systems, including grid management systems, remote monitoring and control systems, building information management systems, supervisory control and data acquisition systems, intelligent monitoring and controlling photovoltaic systems, and other advanced software tools to analyse large quantities of data as it comes in live time. Such tools are used for managing and supervising process operations remotely and in real time. Detailed images of energy site infrastructure are assessed when addressing maintenance-related matters for the plant.

AI is associated with respondent references to using smart machines (that enable clean energy solutions), algorithms and algorithmic trading systems (where computers conduct complicated, online, electricity trading activities, at much faster speeds, based on live energy market data and without human intervention) and, of course, virtual power plants. Virtual power plants are used to relieve the electricity load on the grid by enabling the distribution of excess power generated during off-peak load times to individuals during periods of high demand. Excess electricity may then be traded, algorithmically, on the energy exchange system. Five of the 22 referenced technologies referred to the use of AI, one to algorithmic trading and two to running plants virtually.

ROB is referred to twice without listing any technology names. South African firms surveyed are not using ROB in their operations. The two firms that are using ROB are from China and Germany. MHI-augmented reality using MHI that combines machine and human intelligence, was only mentioned by one respondent. Again, no technology names were provided. Like ROB, technologies enabling MHI are used even less.

A glance at the number of times certain technologies and technology groupings were named suggest a clear disparity between using technologies presented in categories one to four, focusing on accessing, storing, transferring and analysing BRTD and the technologies that drew on AI, ROB and MHI. Most of companies use 4IR technologies to collect and access plant data remotely, using drones and the IoT, and then analyse them using various data management systems. MHI appeared as an uncharted territory in energy, with one German company reporting to be using it. Further investigation is needed. ROB are also minimally applied in China and Germany. None of the South African firms are using ROB in the production and distribution of energy. The 4IR technologies recognised by South African firms all related to the collection, access and analysis of big, real-time data. Algorithmic trading stands out as underutilised, and the development of virtual power plants poor, with only two German companies adopting this.

According to respondents, most of these used technologies originated in the United States, Europe (predominantly Germany) and China. Yet, the German and Chinese companies interviewed indicated that they were not involved in the production and development of these technologies. So, a question that remains is why this may be the case, and which types of companies are producing these technologies in Germany and China (for example, is this a function of company size?).

Table 3 shows how respondents rated the level of company usage for each category of non-specific technology, from 1 being the most and 7 the least used. Calculated frequencies show that half of all respondents felt that using technology facilitating access to BD was of high importance. And those enabling access to real-time, live data was valued even more – in fact, the most. Rating levels 1 and 2 taken together, for the same technologies, equated to 78% of total respondents. The IoT, as the enabler of data access, also showed high levels of importance with 62% of participants scoring this 1 or 2. The inverse is true for AI, MHI and ROB. ROB was viewed by firms as being the least important to use.

Calculated means in Table 4 display the ranking for each variable. Access to BRTD, with a lower mean of 2.50, is ranked the highest in terms of the importance of using these technologies in the surveyed companies. The use of ROB, with the highest mean of 4.73, is ranked the lowest for its importance in the companies, followed by using of MHI (mean = 4.50) and AI (mean = 3.69). This mirrors the global scenario described previously in the paper.

Table 3: Respondent ratings of the level of usage for each criterion (non-specific technology) in their company.

Variables	*Most important*	*2*	*3*	*4*	*5*	*6*	*Least important*
BD (%)	19.2	30.8	7.7	15.4	11.5	7.7	7.7
RTD (%)	38.5	38.5	0.0	3.8	7.7	0.0	11.5
BRTD analysis (%)	19.2	26.9	23.1	19.2	7.7	0.0	3.8
AI (%)	3.8	34.6	19.2	3.8	19.2	7.7	11.5
ROB (%)	15.4	3.8	15.4	7.7	3.8	23.1	30.8
MHI (%)	0.0	23.1	15.4	7.7	7.7	34.6	11.5
IOT (%)	23.1	38.5	15.4	0.0	3.8	7.7	11.5

Table 4: Importance of companies using Fourth Industrial Revolution technologies.

Using:	*Big data*	*Real-time data*	*Big real-time data analysis*	*Artificial intelligence*	*Robotics*	*Machine-human integration*	*Internet of things*
Mean	3.23	2.50	2.85	3.69	4.73	4.50	2.92
Std. deviation	1.92	2.00	1.49	1.87	2.25	1.86	2.04

Table 5: Ranking the efficiency levels of company 4IR technologies.

Efficiency of:	*Big real-time data*	*Big real-time data analysis*	*Artificial intelligence*	*Machine-human integration*	*Internet of things*
Mean	1.73	1.54	2.16	2.20	1.80
Std. deviation	0.667	0.582	0.624	0.645	0.577

Table 6: Respondent ratings of the level of reliability for each criterion (non-specific technology) in their company.

Reliability of:	*Big real-time data*	*Big real-time data analysis*	*Artificial intelligence*	*Machine-human integration*	*Internet of things*
Mean	1.65	1.42	2.16	2.16	1.88
Std. deviation	0.63	0.50	0.80	0.75	0.67

Table 7: Respondent ratings of the level of integration for each criterion (non-specific technology) in their company.

Integrating:	*Big real-time data*	*Big real-time data analysis*	*Artificial intelligence*	*Machine-human integration*	*Internet of things*
Mean	1.96	1.84	2.33	2.33	2.08
Std. deviation	0.45	0.47	0.64	0.56	0.58

After ranking the importance of using different 4IR technologies in their companies. respondents had to consider how efficient they believed the technologies to be (Table 5). Technologies that enabled the analysis of real-time data collected by companies were seen to be the most efficient (mean = 1.54) as this is about how firms can use live data. This can only happen if firms have the tools to collect BRTD (with data access awarded a mean of 1.73) and the IoT that connects both processes together (mean = 1.80).

The technology variables were ranked according to their reliability (Table 6). The rankings were simi-lar to those representing efficiency. Technologies used for analysing real time data were again considered the best in terms of being reliable (mean = 1.42).

The level of integration of each variable within the sampled companies is ranked in Table 7. The integration of data analysis technologies outranks other technologies, with a mean of 1.84. Levels of integration of technologies used for accessing data and connecting multiple devices through the internet (IoT) are ranked second and third. The least integrated of all technologies identified were those using AI and the combining of machine-human intelligence (mean = 2.33).

The importance of using 4IR technologies within energy companies and their contribution to efficiency, reliability and integration were all similarly ranked and clear patterns emerged. Technologies enabling access to BRTD and the processing and analysis of such data were valued the most with respect to all contributing to perceived importance, levels of efficiency, reliability, and ability to be integrated across the energy system. Of course, any analysis of such data will first and foremost require the IoT to store data and enable its transmission to multiple mobile and other devices in real-time. As such, the importance of this IoT was ranked third. ROB was recognised as least important for use by companies. AI and MHI were seen to be profoundly less reliable, efficient and integrated within the surveyed firms. For the GES, the importance of these technologies was the most poorly ranked.

3.2 Country analysis

China rated the importance of 4IR technologies to the GES as being higher than South Africa and Germany, with a mean of 2.6 (Table 8). South Africa and Germany had similar mean values for this construct. China also rated the importance of using 4IR technologies in their companies higher than both Germany and South Africa. The means for Germany and South Africa were, again, much higher (3.9 and 4.4), indicating that they ranked these technologies as less important within their companies. Variances in the mean for the other 4IR technologies variables were minimal, indicating minimal country-level differences.

The Kruskal-Wallis and Mann-Whitney tests were used to assess country-specific differences in the survey data collected. As shown in Table 9, the data analysis calculated a statistically significant difference in the respondents' perceptions for two constructs. The first was in response to their perceived importance of 4IR technologies to the global energy sector. The p-value of 0.002 for this construct was lower than the recognised p-value of 0.05 required for statistical significance.

Secondly, there was a statistically significant difference in the responses of China, Germany and South Africa towards the perceived importance of using 4IR technologies within companies, with p-value = 0.005. Variables measuring efficiency, reliability and integration between countries were not statistically significant as each of the p-values were larger than 0.05 and so are excluded from the analysis (Table 9).

The Mann-Whitney test was used for post-hoc testing. This test was used to identify in which pair

Table 8: Kruskal-Wallis Test.

		N	*Mean*	*Std. deviation*
Importance to GES	China	9	1.8	0.5
	Germany	9	3.1	0.9
	South Africa	8	3.4	0.8
	Total	26	2.8	1.0
Use	China	9	2.6	1.4
	Germany	9	3.9	0.9
	South Africa	8	4.4	1.0
	Total	26	3.6	1.3
Efficiency	China	9	1.8	0.3
	Germany	9	1.9	0.4
	South Africa	8	1.9	0.5
	Total	26	1.9	0.4
Reliability	China	9	1.8	0.6
	Germany	9	1.9	0.3
	South Africa	8	1.9	0.5
	Total	26	1.8	0.5
Integration	China	8	2.1	0.3
	Germany	9	2.2	0.3
	South Africa	8	2.1	0.6
	Total	25	2.1	0.4

Table 9: Statistical significance of country differences.

Mean descriptives	*Importance to GES*	*Use*	*Efficiency*	*Reliability*	*Integration*
Kruskal-Wallis H	12.13	10.71	0.08	0.03	0.39
Asymp. sig. (p-value)	0.002	0.005	0.960	0.986	0.823

Table 10: Mann-Whitney Test Statistics (China and Germany).

	Importance to GES	*Use*
Mann-Whitney U	11.50	11.50
Asymp. sig. (2-tailed) (p-value)	0.01	0.01

Table 11: Mann-Whitney Test Statistics (China and South Africa).

	Importance to GES	*Use*
Mann-Whitney U	3.00	7.50
Asymp. sig. (2-tailed) (p-value)	0.00	0.01

Table 12: Mann-Whitney Test Statistics (South Africa and Germany).

	Importance to GES	*Use*
Mann-Whitney U	29.50	21.50
Asymp. sig. (2-tailed) (p-value)	0.50	0.16

of countries the above differences lay. The p-values indicated in Tables 11 and 12 are lower than 0.05 for both the China/Germany pair (0.01) and the China-South Africa pair (0.00) for both descriptor constructs. There are significant differences between China on the one end and Germany and South Africa on the other (with a p-value of 0.50 in Table 12). In both cases, China has amplified the importance of 4IR technologies in energy globally and at the company level. The results of the Mann- Whitney test also point to significant differences between China, on the one end, and Germany and South Africa (Table 12) on the other. In both cases, China has amplified the importance of 4IR technologies in energy globally and within their companies. What remains uncertain, again, is why this is the case.

Variances in the variables measuring the efficiency, reliability and integration of 4IR technologies were minimal and of no statistical significance and therefore excluded.

In summary, and despite China placing a higher value on the importance of 4IR technologies within Chinese energy firms, there was still a complete recognition of the importance of 4IR technologies by all of the surveyed companies. In fact, 85% of these companies believed themselves to be a part of the 4IR, although in the context of users and not pioneers of these technologies. When ranked according to how important it is to access and use 4IR technologies in energy, particularly for adding to the reliability, sustianability, and interconnectedness of the sector, access to BRTD dominated.

4. Limitations of the study

A key limitation impacting the study was the challenges experienced during the data collection stage. All data were collected during 2020, when the effects of the Covid-19 pandemic in China, Germany and South Africa peaked. Economic lockdowns further reduced the number of responses received, resulting in a smaller than expected sample size. Despite this, the surveys were conducted online and the data findings and analysis concluded are considered statistically reliable. The second occurrence worth considering was that respondents rated variables in some survey questions, rather than ranking them. This did not present a significant limitation and was compensated for by using other forms of ranking techniques: in this case, mean and standard deviation calculations.

5. Conclusions

Despite the smaller than ideal size of the sample surveyed, clear conclusions emerged from this resarch. There was a shared understanding of the meaning of the 4IR and its relationship with the energy sector. Whether viewed separately or together, these meanings included the interactions between human and machines to improve productivity in industry; creating technology to connect globally; developing and using AI in industry; and developing other, new technologies to improve efficiencies. Most energy companies (85%) believed themselves to be playing a recognisable role in the 4IR, although only one (a South African company) described itself as a leader in 4IR technologies development. Additional research should investigate which countries, and which companies are involved in pioneering developments in 4IR energy technologies. Next, the analysis delivered conclusions about the measured importance of using these technologies, as well as the extent to which they are reliable, efficient, and integrated within the energy companies. Surveyed firms identified technologies providing access to and analysis of BRTD as being most important for usage in the wider, global energy sector as well as at local, company level. Energy production and distribution technologies of least importance were MHI technologies, followed by ROB. For levels of efficiency, reliability, and ability to be integrated across the energy system, technologies enabling access to BRTD and the processing and analysis of such data were, again, valued the most. The IoT was ranked the third most important 4IR technology as it enables the storage and transmission of data to multiple devices in real- time. AI and MHI were seen to be much less reliable, efficient and integrated within the surveyed firms.

These conclusions suggest the need for further research on why there are these clear distinctions between the importance and usefulness (in terms of efficiency, reliability and intergratedness) of 4IR technologies linked to BRTD access and data analysis, and that associated with AI, ROB and MHI. Furthermore, it remains to be investigated why Chinese companies place more value on the importance of 4IR technologies in energy, than those of Germany and South Africa.

We recommend that for South Africa to be competitive in the global energy sector it needs to engage with and embrace 4IR technologies to a greater extent. Before this point can be reached, however, there needs to be an understanding as to whether 4IR technologies are being applied in the South African energy sector and, if this is the case, how they are being applied. Research reflected in this paper has shown that South African companies value 4IR technologies as tools to facilitate and improve efficiency, reliability and integration within the energy production and distribution systems, and that a higher value is placed on access to and analysis of BRTD and the IoT. Other 4IR technologies are, however, according to the survey results, not being applied in the South African energy sector. This is despite the fact that literature has also shown that there is huge potential for AI, ROB and MHI to advance the energy sector and that there is much to

learn from countries such as China and Germany, who are already using these technologies. Data collected showed that the reasons were not that these companies had not heard of 4IR technologies but, rather, that the technologies were either too expensive or linked to other conditions, or for reasons not given. These other reasons will be explored during the interview stage of this study. Moreover, although expansion in 5G technology and the IoT does imply huge upfront and implementation costs (particularly in rural areas where infrastructure is lacking), the opportunities that smart cities provide – improved efficiency, better resource management, improved service provision and long- term cost saving (Jordaan et al., 2019) – are hugely appealing and must be explored. The focus of research in energy in South Africa over the past decade has predominantly been on expanding the capacity of Eskom. Research needs to expand into how 4IR technologies may be leveraged at different parts of the production and distribution systems to boost efficiency, reliability and integration.

Acknowledgements

The authors would like to thank the German and Chinese High Commisions in South Africa for their assistance in this project, as well as the respondents that participated anonymously in the survey. Thanks also go to the anonymous reviewers for their useful detailed and constructive comments. NB acknowledges the University of Johannesburg's Capacity Development Grant for funding support. Ethics approval was obtained from the University of the Witwatersrand Ethics Committee (non-medical). The ethics number is H19/07/06.

Author roles

N. Bhagwan was responsible for conceptualising the study, as part of her broader PhD study, collecting, analysing and writing up the data, and was the main author of the publication. M. Evans provided key conceptual and editorial inputs into the redrafting of the publication until its completion.

References

AlSkaif, T., Lampropoulos, I., van den Broek, M. & van Sark, W. 2018. Gamification-based framework for engagement of residential customers in energy applications. *Energy Research & Social Science,* 44, 187-195. Elsevier.

Aspen Institute 2019. *Future of Work Initiative State Policy Agenda*. Aspen Institute Future of Work Initiative. Washington, DC.

Beier, G., Niehoff, S., Ziems, T. & Xue, B. 2017. Sustainability aspects of a digitalized industry – A comparative study from china and germany. *International journal of precision engineering and manufacturing - green technology,* 4(2): 227-234.

Burger, C., Froggatt, A., Mitchell, C. and Weinmann, J 2020. *Decentralised energy – A global game changer*. Ubiquity Press. London.

Chen, C., Wang, J., Qiu, F. & Zhao, D. 2016. Resilient distribution system by microgrids formation after natural disasters. *IEEE transactions on smart grid,* 7(2): 958-966.

Chinese University of Hong Kong. 2020. *Annual report 2019-2020. Chinese university of Hong Kong.* Hong Kong.

Deloitte Insights 2018. *The Fourth Industrial Revolution is here-are you ready?* Deloitte Development LLC.

Department of Mineral Affairs and Energy. 2019. Integrated resource plan (IRP 2019) - October 2019. Pretoria.

Dong, F., Zhang, S., Zhu, J. & Sun, J. 2021. The impact of the integrated development of AI and energy industry on regional energy industry: A case of china. *International journal of environmental research and public health,* 18(17).

ESI Africa 2018. How to survive the 4th industrial revolution. ESI Africa: Africa's Power Journal. Issue (4). South Africa.

German Federal Ministry for Energy and Economic Affairs 2016, "Plattform Industrie 4.0" in *Industrie 4.0 im internationalen Kontext* VDE-Verlag GmbH: 134-137.

Horbach, J. & Rammer, C. 2018. Energy transition in germany and regional spill-overs: The diffusion of renewable energy in firms. *Energy policy,* 121404-414.

Institute for Security and Development Policy 2015. *Made in China 2025.* Institute for Security and Development Policy. Washington.

Jha, S.K., Bilalovic, J., Jha, A., Patel, N. & Zhang, H. 2017. Renewable energy: Present research and future scope of artificial intelligence. *Renewable & sustainable energy Reviews,* 77 297-317.

Jordaan, G., Malekian, N., Malekian, R. 2019. Internet of Things and 5G Solutions for development of Smart Cities and Connected Systems. *Communications of the CCISA,* 25(2).

Kafle, Y.R., Mahmud, K., Morsalin, S., Town, G. 2016. Towards an internet of energy. Conference Paper. September 2016. Powercon.

Knieps, G. 2017. Chapter 13 - Internet of Things and the Economics of Microgrids in *Innovation and Disruption at the Grid's Edge* Elsevier Inc: 241-258.

Kuhlmann, S., Stegmaier, P. & Konrad, K. 2019. The tentative governance of emerging science and technology—A conceptual introduction. *Research policy,* 48(5):1091-1097.

Kuittinen,H. & Velte,D. 2018. *Mission-oriented R&I policies: In-depth case studies Case Study Report Energiewende*.

Liao, X., Wang, H., Niu, J., Xiao, J. & Liu, C. 2019. Research on simulation training system of immersive substation based on virtual reality. *IOP conference series. Materials science and engineering,* 486(1):12112.

Limpopo Economic Development Agency. 2019. *Musina-Machado special economic zone development: Final Scoping Report.* Informa UK Limited.

Lin, B. & Zhu, J. 2019. Determinants of renewable energy technological innovation in china under CO.sub.2 emissions constraint. *Journal of environmental management,* 247662.

Liu, Y., Zheng, F., Guo, R., Wang, J., Nie, Q., Wang, X. & Wang, Z. 2018. Robot intelligence for real world applications. *Chinese journal of electronics,* 27(3): 446-458.

Liu, Z., Zheng, W., Qi, F., Wang, L., Zou, B., Wen, F. & Xue, Y. 2018. Optimal dispatch of a virtual power plant considering demand response and carbon trading. *Energies,* 11(6):1488.

Lund, H., Østergaard, P.A., Connolly, D. & Mathiesen, B.V. 2017. Smart energy and smart energy systems. *Energy (Oxford),* 137556-565.

Lyu, W. & Liu, J. 2021. Artificial intelligence and emerging digital technologies in the energy sector. *Applied energy,* 303117615.

Makala, B and Bakovic, T. 2020. *Artificial intelligence in the power sector.* International Finance Corporation.

Monyei, C.G. & Akpeji, K.O. 2020. Repurposing electricity access research for the global south: A tale of many disconnects. *Joule,* 4(2): 278-281.

Nel, A.J.H., Vosloo, J.C. & Mathews, M.J. 2018. Financial model for energy efficiency projects in the mining industry. *Energy (Oxford),* 163546-554.

Neshat, M., Nezhad, M.M., Abbasnejad, E., Mirjalili, S., Groppi, D., Heydari, A., Tjernberg, L.B., Astiaso Garcia, D., Alexander, B., Shi, Q. & Wagner, M. 2021. Wind turbine power output prediction using a new hybrid neuro-evolutionary method. *Energy,* 229.

Ng,T.C. & Ghobakhloo,M. 2020. *Energy sustainability and industry 4.0.* IOP Publishing.

O'Reilly, J, Ranft, F. and Neufeind, M. 2018. "Identifying the challenges for work in the digital age" in *Work in the digital age: challenges of the fourth industrial revolution* Rowman & Littlefield International. London.

Obiora, C.N., Ali,A. & Hasan, A.N. 2020. Estimation of Hourly Global Solar Radiation Using Deep Learning Algorithms. Conference Paper: 11th International Renewable Energy Congress (IREC).

Ozoegwu, C.G. 2018. The solar energy assessment methods for nigeria: The current status, the future directions and a neural time series method. *Renewable & sustainable energy reviews,* 92146-159.

Pallant, J. 2007. *SPSS Survival Manual: A Step by Step Guide to Data Analysis using SPSS for Windows* London:Open University Press.

Penprase, B.E. 2018. *The fourth industrial revolution and higher education.* In: Gleason, N.W. (eds). Higher Education in the Era of the Fourth Industrial Revolution. Springer. Singapore.

Pfeiffer, S. 2017. The vision of "Industrie 4.0" in the making—a case of future told, tamed, and traded. *NanoEthics,* 11(1): 107-121.

Presidency of South Africa. 2012. National Development Plan 2012. SA Presidency. Pretoria.

Pretorius,R. & Kotze,B.J. 2021. South African Universities Power Engineering Conference. Conference. IEEE. South Africa.

Rahaman, S.A., Urmee, T. & Parlevliet, D.A. 2020. PV system defects identification using remotely piloted aircraft (RPA) based infrared (IR) imaging: A review. *Solar energy,* 206 579-595.

Roth, L., Lowitzsch, J., Yildiz, Ö & Hashani, A. 2018. Does (co-)ownership in renewables matter for an electricity consumer's demand flexibility? empirical evidence from germany. *Energy research and social science,* 46: 169-182.

Schroeder, W. 2016. *Germanys Industrie 4.0 Strategy: Rhine Capitalism in the age of Digitalisation.* Friedrich Ebert Stiftung. London.

Sewnarain, S., Onunka, C., & Akindeji, K. 2020. Assessment of Tidal Energy as Alternative Energy. IEEE Xplore.

Shapsough, S., Takrouri, M., Dhaouadi, R. & Zualkernan, I. 2020. An IoT-based remote IV tracing system for analysis of city-wide solar power facilities. *Sustainable cities and society,* 57102041.

Sigwadi, L. 2020. *Data Science and the Fourth Industrial Revolution (4IR)* Cape Town: University of the Western Cape.

South African Local Government Association. 2018. *SALGA 2018 Energy Summit Discussion Documents: Defining the Energy Future of Local Government* Pretoria: SALGA. South Africa.

Stewart, A. & Stanford, J. 2017. Regulating work in the gig economy: What are the options? *The economic and labour relations review. ELRR,* 28(3): 420-437.

United Nations. 2020. Sustainable Development Report 2020. United Nations Publications. New York.

Urban, B. 2018. Effectuation and opportunity recognition in the renewable energy sector in south africa: A focus on environmental dynamism and hostility. *Journal of developmental entrepreneurship,* 23(2).

Viétor, B., Hoppe, T. & Clancy, J.S. 2015. Decentralised combined heat and power in the German Ruhr valley; assessment of factors blocking uptake and integration. *Energy, sustainability and society,* 5(1):1-16.

Voyant, C., Notton, G., Kalogirou, S., Nivet, M., Paoli, C., Motte, F. & Fouilloy, A. 2017. Machine learning methods for solar radiation forecasting: A review. *Renewable energy,* 105, 569-582.

World Bank. 2019. An analysis of issues shaping africa's economic future. *Africa's pulse. April 2019* (19). World Bank Group. Washington DC.

World Economic Forum. 2017. *The Future of Jobs and Skills in Africa Preparing the Region for the Fourth Industrial Revolution Executive Briefing*.

Wübbeke, J., Meissner, M., Zenglein, M.J. & Ives, J. 2016. *MADE IN CHINA 2025: The making of a high-tech superpower and consequences for industrial countries* China: MERICS.

Yin, E., Zeyl, T., Saab, R., Hu, D., Zhou, Z. & Chau, T. 2016. An auditory-tactile visual saccade-independent P300 Brain–Computer interface. *International journal of neural systems,* 26(1): 1650001.

Yunfeng, Z. & Mingming, P. 2019. Application and prospect of human-machine interaction in power system. *Journal of Physics. conference series,* 1345(3): 32094.

CHAPTER 4: THE CONTRIBUTION OF INDUSTRY 4.0 TECHNOLOGIES TO CHINESE, GERMAN, AND SOUTH AFRICAN ENERGY COMPANIES

4.1. Brief synopsis

Big, real-time data, Artificial Intelligence, the Internet of Things, Robotics, and Machine-Human Integration are Industry 4.0 technologies transforming global energy value chains. This study explores the use of Industry 4.0 technologies in the energy sectors of South Africa, China, and Germany through interviews with energy and technology companies and experts in the energy field. The aim is to determine the extent to which energy companies leverage these technologies and whether these contribute to efficiency in energy production. The Internet of Things and Artificial Intelligence amongst Chinese and German companies are at the forefront of energy production, lessening energy system inefficiencies and driving the transition to a more integrated energy sector. In Germany, using Artificial Intelligence, thousands of decentralised, renewable energy producers and consumers are pooled together into a flexible power system that produces a more stable power grid. China is using robots and Artificial Intelligence for intelligent mine applications and digitising the process of safety inspections, Chinese energy companies benefit from safer working conditions and improved worker satisfaction. Artificial Intelligence optimises plant production processes as a proactive energy solutions tool, reducing plant emissions and boosting efficiency. South African companies distinguish Industry 4.0 technologies as not new, but as improvements to existing technologies. These companies use big, real-time data and data analysis and Internet of Things platforms to flag operational and process-related concerns and perform pre-emptive maintenance, boosting plant efficiencies and increasing productivity. Constraints dominating the South African renewable energy sector that continue to slow down its digitalisation are high technology costs and insufficient political will.

Publication details: Bhagwan, N. and Evans, M. 2024. Understanding the contribution of Industry 4.0 technologies to Chinese, German, and South African energy companies and their energy sectors. Submitted to Renewable and Sustainable Energy Reviews. (Under review)

Journal impact factor: 16.799

THE CONTRIBUTION OF INDUSTRY 4.0 TECHNOLOGIES TO CHINESE, GERMAN, AND SOUTH AFRICAN ENERGY COMPANIES

Bhagwan, N[1*]

The University of the Witwatersrand, School of Geography, Archaeology and Environmental Studies, Faculty of Science, PhD candidate, Johannesburg, South Africa.

nadya.bhagwan@gmail.com

Evans, M[2]

The University of the Witwatersrand, School of Geography, Archaeology and Environmental Studies, Faculty of Science, Assoc. Prof., Johannesburg, South Africa.

Mary.Evans@wits.ac.za

Abstract

Digitalisation driven by Industry 4.0 has transformed energy value chains through technologies like Big Real-Time Data (BRD), Artificial Intelligence (AI), the Internet of Things (IoT), Robotics (ROB), and Machine-Human Integration (MHI). This study investigates how these technologies are utilised in the energy sectors of South Africa, China, and Germany. German and Chinese companies have led the way in integrating IoT and AI, enhancing energy efficiency and system integration. In Germany, AI has facilitated a flexible and highly integrated power system through decentralised energy sources, while in China, a more centralised energy system has strategically enhanced and integrated the use of Industry 4.0 technologies, particularly AI. In addition, Robotics and AI has enhanced mine safety and boosted operational efficiency. Conversely, South African firms view Industry 4.0 as incremental improvements to existing technologies rather than revolutionary and novel, using BRD, data analysis, and IoT for operational enhancements and maintenance. Although some Industry 4.0 technologies are being adopted by South African energy companies, such usage remains limited and fragmented. Challenges facing South African energy companies include high technology costs and limited political support for digitalisation, particularly in renewable energy sectors.

Highlights

- Industry 4.0 is embedded in the energy strategies in China and Germany, emphasising AI, IoT, and Robotics.
- Despite differences in how their energy systems are arranged, China and Germany have both integrated Industry 4.0 technologies systemically.
- South African firms see Industry 4.0 as enhancements to existing processes, not transformative or novel technologies.
- In South African energy firms, using Industry 4.0 technologies is limited to Big, Real-Time Data and IoT, and fragmented.
- High costs and political obstacles stall South Africa's renewable energy digitalisation.

Keywords: Industry 4.0 energy production technologies; energy efficiency; energy companies; energy system China; Germany; South Africa

Word count: 9018

Abbreviations

AI	Artificial Intelligence
BRD	Big, Real-Time Data
EMDAS	Energy Management and Data Acquisition System
IoT	Internet of Things
IPPs	Independent Power Producers
MHI	Machine Human Integration
PPP	Public-Private Partnership
ROB	Robotics
SOE	State Owned Enterprises
VPP	Virtual Power Plant

1. Introduction

The global energy sector is dynamic, influenced by shifting demand, supply dynamics, digitalization, and environmental imperatives for achieving zero emissions (Zou et al., 2023; Blondeel et al., 2021; Kober et al., 2020). These interconnected factors prompt nations to adopt advanced digital technologies to expand renewable energy sources, meet growing energy needs, lower emissions, and foster sustainability (Pandey et al., 2023; Borowski, 2021). The emergence of Industry 4.0, or the Fourth Industrial Revolution (4IR), is instrumental in reshaping the energy sector. Smart grids, the Internet of Things (IoT), and Artificial Intelligence (AI) are essential technologies that contribute to increasing energy efficiency, integrating renewable energy sources, and optimizing energy management (Ghenai et al., 2022; Wang et al., 2022; Lyu & Liu, 2021). These innovations are crucial for meeting global energy and climate goals, fostering a more sustainable and equitable energy future (Beier, 2017).

South Africa is grappling with a severe energy crisis widely covered in the media (United Nations Sustainable Development Report, 2020; Cohen, 2023; Winkler, 2024; Rose, 2024), severely impacting its developing economy and industrial supply chains. As a key economic player in Africa, South Africa struggles to provide essential electricity services while fulfilling sustainability commitments (Bhagwan & Evans, 2022). The crisis stems from a fragile energy infrastructure, inadequate planning, and a lack of political will, resulting in long-term damage (Cotterill, 2023). The renewable energy sector is particularly affected, embroiled in political and financial challenges within Eskom, the state-owned electricity supplier dominating the local market (Lawrence, 2020). Efforts focus on resolving issues caused by years of mismanagement, insufficient maintenance, corruption, and accountability among Eskom executives (World Intellectual Property Organization, 2021). South Africa is making major investments in the maintenance of its ageing fleet of coal-fired power stations to extend its lifespan, creating new coal-fired capacity at Kusile and Medupi, and exploring further opportunities to invest in cleaner and more efficient coal technologies, including Carbon Capture Utilisation and Storage technologies (Draft Integrated Resource Plan, 2024). However, these are temporary measures that will only help for as long as these power stations are kept open. Unit 1 of the Koeberg nuclear power plant has undergone significant maintenance and upgrades, resulting in the successful extension of its operational lifespan by an additional twenty years, until 2044 (Eskom, 2024). “The potential for South Africa really lies in investment in the smart grid (Blockchain and AI) and, in the context of advanced renewables” (African Development Bank Group, 2019, 33).

Literature on the application of Industry 4.0 technologies in the South African energy sector remains fragmented, primarily consisting of micro-level, project-based studies (see Gayoor et al., 2021; Potts and Walwyn, 2020; CSIR, 2025). At a broader level, the country report for South Africa on *Unlocking the potential of the fourth industrial revolution in Africa,* explores the opportunities and challenges associated with 4IR adoption across key sectors, including energy, agriculture, manufacturing, and finance (African Development Bank Group, 2019). The report recognizes that, while South Africa has achieved notable progress in infrastructure and technological advancements, challenges remain in fully harnessing 4IR technologies within the energy sector. It highlights the importance of strategic investments in digital infrastructure, policy reforms, and capacity building to facilitate the adoption of advanced technologies in energy production and distribution. Expanding public-private partnerships and "innovation ecosystems" (or interconnected networks of stakeholders) are seen as key to promoting the adoption of 4IR solutions to enhance efficiency, sustainability, and accessibility in South Africa's energy sector (African Development Bank Group, 2019, 48). A report recently published by the Presidential Commission on 4IR provides an in-depth discussion on the potential applications of these technologies in the energy sector (South African Presidency, 2020).

The centralisation of China's energy sector, set through five-year plans and other central government directives, allows the government to ensure energy security, drive large-scale infrastructure projects, and implement long-term sustainability goals (Lo & Ma, 2024). It has also resulted in China having more coordinated, strategic direction to integrate 4IR technologies into the energy sector, producing a unified vision of technological integration through policies such as Made in China 2025 (Wübbeke et al., 2016), the 2020 White Paper on Energy in China's New Era (State Council of China, 2020) and China's Energy Transition White Paper (State Council of China, 2024). Centralisation has enabled better coordination between stakeholders (government bodies, SOEs, and private sectors), the ability to make large-scale investments in modernising the country's energy sector and facilitated the scaling-up and deployment of Industry 4.0 technologies across vast areas. Notwithstanding the fact that 61% of its total energy supply in 2021 was coal-based, China leads global renewable energy technology development, holding numerous patents in wind turbines, PV modules, LED packages, and lithium-ion batteries (International Energy Agency, 2021; IRENA, 2025). China's intentions to digitise its energy sector and significantly reduce its carbon footprint (International Energy Agency, 2021) are evidenced by initiatives like establishing a highly automated virtual power plant (VPP) management centre in Shenzhen, enhancing grid reliability with over 1.5 million kilowatts of capacity (Shenzhen Municipality, 2023). China's

14th Five-Year Plan (2021-2025) forecasts a 50% increase in renewable energy production (of 1 trillion kWh from 2020 production levels to a staggering 3.3 trillion kWh in 2025), resulting in cutting carbon emissions by 2.6 gigatons annually, with a long-term goal of achieving carbon neutrality by 2060 (Energy Foundation China, 2022).

As a champion of Industry 4.0 and leader in renewable energy, and its commitment to prioritising Industry 4.0 in national policy, particularly Energiewende and the Roadmap for Energy Efficiency Strategy 2050, Germany aims for climate neutrality by 2050 (Kuittinen et al., 2018). “Energy transition in Germany is best understood as a long-term strategy which transforms not only the energy system but the entire way the economy and society function” (Federal Ministry for Economic Affairs and Energy, 2020). Adopting a two- pronged approach to achieving this goal, the country is rapidly expanding renewables (to a 65% share by 2030) and promoting energy efficiency by drastically reducing primary energy consumption by 30% of its 2008 level (Federal Ministry for Economic Affairs and Energy, 2020). According to Germany’s Federal Ministry for Economic Affairs and Energy (2020), energy efficiency is about consuming less energy, reducing energy costs for companies, and boosting their competitive advantage. Regarding technology, particular attention is paid to AI by “increasingly considering the fields of energy and climate through the prism of AI” (Deutsche Energie-Agentur, 2019). Moreover, developing an AI Standardisation Roadmap and a Specialist Unit for Artificial Intelligence has been a priority of the German Federal Ministry for Economic Affairs and Energy. Germany and China collaborate through the Sino-German Energy Partnership, which focuses on climate policy and energy issues (Deutsche Energie-Agentur, 2019). Established in 2016, this bilateral initiative fosters dialogue, business-to-government exchanges, and the sharing of technological and regulatory solutions for sustainable energy transitions (Sino-German Energy Partnership, 2021).

What can South Africa’s energy sector learn from China and Germany's Industry 4.0 experiences? This study assesses how these countries use Industry 4.0 to enhance energy the efficiency of their respective energy systems.

2. Methodology and interview participants

This qualitative study involved interviews with participants from ten energy sector companies, both producers and technology companies: three South African (a South African chemicals company operating its own power plant, an international energy plant consortia with a South

African partner and an IT and digital solutions company providing IoT and other digital services to Eskom) , four Chinese (two electricity utilities companies, and two ICT companies, one of which is a large global player), and three German (three ICT and digital solutions companies, one of which includes a large operator of a virtual power plant) interviewed online due to COVID-19 challenges). As the largest producer and distributer of power resources in South Africa, Eskom was approached as a key stakeholder to be interviewed. Unfortunately, the request to interview Eskom employees responsible for technology development and implementation at the State-Owned-Entity, and to visit local plants, was denied given the apparent sensitivity of information relating to technological innovations and the fact that the Eskom plants were considered strategic, national assets that could not be accessed by the public. It should be noted that this was a time in which Eskom was facing harsh criticism in the media over poor governance and regular blackouts, with access to its data inhibited. To attempt to compensate for the non-participation of Eskom, two of the South African companies chosen to be interviewed were selected because of their relationship with Eskom in providing energy resources to the national grid as well as IoT and other digital services. In addition to company interviews, six South African energy experts were interviewed. Interviews explored perceptions of Industry 4.0 technologies, categories used or developed, the value-add created, and challenges in technology access and implementation. Data collection spanned 2021-2022, with German data sourced online. Thematic analysis, guided by predetermined themes, was applied. Ethical clearance (Ethics Committee for Non-medical Research, University of the Witwatersrand, H190706) was obtained, ensuring confidentiality with pseudonyms used where necessary.

Table 1 lists participants from South African (SAC1-SAC3), Chinese (CHC4-CHC7), and German (GEC8-GEC10) companies, as well as experts (EXP11-EXP16) in the energy sector. Participants, including engineers, CEOs, COOs, and other representatives, were selected for their expertise in digital technologies in energy production. This diverse group provided insights into Industry 4.0 technology development and utilisation within energy producers, utilities, and technology firms. Experts included university academics with research expertise in the South African energy sector, one of whom held a senior position at Eskom for over ten years, the director of an international energy agency of the German government, the head of a South African energy development institute, and the director of national Industry 4.0 research centre, enriching the study with strategic perspectives. Interview questions included the following:

- Explain your understanding of the Industry 4.0 and associated technologies.
- What are the Industry 4.0 technologies that your company develops or uses?
- Describe the value-add of Industry 4.0 technologies your company develops or uses and how such value-add is measured.
- Are Industry 4.0 technologies developed or used, new or simply enhancements to existing technologies?
- What are some of the challenges impeding the implementation of Industry 4.0 technologies?

Table 1: Company participant identifier, participant designation, company type and location. SAC= South African Company; CHC = Chinese Company; GEC = German Company.

Participant identifier	Participant Designation	Company Type/ institution	Location
SAC1	Plant Engineer	Large chemicals manufacturer generating power to run its plant	South Africa
SAC2	Chief executive officer	IT and digital solutions providing IoT and other digital services to Eskom	South Africa
SAC3	Chief operations officer	International energy plant consortia with local partner, providing energy to the national grid	South Africa
CHC4	Company representative	ICT and digital solutions	China
CHC5	Company representative	State-owned electric utilities company	China
CHC6	Company representative	Global ICT and digital solutions	China
CHC7	Company representative	Electric utilities	China
GEC8	Company website	IT company & largest operator of a virtual power plant	Germany
GEC9	Company website	IT and digital solutions	Germany
GEC10	Company website	IT and digital solutions	Germany
EXP11	Academic	University	South Africa
EXP12	Director	International development agency of German Government	South Africa
EXP13	Academic	University	South Africa
EXP14	Centre head	4IR research centre	South Africa
EXP15	Unit head	National Energy Development Institute	South Africa
EXP16	Academic	University	South Africa

3. Results

The results of the interviews are presented below and grouped by country.

3.1. South African companies

Table 2 outlines insights from interviews with South African companies in the energy sector, detailing their backgrounds and use of Industry 4.0 technologies. SAC1, a chemicals and energy company, operates Africa's largest natural gas-fired power plant solely for internal operations. They utilise IoT platforms and data analysis for real-time monitoring, managed by process engineers rather than AI (SAC1, Table 2). SAC2, a software developer, focuses on 4IR architecture for coal-based power plants, including Eskom's EMDAS system for energy management and forecasting. They define Industry 4.0 as optimising the same processes across the entire value chain through better-connected technologies (SAC2, Table 2). SAC3, an independent power producer, operates large diesel-fuelled turbines contributing 1006 megawatts to the national grid. They integrate advanced technologies from suppliers like Siemens, employing IoT and telecoms for monitoring and asset control (SAC3, Table 2). They emphasise these technologies as enhancements rather than novel innovations. SAC3 said, “Many of these technologies are not new, but simply improved.”

All companies highlight the significance of IoT and data analytics in their operations, underscoring these as evolutions of existing technologies within a more interconnected framework.

Table 2: Company relation to the energy sector and background, type of Industry 4.0 technology used, and defining Industry 4.0 technologies.

Participant identifier	**Relation to the energy sector**	**Company background**	**Type of Industry 4.0 technology used**	**Defining Industry 4.0 technologies**
SAC1	Energy producer	Gas-fired power plant, generating 140 megawatts to run the plant.	Remotely controlled pressure and temperature transmitters to collect Big, Real-Time Data; Internet of Things	4IR technologies refer to big data, artificial intelligence, and real-time monitoring platforms.
SAC2	Technology company servicing the energy sector.	Develops IOT, business process optimisation, and visualisation technology for coal-based energy plants. Currently developing an EMDAS system for Eskom.	Big, Real-Time Data; Internet of Things	4IR optimises the same processes using a connected architecture, including more advanced technologies. You cannot look at each part of the energy value chain in isolation, as they all interrelate.
SAC3	Energy producer	IPP operates two energy plants. It uses diesel to fuel open-cycle gas turbines, generating 1006 megawatts of energy.	Sensors and transmitters to collect Big, Real-Time Data; Internet of Things	The identified categories of 4IR technologies used (BRD, IoT) in the study are appropriate, although many of these technologies are not new but improved.

Industry 4.0 technologies enhance energy plant operations by reducing maintenance costs and optimising production processes. Table 3 details their impact: SAC1 uses data for pre-emptive maintenance and fault correction, boosting reliability and sustainability while lowering costs. SAC2 measures efficiency through optimal power generation despite constraints like temperature and pressure. SAC3 sees improved reliability and sustainability, attracting investors through enhanced plant performance and reduced downtime and costs. These technologies' value-add is quantified by input-output efficiency improvements and reduced operational disruptions (SAC3, Table 3). Although there is no increase in physical energy production at the plant, the plant performs better and more optimally, and there are cost savings. “If you know the plant better and can maintain it more effectively, it attracts investors and becomes more sustainable” (SAC3, Table 3).

Table 3: The value-add of Industry 4.0 technologies and how this is measured.

Participant identifier	**Value-add of 4IR technologies**	**Measuring value-add**
SAC1	The plant operates at optimal efficiency levels, ensuring the system's reliability and sustainability. By optimising output levels, process-related and maintenance costs are also reduced, and productivity increases.	Look at current versus intended production. Measure constraints: ambient temperature, pressure levels, water quality, energy efficiency as a megajoule per kilowatt, the megawatt ratio, the ratio of steam-to-coal, level, and quality of output.
SAC2	Improved efficiencies in plant process functioning. This improves plant reliability and sustainability.	Efficiency indicators: megawatts of power produced per hour, actual versus expected production
SAC3	Plants become more efficient, reliable, and sustainable. Although physical energy production does not increase, the plant performs better and more optimally, and cost savings occur. More effective plant maintenance attracts foreign investors.	It measures a plant's overall input and output efficiency, resulting in less downtime and reduced operating costs.

South African companies do not view Industry 4.0 technologies as new but as enhancements to existing technologies. This is the consensus reached amongst all South African companies interviewed, as seen in Table 4. For SAC1, such monitoring systems interfacing with the software programme is not new, but “the amount and quality of the data collected is better because of the sensors and access to real-time, big data, and the analysis of the data has been improved as software programmes have improved” (Table 4). SAC2 also highlighted that “4IR is the optimisation of the same process but using a connected, more sophisticated architecture” (Table 4). According to SAC3, “software programs for analysis and prediction of the data have always existed. However, these programs have become smarter and faster with more computing ability. Many software programs and hardware devices are produced abroad in Germany and China. These countries would be using the same thing but using the newest version” (Table 4). SAC3 reiterated that such technologies have “enhanced those that have already been in operation, that is, there has been an evolution of existing technologies over the past twenty years” (Table 4).

Table 4: Industry 4.0 technologies as new or enhancements to existing technologies

Participant identifier	**Are Industry 4.0 technologies new or enhancements to existing technologies?**
SAC1	Such monitoring systems interfacing with SCADA software have been around for a while, but the amount and quality of the data collected are better because of the sensors and access to real-time, big data. Also, the data analysis has improved as software programs have improved. There is no AI incorporated into the programmes at this point.
SAC2	4IR is optimising the same processes but using a connected, more sophisticated architecture.
SAC3	The technologies have enhanced those that have already been in operation. There has been an evolution of existing technologies over the past twenty years. Many software programs and hardware devices are produced abroad in Germany and China. These countries would use the newest version of the same thing.

Table 5 indicates the Industry 4.0 technologies that are ‘missing’ or not being used by the interviewed South African companies. AI was identified as the missing technology among all South African companies interviewed. For SAC1, the main reason for this was the excessive cost of AI technology. Again, in SAC2, AI was identified as the missing technology, and the reasons provided for this included high technology costs and a lack of political will (Table 5). For SAC3, constraints in implementing 4IR technologies in the SA energy sector included high technology costs and the inadequate political will to drive digitalisation in South Africa’s energy sector. “It is not about a lack of engineering or technological skills” (Table 5). Missing MHI and ROB technologies were identified because they did not apply to the energy sector or their niche position in the energy sector.

Table 5: Missing 4IR technologies and challenges impeding the implementation of 4IR technologies in the energy sector.

Participant identifier	**Missing technology**	**Challenges impeding 4IR technology implementation**
SAC1	AI	High technology costs
SAC2	AI, MHI	High technology costs and a lack of political will make MHI unsuitable for the energy sector, as it deals with wearable and sensory devices rather than energy production.
SAC3	AI, ROB	It boils down to cost and the political will to drive digitalisation in South Africa’s energy sector. It is not about a lack of engineering or technological skills. Robotics are an extremely niche part of the energy sector.

3.2. Chinese Companies

Table 6 outlines key Chinese companies in the energy sector, detailing their background and utilisation of Industry 4.0 technologies. CHC4 is a global technology developer that entered China's renewable energy market in 2017, specialising in telecommunications. It holds a significant global market share in inverters and photovoltaic products and offers intelligent solutions for solar and wind power plants. Additionally, it innovates in the traditional coal energy sector, employing AI and 5G for digital and automated mining solutions. According to CHC4, Industry 4.0 revolves around big data, AI, and the Internet of Everything, enhancing safety in traditional energy production. CHC5, a state-owned electric utility company, manages and operates most of China's power grids, covering over 88% of the country's land area and supplying electricity to more than 1.1 billion people. It views Industry 4.0 as integrating advanced ICT, control, and energy technologies crucial for clean and low-carbon energy transformation. CHC5 emphasises using big data, IoT, AI, and mobile internet to create holographic models for predicting new energy generation, citing holography as transformative for Industry 4.0. CHC6 focuses on AI development across various sectors, including energy, home appliances, education, health, and aerospace. It pioneers AI, IoT, robotics, MHI (Machine-Human Integration), and blockchain technologies for smart appliances, industrial robots, intelligent vehicles, drones, and energy trading platforms. CHC6 emphasises that Industry 4.0 technology, especially AI, proactively enhances energy efficiency, reducing reliance on energy imports, promoting clean energy, and mitigating greenhouse gas emissions. CHC7, a state-owned energy investment and development platform, aims to lead in integrated energy services and supplies. It collaborates with tech firms to provide smart heating and gas services. Using Industry 4.0, CHC7 accelerates energy structure transformation, scales up clean energy provision, and advances energy industry upgrades.

These Chinese companies illustrate how Industry 4.0 technologies enhance efficiency, sustainability, and innovation across the energy sector. They utilise AI, IoT, and advanced ICT to optimise operations, predict energy generation, and transform traditional energy production methods. These efforts align with China's strategic goals of reducing dependence on energy imports, enhancing energy security, and promoting clean and renewable energy sources in line with global environmental goals.

Chinese companies are using their experience in telecommunications and mobile technologies to position themselves within the energy sector. These companies specialise in IoT and AI and use these technologies as the basis for transforming the local energy sector, making traditional energy safer and more efficient, and growing clean energy through renewables. As reflected in how Chinese companies define Industry 4.0 technologies in Table 6, such technologies appear pivotal to the longer-term transformation of the Chinese energy sector and are very much a part of their growth trajectories.

Table 6: Company relation to the energy sector, background, and type of Industry 4.0 technology used.

Participant identifier	**Relation to the energy sector**	**Company background**	**Type of Industry 4.0 technology used**
CHC4	Technology company servicing the energy sector.	Develops intelligent digital solutions using AI, 5G and IoT technology for coal mines and renewable energy industries—leader in photovoltaic products and inverters.	IoT and AI
CHC5	State-owned energy producer	Construction and operation of power grid. Produces 1560 gigawatts of energy. We are building the world's largest energy cloud platforms.	Big data; IoT, AI; Holography; Cloud Computing
CHC6	Technology company servicing the energy sector	Emphasis on AI solutions across the industry.	AI; IoT; ROB; MHI; Blockchain
CHC7	State-owned energy producer	We cooperate with technology companies to construct an industrial internet and big data platform for intelligent gas supply, smart heating, and smart energy services.	IoT, AI, ROB, cloud computing, MHI

Table 7 summarises the value-add (impact) and measurement of Industry 4.0 technologies in Chinese energy companies. CHC4 employs high-definition real-time video for remote problem-solving and AI for reliable safety inspections, measuring workforce saved and worker satisfaction. CHC5 enhances traditional grids with Industry 4.0 for intelligent energy management and predictive holography, evaluated through benefit indices. Industry 4.0 technologies have made "existing technologies cooperate and produce the effect of energy fusion through the fusion of technology and application" (CHC4). According to CHC5 (Table 7), "4IR technology empowers the traditional power grid," optimising intelligent energy production and management. CHC6 optimises steam production using AI for energy efficiency and emission reduction, emphasising proactive solutions. CHC7 utilises cloud computing, big data, AI, and IoT for real-time control and safety, enhancing operational efficiency and customer service. These technologies collectively enhance production, efficiency, and safety across all companies.

Table 7: The value-add of 4IR technologies and how this is measured.

Participant identifier	Value-add of 4IR technologies	Measuring value-add
CHC4	Improved production efficiency and safety capabilities using AI.	Number of workers injured/dying, worker satisfaction levels.
CHC5	4IR technology empowers the traditional power grid, optimising intelligent energy production and management.	Efficiency levels are measured using the Benefit Evaluation Index System.
CHC6	AI optimises steam flow and balance and generates efficient energy levels. It enhances intelligent business development and industry reform.	Measure the decrease in the input of functional personnel and the change in the input of the database from the physical to a cloud server.
CHC7	Using cloud computing, big data, IoT, and AI, companies can perform real-time production control and intelligent inspection.	Using data mining, predictions have become more detailed and accurate.

Table 8 shows that Chinese energy companies recognised that Industry 4.0 technologies were implemented as new, not just enhancements or improvements to existing technologies. That said, Industry 4.0 technologies have enhanced production and operational efficiency at these firms. Moreover, “4IR technologies have been central to “enhancing the intelligent development and reform of enterprises” (CHC6, Table 8) and have “enhanced technological reform and innovation within energy enterprises” (CHC7, Table 8).

Table 8: 4IR technologies as new or simply enhancements to existing technologies in energy

Participant identifier	Are Industry 4.0 technologies new or enhancements to existing technologies?
CHC4	New technologies have i. Replaced the work of some workers, increased the safety of the whole work, and enhanced the production efficiency of enterprises. ii. Made existing technologies cooperate and produce the effect of energy fusion through the fusion of technology and application.
CHC5	New technologies have empowered the traditional power grid, improved its perception ability, interaction level, and operation efficiency, supported the access and comprehensive utilisation of various energy sources, and improved energy efficiency.
CHC6	New technologies have been central to enhancing the intelligent development and reform of enterprises.
CHC7	New technologies have replaced and eliminated backward production capacity, reduced air pollutant emissions, and enhanced technological reform and innovation within energy enterprises.

Chinese companies reported no gaps in Industry 4.0 technology implementation, unlike South Africa. However, challenges persist in fully embedding these technologies. Table 9 cites reasons such as varying project demands, imperfect product standardization, and industry planning shortcomings, slowing overall progress (CHC4). CHC5 struggles with integrating core technologies in traditional coal sectors with renewables (Table 9). Economic constraints post-COVID-19 hinder CHC6's technology customization (Table 9). CHC7 faces bureaucratic delays in securing technology funding, constraining China's technological innovation (Table 9). According to CHC7, the overall outcome of such challenges is that “China’s technological creativity is constrained.”

Table 9: Missing 4IR technologies and challenges impeding implementing of 4IR technologies in the energy sector.

Participant identifier	Missing technology	Challenges impeding Industry 4.0 technology implementation
CHC4	No missing technology	Inadequate spending on technologies is due to insufficient depth in applying them, producing a more fragmented architecture for Industry 4.0 technology implementation.
CHC5	No missing technology	The core technology and independent R&D capability need to be broken when implemented.
CHC6	No missing technology	Due to economic constraints and reduced profits due to COVID-19, the business model of Chinese enterprises cannot be generalised, and technological change needs specific analysis.
CHC7	No missing technology	Dealing with government departments is time-consuming and labour-intensive.

3.3. German Companies

Table 10 provides insights into German energy companies leveraging Industry 4.0 technologies. One of Europe's largest Virtual Power Plants (VPPs) which creates an integrated system of decentralized producers and consumers of electricity is operated by GEC8. The VPP optimises operation schedules through a central control system and Next Box units, facilitating real-time adjustments to grid stability amidst renewable energy fluctuations (GEC8). GEC8 describes itself as “the power of many for the energy transition.” While GEC8 focuses on building an integrated system, GEC9 specializes in digitization solutions for decarbonizing the energy sector, emphasizing AI and data analytics (GEC9). According to a company representative, “the digitisation of the energy sector cannot be stopped - data are the raw material of the future” (GEC9). Meanwhile, GEC10 focuses on IoT solutions to enhance the integration and reliability of renewable energy sources, advocating for digital platforms, big data analytics, IoT, IT security, and cloud solutions to ensure future readiness in the energy sector (GEC10). These companies highlight Germany's advanced adoption of Industry 4.0 to drive efficiency and sustainability in energy production and distribution.

“The German government sees AI as a key strategy for mastering some of the greatest challenges of our time, such as climate change and pollution” (GEC8). “The Internet of Things offers you new possibilities, greater flexibility and scalability so that you can react better and faster” (GEC10).

Table 10: Company relation to the energy sector and background, type of Industry 4.0 technology used, and defining Industry 4.0 technologies.

Company identifier	Company relation to the energy sector	Company background	Type of Industry 4.0 technology used
GEC8	Technology company servicing the energy sector	Operates one of the largest virtual power plants in Europe.	IoT, BRD, AI (Nextbox)
GEC9	Technology company servicing the energy sector.	Provides IoT sensor technology and energy data management services to energy companies	IoT sensor technology, Big Data and Analytics, AI
GEC10	Technology company servicing the energy sector	Provides digital and IoT solutions.	IoT solutions

Table 11 describes the value-add created through implementing Industry 4.0 technologies within the sample of German companies studied. The value-added attributed to Industry 4.0 technologies, especially AI and IoT, and access to and analysis of BRD are considerable. This is particularly evident for VPPs. As explained by a company representative,

"Individual small plants can, in general, not provide balancing services or offer their flexibility on the power exchanges. This is because their generation profile varies too strongly, or they do not meet the minimum bid size of the markets. By aggregating the power of several units, a VPP can deliver the same service and redundancy and subsequently trade on the same markets as large central power plants or industrial consumers" (GEC8).

IoT and big data (BD), together with the use of smart sensors, monitor and regulate underground cable temperatures, and in so doing prolong their functioning life. The continuous production of such data and a significant data analytics capacity enable power companies to optimise energy flow, adjust distribution as needed, and enhance transparency in decentralized energy systems (GEC9). Despite challenges like high costs and data security concerns, GEC9 stresses the importance of intensifying research and development efforts in implementing Industry 4.0 technologies. GEC10 combines AI and other advanced solutions to manage vast IoT-generated data, helping clients effectively utilise and interpret data for informed decision-making (GEC10).

Table 11: Value-add created by Industry 4.0 technologies and potential challenges impeding implementation.

Participant identifier	Value-add	Challenges impeding 4IR technology implementation
GEC8	VPPs help to stabilise the power grids and create the preconditions for integrating renewable energies into the markets.	No data
GEC9	Access to BD and data analysis allows energy providers and network operators to optimise forecasts and introduce cost-reduction measures.	Excessive costs; security concerns about hacking; lack of expertise; technologies not prioritised.
GEC10	Using a combination of new technologies and retrofitted solutions, the company helps clients navigate the large amounts of data accessed via IoT to make sense of this data and use it sensibly.	No data

3.4. Expert interviews

Table 12 summarizes insights from expert interviews (EXP11-EXP16) on Industry 4.0's impact on South Africa's energy sector. Significant R&D focuses on smart meters and AI applications. One organization emphasizes using Industry 4.0 to model energy systems, pathways, and options for industries and municipalities (EXP14). They employ advanced algorithms, big data analytics, and open-source models for scenario visualization with AR and VR. AI detects PV panel failures and simulates energy futures, enabling interactive exploration of CO2 emissions and costs associated with different energy mixes. AI has made this modelling process more interactive. EXP14 describes this as follows:

“With AI, you use the same data and your hands and eyes to interact with it. We can model the disruptive impact of new technology. For example, what happens when batteries get cheaper, when solar costs decline, etc” (EXP14)?

There is an overwhelming consensus on using Industry 4.0 technologies to harness renewable energy resources better and manage energy infrastructure. Respondents were sceptical about whether the public sector is ready to exploit such technologies (EXP12-EXP16) fully. For example, EXP13 states the following:

"In South Africa, there is a disconnect between how we imagine and conceptualise 4IR and how this plays out in reality. This exists because of gaps in 4IR enabling factors. Although the SA energy sector has an established ICS system and enormous potential to operate in the 4IR, inequality in access to and availability of basic services continues to hinder this" (EXP13).

According to EXP14,

“There is immense potential for energy infrastructure management using 4IR technologies. You can manage assets well with adequate meters and remotely turn things on and off. However, to do so requires adequate metres and smart grids” (EXP14).

Experts collectively view Germany as the model for South Africa's energy sector, despite acknowledging China's advancements in renewables (EXP11-EXP15). Germany's integration of household solar panels and smart meters in a competitive renewable market is lauded (EXP11). However, South Africa's energy landscape differs significantly due to infrastructure, resources, and political dynamics (EXP15). Therefore, adopting German or Chinese technologies requires adaptation to local conditions. Singapore is highlighted in academic research as a leader in smart grid technology, suggesting its energy sector as a valuable case study (EXP16).

Table 12: Expert interview responses to understanding Industry 4.0 and its impact on the South African energy sector.

Participant identifier	**Participant's area of expertise**	**Understanding Industry 4.0 and its impact on the South African energy sector**
EXP11	Academic researching energy access and energy poverty	Climate change concerns have mainly driven the energy transition, and 4IR is enabling this transition.
EXP12	Development Agency of the German government.	The potential of 4IR is recognised, but the public sector is not ready to fully exploit this.
EXP13	Geography and Environmental Sciences lecturer	In South Africa, there is a disconnect between how we imagine and conceptualise 4IR and how this plays out in reality. This exists because of gaps in 4IR enabling factors.
EXP14	Head of Energy Unit at the 4IR Centre	We still have much lobbying to do. The country is emotive and, understandably, about shifting from coal to renewables; we have a confusing policy landscape in South Africa. We need to create a market that people will invest in every year with increasing local component requirements.
EXP15	Renewable Energy Unit Head	A correct blend of fossil fuels, renewables, and nuclear will ensure our energy security in the future. The extent to which these are mixed is variable; technologies are there to harness the resources, but the challenge is getting them integrated sustainably into the energy system. We have become much smarter.
EXP16	Academic research on renewables, smart grids, and power generation.	We are at the beginning of the smart grid development and implementation. End users are more likely to adopt smart grid technologies than the utilities. We do not have smart metering, which customers need to sell back to the municipality.

4. Discussion

The interviews produced a variety of key themes, including varying perceptions of the novelty of Industry 4.0 technologies and their impact on energy production. Differences existed in the types of 4IR technologies used and their perceived value-add. Additionally, challenges hindering the development and adoption of these technologies in the energy sectors of South Africa, China, and Germany were analysed.

4.1. Contextual differences in understanding 4IR technologies in energy

Common understandings of 4IR technologies in the energy sector were clearly defined in the interviews. Integrating IoT, real-time data and analytics, drawing on AI for data analysis and forecasting and using robotics to improve processes for some (such as the coal-fired power plants in China) were reported by companies. References to these technologies align with current research trends on energy sector technologies with research gaps in Robotics and Machine Human Integration (MHI) (Bhagwan & Evans, 2023). However, the sentiments of South African companies interviewed were that 4IR technologies are not new or transformative but additive to existing technologies (SAC3, Table 2), "smarter and faster with more computing ability", and the "amount and quality of the data collected is better because of the sensors and access to real- time, big data" (SAC1, Table 4). The data concurs with an essential finding by (Bhagwan & Evans, 2023). South African companies value access to extensive, real-time data and IoT-linked technologies in terms of efficiency, reliability, and integration within the energy production and distribution system. A Scopus literature review (Bhagwan & Evans, 2023), not surprisingly, shows that publications on the impact of 4IR technologies on energy production in South Africa are scant. A South African technology company described 4IR as "the optimisation of the same processes but using a connected architecture, where 4IR technologies help energy plants move from the actual to the ideal scenario" (SAC2, 2022).

In China, the definitions of 4IR technologies that the interviewees embraced were closely tied to a growth-related mindset, innovation and "the progress of human civilisation" (CHC5, 2022). 4IR technologies are understood in the context of a bigger picture, this being their contribution to promoting an "energy production and consumption revolution" by deepening "the integration of industrialisation and informatisation" (CHC6, 2022). One Chinese company described the application of 4IR technologies in energy production as "promoting the healthy development of the energy sector" (CHC6, 2022). For these companies, advanced 4IR energy technologies are a deeply integrated part of supporting the "clean and low-carbon transformation", a defined and critical contributor to upgrading the sector (CHC5, 2022). Interview data here correlates with a previous study by (Bhagwan & Evans, 2023) in which surveyed Chinese energy companies placed "more value on the importance of 4IR technologies in energy than their German and South African counterparts." It makes sense, therefore, that China produced the most sizable number of publications in all technology categories in energy and energy production," even more than Germany, a global leader in Industry 4.0 (Bhagwan & Evans, 2023).

German companies, similarly, place 4IR technologies at the centre of their integrated energy transition. According to the Deutsche Energie-Agentur (Dena), in *Project EnerKI – Using AI to optimise the energy system*, “AI represents the opportunity to technologically master the complexity of a decentralised and integrated energy transition” (Deutsche Energie-Agentur, 2024). A South African expert in renewable energy explains that “globally, the energy sector is evolving,” albeit to varying extents and speeds, and 4IR technologies are essentially “enablers” for the “smart integration of different types of energy across the system” (EXP15, 2021). The South African energy context is complex. “On planet Earth, we only have three sorts of energy: fossil fuels, renewables and nuclear. A correct blend will ensure our (South Africa’s) energy security in the future. The extent to which these energy types are mixed is variable; technologies are there to harness the resources but integrating them sustainably into the energy system is a challenge” (EXP15, 2021). “South Africa lacks the infrastructure, energy resources and political will as Germany. We can adopt these technologies but must adapt them to meet local needs” (EXP15, 2021). A fundamental strength of integrating 4IR technologies into the South African energy sector lies in its ability to provide options for alleviating energy poverty without the need to be connected to the grid (EXP13, 2021). However, the interviewee highlights South Africa's dilemma: the “disconnect between how we imagine and conceptualise the 4IR and how this plays out " (EXP13). This exists because of gaps in 4IR enabling factors. Although the South African energy sector has an established Information and Communication System (ICS) and the potential to operate in the 4IR, “inequalities in access to and availability of essential services continue to hinder this realisation” (EXP13, 2021). In other words, the government's primary focus has been on the best way to provide energy, addressing an immediate energy crisis, rather than a longer-term, proactive strategic shift towards renewables. Integrating 4IR technologies across the energy value chain is not a quick fix and must be carefully researched, tested, and incentivised (EXP14, 2021).

4.2. 4IR technologies used or developed and their value-add within the energy companies

The company and expert interviews all suggest some level of connection with 4IR technologies, whether using these technologies directly or developing and implementing these technologies as part of digital solutions (Company interviews, 2022). This corresponded with a survey of energy companies in South Africa, China, and Germany conducted by (Bhagwan & Evans, 2022), in which 85% of all companies surveyed felt connected to the 4IR, and 8% reported not participating in the 4IR. Interesting patterns emerged regarding the types of 4IR technologies used or developed. Access to big, real-time data is crucial to the energy sector, particularly renewables. All the companies interviewed and studied, whether producing energy or developing software programmes and or technologies, relied on being able to collect big data in real-time.

Technologies enabling the data collection were sensors and actuators used at the energy plants. These technologies collect and transmit big data to multiple computer networks and servers. Differences emerged in how such data is then analysed and used. For South African companies, the data analysis was carried out by either the engineers or the IT personnel using computer software programmes for modelling and forecasting, as “there is no AI incorporated into this software” (SAC1, 2022). “Software programs for the analysis and prediction of data have always existed. However, these computers have become smarter and faster with more computing ability” (SAC3, 2022). In the case of Eskom, a Coulumb Counter has traditionally been used to collect and store historical data from coal power plants for reporting purposes and not for forecasting and prediction (SAC2, 2022). A new Energy Management and Data Acquisition System (EMDAS) will change this (SAC2, 2022). Interviews with industry experts suggest that experimentation with AI in the South African energy sector is still in its initial stages within research labs and 4IR centres. AI is being used to explore different energy futures. For example, “using headsets to visualise and interact with data, we can explore a variety of future energy mixes using modelling, their associated carbon dioxide emissions, relative costs, etcetera.” So, with AI, you are using the same data and your hands and eyes to interact with the data. AI has meant that “we can model the disruptive impact of new technologies” using multiple scenarios (EXP14, 2021). That said, a literature review by (Bhagwan & Evans, 2023) found zero publications on South Africa using AI as a technology in energy production. For Germany, the percentage of publications on AI in energy production was 37%, whilst for China, it was 63% (Bhagwan & Evans, 2023). In Germany, AI is being integrated across several policy platforms. The Federal Ministry for Economic Affairs and Energy in Germany has launched its AI Standardisation Roadmap and put together a particular unit on AI (DENA, 2019).

As expected, in addition to big data, the Chinese companies interviewed indicated they were developing or using AI, IoT, and robotics technologies in renewables and non-renewables (coal). A desktop analysis confirmed the importance of IoT and AI technologies for German companies in the local energy sector. In fact, according to one German company, AI is considered the fastest-growing sub-sector of the high-tech industry (GEC8, 2022). The finding is aligned with the outcome of a survey of 250 executives in the German energy sector conducted on behalf of the Deutsche Energie Agentur (DENA, 2019), in which points to 74% of all respondents believing that AI will have a positive impact on the energy transition in Germany (DENA, 2019). The DENA study identified the application of AI in the German energy sector as most relevant for data processing (96%) and signal processing (88%) (DENA, 2019). Machine Human Integration, or MHI, did not feature in all three countries, and one company described it as “not applicable to energy production as it deals largely with wearable, sensory devices” (SAC2, 2022). It appears to be the “unchartered territory in energy” that Bhagwan and Evans (2022) describe in their survey of South African, German, and Chinese energy companies. This aligns with the findings of Bhagwan and Evans

(2023) regarding the hierarchy in the number of global publications on 4IR technologies in energy production. In this study, AI, IoT and Big Data accounted for 72% of all publications, whilst MHI accounted for just 1%.

The overall value-add created by whichever 4IR technologies are used is clear – optimisation of the plant contributes to reduced maintenance and operational costs, boosting efficiency, reliability, and sustainability at energy plants, consequently expanding productivity (Company interviews, 2022). Despite variances in the size of the value-add created by different 4IR technologies in energy for improving efficiency and reliability, Bhagwan & Evans (2022) recognised considerable value created by these technologies for Chinese, German, and South African energy companies. In this study, South African energy companies achieved this using remotely controlled actuators, switches, and simulation models that facilitated plant forecasting and prediction. In the case of a new plant build, access to sophisticated computer software that analysed real-time data on environmental and other site-based conditions was crucial. The interviews with South African energy companies showed a preference towards the value obtained using big, real-time data and data analysis technologies. Similarly, in a survey of South African energy companies in 2022 (Bhagwan & Evans, 2022), "for levels of efficiency, reliability, and the ability to be integrated across the energy system, technologies enabling access to BRTD (Big et al.) and the processing and analysis of such data were, again, valued the most. The IoT was ranked the third most important 4IR technology as it enables the storage and transmission of data to multiple devices in real time. AI and MHI were seen to be much less reliable, efficient, and integrated within the surveyed firms.

At the Chinese companies, AI-enabled what one company called "intelligent mine application cooperation" (CHC4, 2022), where repeated safety inspection work is done by robots and AI, "far more stable and reliable than underground workers." In China, where coal mining is still a considerable part of the energy production system and where worker safety and worker satisfaction need to be improved, integrating AI and Robotics in coal production is centrally important. Furthermore, AI is being implemented as a proactive energy solutions tool, optimising production processes so that plants reduce their emissions and operate more efficiently. The German energy companies also identified AI, IoT and big data in energy. IoT-connected components are considered "easier to understand and control, or they control themselves." and can "regulate themselves in the event of problems" (GEC10, 2022). Applying big data and IoT technologies has promoted integrating renewable energy on a much larger scale, extending underground power cables' lifespan, improving energy transmission and redistribution, and facilitating better grid management. Improved transparency created by such technologies has dramatically improved the functioning of a highly decentralised German energy sector. For the operator of one of the largest virtual power plants in Europe, AI is seen as "a key strategy to master some of the greatest challenges of our time, such as climate and environmental protection." Using

IoT and AI, thousands of electricity producers and consumers are digitally networked, controlled, and coordinated from a central point. A flexible power system can ensure that energy fluctuations are better compensated, stabilising the power grid. The bundling of energy producers and units has "created the conditions for integrating renewables" into the energy market (GEC8, 2022). Other studies reiterate the role of IoT and AI in supporting "the realisation of cross-commodity energy sharing in local, decentralised energy systems" and go further to suggest that such "energy-sharing communities called smart cities can address costs associated with a lack of economies of scale in a decentralised energy model" (Paho et al., 2021, as cited by Bhagwan and Evans, 2023, 44). 4IR technologies have significantly improved managing often unreliable, renewable energy resources (EXP11, 2021). Notwithstanding these interview findings, the level of impact on actual energy production remains uncertain. So, there is a gap in empirical, form-level data on how Industry 4.0 technologies affect energy production, something also emerging in the literature gap discovered by Bhagwan & Evans (2023).

Further along the energy value chain, the emphasis shifts to developing and implementing smart grid technology; intelligent energy grids with multidirectional communication between producers, distributors, and consumers - "a technology with the ability to transform the energy sector in South Africa, Africa, and the world" (EXP16, 2021). According to a local renewables and smart grid expert, South Africa is in the preliminary stages of development and implementation. It has much to learn from countries like Germany and Singapore (EXP16, 2021). Globally, a large part of the literature on using 4IR technologies in the energy sector "deals with energy distribution via smart grids, enabling better planning and communication between the grid and energy users" (Bhagwan and Evans, 2023, 47; Hao et al, 2019; Jiang et al, 2019). There is a "void in research targeting the middle parts of the energy value chain" (Bhagwan and Evans, 2023, 47).

4.3. Challenges in implementation

In South Africa, barriers to adopting 4IR technologies in the energy sector include excessive costs and a lack of political will despite having sufficient engineering and technological skills (SAC1-SAC3, 2022) (Bhagwan & Evans, 2022). Unlike Germany, where a competitive energy market and supportive policies drive technology adoption, South Africa's public sector is less proactive in implementing these innovations, with some experts believing that "the public sector in South Africa "is not ready to exploit 4IR technologies" fully (EXP12). Experts note that South Africa faces challenges transitioning from coal to renewables due to complex policies and coal dependency issues, impacting infrastructure planning and causing power shortages (Lawrence, 2020). "South African policymakers' failure to embrace a rapid transition to renewable energy (RE) generation results not simply from the insufficient appreciation of its immediate and longer- term benefits, but from their protracted deterrence of this option" Also, "an absence of transparency and accountability—and the growing challenges of sourcing affordable coal for electricity generation—have conspired to make inadequate infrastructure planning and resultant power outages also increasingly likely" (Lawrence, 2020, 59). .

Reasons for inadequate 4IR technology implementation by Chinese energy companies included budgetary constraints caused by inadequate government spending and reduced company profits due to the COVID-19 pandemic. According to the China Energy Transition Status Report (Sino-German Energy Transition Project, 2020, 2), "Before the coronavirus hit, 2020 was already shaping up to be a year of transition in energy and climate policy. The worldwide economic disruption of 2020 adds significant uncertainty about both fields." However, there were also mentions of imperfections in product standardisation and the lack of industry planning and standards linked to 4IR technologies in the sector. There was a reference to the need to separate research and development in core technologies from other independent technologies. Another issue raised by scholars such as Massel (2018) and Alekseev et al. (2019) that may also be presenting a challenge to 4IR technology implementation in China and Germany is "the lack of scientific research because of limited and inconsistent data collection on digitisation in energy (as cited by Bhagwan and Evans, 2022, 46). Put differently, "unless there is baseline data to illustrate the positive impact of Industry 4.0 technologies in energy production, energy companies will be cautious about investing in Industry 4.0 technologies" (Bhagwan and Evans, 2022, 46-47).

5. Conclusion

Companies agree that Industry 4.0 or 4IR technologies are pivotal within the energy sectors of China, Germany, and South Africa, enhancing efficiency, sustainability, and integrating renewables. In all three countries, big data and IoT-linked technologies are fundamental to improving plant efficiency and reliability through predictive maintenance and reduced downtime. The use of AI within South African energy companies is limited and fragmented, and existing AI projects are largely at a developmental stage or being piloted at a piecemeal level. In fact, South African experts see these technologies as enhancing existing systems rather than revolutionising them through novel technologies. In China, the extensive application of AI and Robotics in energy aligns with China's broader objectives of advancing smart technologies through its Made in China 2025 initiative, as well as its dedication to reducing carbon emissions. Chinese companies are using AI and Robotics to optimise operations and safety. Germany uses AI for smart grids, coordinating decentralised energy sources efficiently. Industry 4.0 is embedded into the energy strategies of China and Germany, emphasising AI, IoT, and Robotics. Despite differences in how their energy systems are arranged, with China exemplifying a more centralised energy system, both China and Germany have integrated Industry 4.0 technologies systemically. South Africa faces certain barriers like inflated costs and political obstacles, hindering the widespread adoption of Industry 4.0 technologies in its energy sector. In contrast, China and Germany grapple with industry standards rather than political will in advancing 4IR technologies.

References

Alekseev AN, Lobova Sv, Bogoviz Av, Ragulina Yv. (2019). Digitalization of the Russian energy sector: state-of-the-art and potential for future research. Int J Energy Econ Pol 2019;9(5):274–80

African Development Bank. (2019). Unlocking the potential of the Fourth Industrial Revolution in South Africa: Country case study*. African Development Bank. https://4irpotential.afdb.org/

Beier, G., Niehoff, S., Ziems, T., & Xue, B. (2017). Sustainability aspects of a digitalized industry – A comparative study from China and Germany. International Journal of Precision Engineering and Manufacturing-Green Technology, 4(2), 227-234

Bhagwan, N., & Evans, M. (2022). A comparative analysis of the application of Fourth Industrial Revolution technologies in the energy sector: A case study of South Africa, Germany, and China. Journal of Energy in Southern Africa

Bhagwan, N & Evans, M. (2023). A review of industry 4.0 technologies used in the production of energy in China, Germany, and South Africa, Renewable and Sustainable Energy Reviews, Volume 173, 2023, 113075, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2022.113075. Available at: https://www.sciencedirect.com/science/article/pii/S136403212200956X)

CSIR. (2025). Development of power system operator model for short-term variable renewable energy forecasting. Retrieved from https://www.csir.co.za/development-power-system-operator-model-short-term-variable-renewable-energy-forecasting

Dentici, I. (2024, April 8). Transforming automotive simulation with AI: The rise of virtual prototyping. Hexagon Manufacturing Intelligence. Retrieved from https://blog.manufacturing.hexagon.com/transforming-automotive-simulation-with-ai-the-rise-of-virtual-prototyping/

Deutsche Energie-Agentur (DENA: German Energy Agency). (2019). Survey: Artificial Intelligence in the energy industry. Berlin

Department of Mineral Resources and Energy. (2024). Draft Integrated Resource Plan 2023. Republic of South Africa

Eskom Media Statement. (2024, July 15). Koeberg operating licence extended for further 20 years. Retrieved from https://www.eskom.co.za/koeberg-operating-licence-extended-for-further-20-years/

German Federal Ministry for Economic Affairs and Energy. (2020). Germany's Energy Efficiency Strategy 2050. Federal Ministry for Economic Affairs and Energy. Public Relations Division. Berlin Available at: www.bmwi.de

Ghayoor, F., Swanson, A., & Sibanda, M. (2021). Optimal sizing for a grid-connected hybrid renewable energy system: A case study of the residential sector in Durban, South Africa. Journal of Energy in Southern Africa, 32(4), 1–12. https://doi.org/10.17159/2413-3051/2021/v32i4a10356

Ghenai, C., Alhaj Husein, L., Al Nahlawi, M., Hamid, A. K., & Bettayeb, M. (2022). Recent trends of digital twin technologies in the energy sector: A comprehensive review. Sustainable Energy Technologies and Assessments, 54, 102837. https://doi.org/10.1016/j.seta.2022.102837

Haleem, A., Javaidt, M., Singh, R.P., Suman, R., Rab, S. (2022). Holography and its applications for industry 4.0: An overview. Internet of Things and Cyber-Physical Systems 2 (2022) 42–48

Hao, H., Wang, Y., Shi, Y., Li, Z., Wu, Y., & Li, C. (2019, October). IoT-G: a low-latency and high-reliability private power wireless communication architecture for smart grid. In 2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm) (pp. 1-6). IEEE

Jiang, A., Yuan, H., Li, D., & Tian, J. (2019). Key technologies of ubiquitous power Internet of Things-aided smart grid. Journal of Renewable and Sustainable Energy, 11(6)

Lawrence, A. (2020). Eskom and the Dual Character of the South African State. In: South Africa's Energy Transition. Progressive Energy Policy. Palgrave Pivot, Cham. Pp. 59-83. https://doi.org/10.1007/978-3-030-18903-7_3

Massel, L. V. (2018). Methods and intelligent technologies for scientific substantiation of strategic solutions on digital trans-formation of energy industry. Energy policy, 5, 30-42

Paiho, S., Kiljander, J., Sarala, R., Siikavirta, H., Kilkki, O., Bajpai, A., ... & Weisshaupt, T. (2021). Towards cross-commodity energy-sharing communities–A review of the market, regulatory, and technical situation. Renewable and Sustainable Energy Reviews, 151, 111568

Pan, E; Liu, S; Liu, J; Qi, Q and Guo, Z. (2020). The state grid corporation of China's practice and outlook for promoting new energy development. Energy Convers. Econ. 2020; 1:71–80. DOI: 10.1049/enc2.12007

Potts, S., & Walwyn, D. R. (2020). An exploratory study of the South African concentrated solar power sector using the technological innovation systems framework. Journal of Energy in Southern Africa, 31(2), 1–13. https://doi.org/10.17159/2413-3051/2020/v31i2a7745

Presidential Commission on the Fourth Industrial Revolution. (2020). Report of the Presidential Commission on the Fourth Industrial Revolution. The Presidency, Republic of South Africa

Sino-German Energy Partnership. (February 2021). Sino-German Energy Partnership Annual Report. On behalf of the Federal Ministry for Economic Affairs and Energy (BMWi). Berlin

The State Council of China. (2020). White Paper on Energy in China's New Era. Available at: https://english.mee.gov.cn/Resources/publications/Whitep/202012/t20201222_814160.shtml

The State Council of China. (2024). China’s Energy Transition. Foreign Languages Press Co. Ltd, Beijing, China. ISBN 978-7-119-14016-2

United Nations. (2020). Sustainable Development Report 2020. United Nations Publications. New York

Yan, X., Tian, X., Li, H., & Guo, H. (2024). Research on technical cooperation path of renewable energy between China and South Africa. Frontiers in Energy Research, 12, 1411546. https://doi.org/10.3389/fenrg.2024.1411546

CHAPTER 5: DISCUSSION

5.1. Introduction

This chapter discusses the main themes presented across the research papers, as documented in chapters 2 to 4: the literature review, the online survey, and the interviews with companies and energy experts. Each of these papers advanced, in some way, the meeting of objectives for this study and contributed to its overall aim. This research aimed to determine the uptake of Industry 4.0 technologies by the South African energy sector, how such usage compares to China and Germany, and the extent to which the level of uptake of such technologies in South Africa could exacerbate challenges facing the sector. The study was guided by three objectives, as laid out in Chapter 1. Chapter 5 is structured according to the key themes identified across the literature review, survey, and interviews of the PhD study. In the discussion, and where necessary, reference is made to relevant data contained within tables and figures in the publications reproduced chapters two to four.

5.2. Research gaps related to the deployment of Industry 4.0 technologies in the energy sectors of Germany, China and South Africa

5.2.1. Scopus publications on using Industry 4.0 technologies in energy production

Several interesting findings emerged in the literature review paper contained in Chapter 2. Firstly, at a global level, the number of publications generated through the search were even less for using 4IR technologies in energy production, compared to their use in the energy sector overall (Figure 1a and Figure 1b, Chapter 2. Bhagwan & Evans, 2023). This is despite the significance of the initiatives of the World Bank (2021), International Energy Agency (2022), and United Nations Industrial Development Organisation (2018), aimed at globally enhancing digitalisation in energy, improving efficiencies, reducing harmful emissions and promoting environmental sustainability. Secondly, both China and Germany produce far more publications on 4IR technologies in the energy sector, than South Africa (Figure 2a, Chapter 2, Bhagwan & Evans, 2023). According to Tymoshenko et al., (2022), China has strategically chosen a path of energy independence, with technologies playing a pivotal role in this journey. China's growth in publishing research in energy is reiterated by Chen et al., (2016), who explain that even though there is some unevenness regarding the quality of the journals in which Chinese researchers are publishing, the number of publications increased dramatically from 1993 to 2012. This finding was supported by the survey results (Bhagwan & Evans, 2022) which revealed that Chinese energy companies place a higher value on the importance of Industry 4.0 technologies to the global energy sector (GES) compared to their counterparts in Germany and South Africa (Table 8, Chapter 3, Bhagwan & Evans, 2022). Although Germany lags China slightly in terms of the number of papers published in this area, Germany has made strides in implementing Industry 4.0 technologies in the energy sector through its Energiewende initiative. Furthermore, a significant proportion of digital technologies relevant to the energy sector are produced in Germany (Chapter 3, Bhagwan & Evans, 2022). Through its Made in China 2025 initiative, China is promoting and incentivising research and innovation in the energy sector while supporting the local production of Industry 4.0 technologies (Liu, 2016). For wind renewable energy, China has outstripped Germany as the world's biggest producer, despite Germany's expansive experience in this market and the intensive support that it receives from the German government (Chang et al., 2021).

Müller and Voigt (2018) conducted a study of 329 small and medium enterprises in which they assessed the level of impact created by "Industrie 4.0" in Germany and "Made in China 2025" in China. A central finding of these authors that supports the study by Bhagwan and Evans (2022), is that German small and medium-sized enterprises see "Industry 4.0" as beneficial mainly from an operational standpoint, focusing on improving their day-to-day processes. In contrast, Chinese small and medium enterprises view "Industry 4.0" as offering both strategic and operational benefits, meaning they see it as a strategy to improve not only their daily operations but also their long-term business strategies. Müller and Voigt (2018) explain that the expectation by these German companies is that "Industry 4.0" is far more beneficial for large businesses, whilst similar-sized Chinese businesses accentuated the social benefits from adopting these technologies, enhancing community well-being and addressing societal needs. When compared to China, Germany, and all other BRICS nations, South Africa has performed poorly in terms of the number of publications produced (Figure 4, Chapter 2, Bhagwan & Evans, 2023), across all categories of Industry 4.0 technologies, in terms of their use in the energy sector. This is understandable given that energy policy in South Africa is nascent in the sense that the 2023 Draft

Integrated Resource Plan (South African Department of Mineral Resources and Energy, 2024) and the South African Renewable Energy Masterplan (2024) are recent. The energy sector remains coal-driven, with renewable energy, while increasing in scale, not yet adequately represented (Hanto et al., 2022). The finding concurs with Sutherland's (2020) view that it is neither realistic nor convincing for South Africa to compare itself to other BRICS nations, given the inconsistent policy development of the South African government for instance, in its approach to the role of the private sector. In South Africa, the focus has been on energy security and expanding access to energy resources. This emphasis is due to the state's failures in proper planning and investment, financial challenges, and poor maintenance programmes for existing power plants (Lawrence, 2020; Cotterill, 2023).

5.2.2. Total publications as an indication of Industry 4.0 technology usage in energy production

If the number of publications on the use of particular Industry 4.0 technologies in the energy sector is an indication of the extent of their usage in the sector (Figure 2b, Chapter 2, Bhagwan & Evans, 2023), then the higher number of publications on Big, Real-Time Data, IoT, and AI (with each accounting for 24%), means that these technologies are being used more in energy production globally, compared to Robotics (at 7% of publications) and Machine-Human Integration (a mere 1% of publications). It should be noted that these percentages are based on the number of papers listed in Chapter 2. Also, if the number of publications on Industry 4.0 technologies in the energy production reflects usage of such technologies, then this finding is supported by the survey of energy companies, whereby the use of big, real-time data, and IoT technologies was rated more important regarding their contribution to efficiency, reliability and integration within the company (Tables 4-6, Chapter 3, Bhagwan & Evans, 2022). Nevertheless, it is still worthwhile expanding research in Robotics and Machine-Human Integration, given their potential to boost efficiency and sustainability in the energy sector (Kasza, 2019; Lyu & Liu, 2021; Govender et al., 2021)

It emerged through the company survey and interviews (Chapter 3, Bhagwan & Evans, 2022; Chapter 4, Bhagwan & Evans, 2024) that Industry 4.0 technologies are used along the entire length of the energy value chain, from the extraction of raw materials to producing, distributing, and consuming electricity. That said, there is more focus on Industry 4.0 technologies being used at the beginning and end stages of the energy value chain, in the literature. For instance, intelligent robots enhance the extraction of high-quality raw materials like coal, higher up in the energy value chain (Ge, 2020). Further along the value chain, literature on energy distribution via smart grids remained significant, and improved planning and communication between the grid and users (Jiang et al., 2019; Hao, et al., 2019). Technologies are being used to better manage energy demand and supply through better energy information processing (Wang et al., 2020; Brown et al., 2020), real-time monitoring and control using systems like Supervisory Control and Data Acquisition (Narayan et al., 2019), digital twin technology (Gao et al., 2021), 'source-network-load-storage' coordination optimisation (Lu et al., 2021), simulation technology, and energy forecasting systems (Wang et al., 2021; Wu et al., 2021) The lack of research focusing on the middle parts of the energy value chain warrants attention to determine if such disparities in applying Industry 4.0 technologies are consistent globally and across different energy sectors.

5.2.3. Literature content foci on materials-processing technologies and using Industry 4.0 technologies to promote environmental sustainability

More than half of the Scopus-generated publications looked at using advanced materials-processing technologies to create materials that are more flexible, stretchable, agile, and capable of withstanding harsh environmental conditions (Sun, 2019; Castro-Hermosa, 2021). These are proof-of-concept articles where new and often improved technologies were conceptualised, developed, and tested up to the implementation stage. Some authors investigate energy efficiency in wireless sensors, including triboelectric sensors and nanogenerators in wearable devices and self-powered nano-systems, to enhance human-machine interfaces (Chen, 2017; Choy, 2018; Fan, 2020). Although dielectric elastomer actuators are not directly relevant to energy production, they are used in soft robots and wearable devices to harvest and store ambient energy, making these devices self-powered (Dong, 2021; Neu, 2021; Gao, 2021; Gotz, 2018; Ma, 2019).

Many studies look at Industry 4.0 technology as an avenue for addressing climate change and promoting environmental sustainability (International Energy Agency, 2021; Oláh et al., 2020; Zhang, 2018). The studies emphasise creating efficiencies and reducing production costs, by optimising energy resources for production processes (Weigel, 2019). However, the focus is primarily on environmental impact rather than assessing how and to what extent these technologies influence processes across the entire energy production chain, leaving a gap in the reviewed literature. In other studies, such as that done by Alsaleh and Abdul-Rahim (2021), cost-efficiency forecasting models emphasised the importance of advanced technology in bioenergy production. However, the study offers a broad evaluation of 'information and communication technologies' without specifying the types of technology, particularly those related to Industry 4.0. It does not detail where these technologies are used in energy production chains or assess their impact on firm-based energy production by measuring actual productivity at energy plants.

5.2.4. The impact of empirical research gaps on using Industry 4.0 technologies in the energy sector

This study shows that, although firm-specific empirical research in South Africa is valuable, it remains limited, particularly concerning the impact of Industry 4.0 technologies on energy production, plant productivity, and revenue. More research drawing on empirical, firm-level data would enhance understanding of the sector's adaptation to the Fourth Industrial Revolution and its ongoing crisis, revealing how these technologies can improve energy productivity and efficiency. Without baseline data demonstrating the positive impact of Industry 4.0 technologies on energy production, energy companies will likely remain hesitant about investing in these technologies. This review aligns with the perspective of Massel (2018), as cited by Alekseev et al. (2019), highlighting a shortage of scientific research due to limited and inconsistent data collection on digitisation in the energy sector. Limiting research to a materials approach does not help measure the impact of Industry 4.0 technologies on energy production and other parts of the energy value chain. Similar sentiments are shared by authors such as Weigel et al., (2019) in their findings on the Russian energy sector. According to these authors, Russia’s energy sector also experiences scientific and technological constraints, including a lack of research and experimental development in digital energy, a limited number of digital devices at power facilities, and the absence of a standardised methodology for evaluating the impact of implementing digital energy elements, among other factors. The findings will inform evidence-based policies to expand Industry 4.0 technologies to build an efficient and sustainable energy sector in South Africa.

5.3. Comparing and contrasting the importance and use of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa

The global importance of Industry 4.0 technologies was clearly emphasised amongst all survey respondents, with 73% describing these technologies as very important, 23% as important and only 4% as somewhat important (Figure 2, Chapter 3, Bhagwan & Evans, 2022). Secondly, considered most important, were technologies providing access to big, real-time data, likely influenced by the sector's widespread use of drones, AUVs, and ROVs. In contrast, Robotics and Machine-Human Integration were considered the least important to the global energy sector (Table 2, Chapter 3, Bhagwan & Evans, 2022). Most companies (85%) felt connected to Industry 4.0 and were confident about such participation (Figure 3, Chapter 3, Bhagwan & Evans, 2022). Companies were questioned about their perceived importance of Industry 4.0 technologies in relation to their level reliability, efficiency, and integration. In Table 4 (Chapter 3, Bhagwan & Evans, 2022), surveyed firms identified technologies that provide access to and analysis of big, real-time data as the most important for use in the global energy sector and at the local company level. In contrast, Machine-Human Integration technologies were deemed the least important for energy production and distribution, followed by Robotics. Regarding efficiency, reliability, and integration across the energy system (represented by Tables 5-7, Chapter 3, Bhagwan & Evans, 2022), technologies that enable access to big, real-time data and the processing and analysis of such data were highly valued. The Internet of Things was ranked the third most important Industry 4.0 technology because it allows real-time data gathering, storage and transmission to multiple devices. In contrast, Artificial Intelligence and Machine-Human Integration were considered much less reliable, efficient, and integrated within the surveyed firms. However, using Kruskal-Wallis and Mann-Whitney tests, country-specific differences in the survey data emerged, with China valuing the importance of Industry 4.0 technologies to the global energy system and within their energy companies much higher than both South Africa and Germany (Table 8-1, Chapter 3, Bhagwan & Evans, 2022). The views of the companies interviewed are representative of China’s national commitment to integrate Industry 4.0 technologies across the energy value chain, driven centrally, but carried out by SOEs, as stated in key policy documents on energy, such as White Paper on Energy in China's

New Era and its 2024 Energy Transition Strategy (The State Council of China, 2020; The State Council of China, 2024).

After rating their company's involvement in Industry 4.0, survey respondents were asked to describe the usage of 4IR technologies within their respective companies. Company respondents named these technologies differently, some using generic 4IR technology categories and others using actual technology names. Nevertheless, some clear trends emerged (Bhagwan & Evans, 2022, pp. 7-8). Firstly, most companies (more than 50%) utilised 4IR technologies to remotely collect and access plant data through drones and the Internet of Things, followed by its analysis using various data management systems, in other words, technologies for collecting big data, transmitting this data, and conducting an analysis of such data. Seven of the 22 (less than a third) referenced technologies may be categorised as Artificial Intelligence, one of which involved a Chinese company using Artificial Intelligence for algorithmic trading and two German companies using Artificial Intelligence to run virtual energy plants. These systems allowed computers to perform complex online electricity trading activities faster using live energy market data, all without human intervention (Bhagwan & Evans, 2022, p. 8). Only two firms (under 10%), one Chinese and the other German, reported using Robotics. Only one company reported on using Machine-Human Integration. It's important to acknowledge that South African companies surveyed used neither Robotics nor Machine-Human Integration. Survey respondents further indicated that most of these technologies originated in the United States, Europe (mainly Germany), and China. However, the German and Chinese companies interviewed reported that they were not involved in producing and developing these technologies (Bhagwan & Evans, 2022, p. 8). Through interviews with energy companies, in the next part of this PhD study, it became apparent that Chinese and German companies (particularly large mobile companies) are leading the way in Industry 4.0 technology development (Table 6 & Table 10, Bhagwan & Evans, 2024). This finding makes more sense because China now has the world's largest number of renewable energy patents (World Intellectual Property Organization, 2021, as cited by Bhagwan and Evans, 2024).

Regardless of whether they were producing energy or developing software programmes and technologies, all the companies interviewed and studied depended on the ability to collect big data in real time (Tables 2, 6 & 10, Chapter 4, Bhagwan & Evans, 2024). This data collection was facilitated by sensors and actuators used at the energy plants and transmitted to multiple computer networks and servers. However, the methods of data analysis and usage varied. In South African companies, engineers or IT personnel conducted the data analysis using computer software programs for modelling and forecasting, with no Artificial Intelligence incorporated into the software. Although a new Energy Management and Data Acquisition System (EMDAS) may change this through the integration of Artificial Intelligence capability (SAC2, Chapter 4, Bhagwan & Evans, 2024), industry expert interviews (EXP14, Chapter 4, Bhagwan & Evans, 2024) indicate that experimentation with Artificial Intelligence in the South African energy sector is still in its early stages, primarily occurring within research labs and 4IR centres. As one of the fastest-growing sub-sectors of the high-tech industry, a survey by Deutsche Energie Agentur (DENA) in 2019 suggests that 74% of respondents believe that the energy transition in Germany will benefit positively from Artificial Intelligence. Germany has also positioned Artificial Intelligence at the centre of various policy platforms (DENA, 2019). Similarly, interviews with Chinese energy and technology companies showed that these companies are using and developing Artificial Intelligence, the Internet of Things, and Robotics technologies in renewables and non-renewables (especially coal) (Chapter 4, Bhagwan & Evans, 2024). Artificial Intelligence is improving efficiency in operations within the energy production, distribution, and consumption pipeline, as part predictive maintenance solutions, demand and supply forecasting, and smart grid management systems (Li & Zhang, 2024), and facilitating China's transition to renewables (Zhang et al., 2024).

The data collected indicated that the reasons for limited adoption were not due to a lack of awareness of Industry 4.0 technologies but rather because the technologies were considered too expensive (Bhagwan & Evans, 2022, p. 6). Furthermore, Chang et al., (2021) explain that there remains a limited understanding of Industry 4.0 and its effects on the energy sector because the changes brought about by the Fourth Industrial Revolution have coincided with an array of global, environmental and societal challenges including food insecurities, environmental degradation, climate change and other conflicts.

5.4. To establish the extent to which the level of uptake of such technologies could exacerbate challenges facing the South African energy sector

5.4.1. The role of Industry 4.0 technologies in the energy sectors of South Africa, Germany, and China, based on how these technologies are being used and their value-add

South African, Chinese, and German companies interviewed (Chapter 4, Bhagwan & Evans, 2024) all used Industry 4.0 technologies, be it collecting and analysing vast amounts of real-time data, connecting machines and devices through the Internet of Things that produce streams of data, using Artificial Intelligence for forecasting, or improving plant processes using Robotics. This study shows, however, that the extent to which these technologies are used differs in the energy sectors of the 3 countries. In South Africa, usage of 4IR technologies was skewed towards access to and analysis of big, real-time data, the Internet of Things to optimise the functioning of energy plants by reducing maintenance and operational costs, improving efficiency, reliability, and sustainability at energy plants, ultimately boosting productivity (Chapter 4, Bhagwan & Evans, 2024). This is mirrored in the research foci of the energy sector on these technologies (Chapter 2, Bhagwan & Evans, 2023). Robotics and Machine-Human Integration were considered far less reliable and efficient amongst both survey and interview participants (Chapter 3, Bhagwan & Evans, 2022; Chapter 4, Bhagwan & Evans, 2024). In contrast with German and Chinese companies interviewed, South African companies interviewed expressed that while 4IR technologies were not new or novel, they were used to improve the functioning of existing technologies through being “smarter and faster with more computing ability” (CHC5, Table 2, Chapter 4, Bhagwan & Evans, 2024). In the words of a South African technology company, Industry 4.0 technologies help with “the optimisation of the same processes but using a connected architecture, where 4IR technologies help energy plants move from the actual to the ideal scenario” (Table 4, Chapter 4, Bhagwan & Evans, 2024).

Given that coal mining remains a significant component of China's energy production system (International Energy Agency, 2021), the focus on enhancing worker safety by integrating Artificial Intelligence and Robotics is paramount. This integration has resulted in safer working conditions and higher worker satisfaction. Additionally, Artificial Intelligence is employed as a proactive tool for energy solutions, optimising production processes to reduce emissions and improve plant operational efficiency (Chapter 4, Bhagwan & Evans, 2024). In China, the use of 4IR technologies is defined in terms of a growth-oriented mindset. It is understood in the context of a larger socioeconomic paradigm, such as "the progress of human civilisation" and promoting an "energy production and consumption revolution" (CHC6, Chapter 4, Bhagwan & Evans, 2024). For Chinese companies, advanced 4IR energy technologies are deeply integrated into supporting the "clean and low-carbon transformation," a crucial contributor to upgrading the sector (CHC5, Chapter 4, Bhagwan & Evans, 2024). These conceptualisations explain why Chinese companies place more value than South Africa and Germany on Industry 4.0 technologies in the energy sector (Chapter 3, Bhagwan & Evans, 2022) and why the country produces such a high number of publications on this topic (Chapter 4, Bhagwan & Evans, 2024). Placing Industry 4.0 technologies within a growth-orientated mindset, is aligned to China's bigger, national agenda to prioritise innovation-driven development, within strategic sectors of importance such as energy, to increase its capacity for scientific and technological innovation and address major environmental issues and challenges (The State Council of China, 2020; The State Council of China, 2024).

German energy companies similarly acknowledged the importance of artificial intelligence, the Internet of Things, and big data in the energy sector. After all, the Internet of Things-connected components are considered "easier to understand and control, or they control themselves." and can "regulate themselves in the event of problems" (GEC10, Chapter 4, Bhagwan & Evans, 2024). The application of Big Data and the Internet of Things technologies has significantly promoted the large-scale integration of renewable energy in Germany. These advancements have also extended the lifespan of underground power cables, enhanced energy transmission and redistribution, and facilitated better grid management. Additionally, the improved transparency provided by these technologies has greatly enhanced the functioning of Germany's highly decentralised energy sector and has facilitated cross-commodity energy sharing amongst local communities (Burger, & Weinmann, 2013; Beermann & Tews, 2017). According to the operator of one of the largest virtual power plants in Europe, in Germany, Artificial Intelligence is considered "a key strategy to master some of the greatest challenges of our time, such as climate and environmental protection" (GEC8, Chapter 4, Bhagwan & Evans, 2024). German companies place 4IR technologies at the core of their integrated energy transition, with artificial intelligence representing an "opportunity to technologically master the complexity of a decentralised and integrated energy transition" (DENA, German Energy Agency, 2024).

5.4.2. Challenges in implementing Industry 4.0 technologies in the South African, German, and Chinese energy sectors

In contrast to Germany, where a competitive, decentralised energy market and supportive Energiewende policies drive technology adoption (Kuittinen et al., 2018; German Federal Ministry for Economic Affairs and Energy, 2020), or China, which uses a more centralised energy model to drive innovation in energy technologies (Lo & Mah, 2024; Yan et al., 2024), South Africa's government and the public utility are less proactive in implementing these innovations. Some experts believe that "the public sector in South Africa is not ready to exploit 4IR technologies" fully (EXP12, Chapter 4, Bhagwan & Evans, 2024). Policy dissonance has characterised the South African energy sector, driven by a number of factors.

- Firstly, experts note that South Africa faces significant challenges in transitioning from coal to renewables due to complex policies and coal dependency issues, which impact infrastructure planning and contribute to power shortages (Presidential Commission on the Fourth Industrial Revolution, 2020). There has been a publicly visible tension between the Department of Mineral and Petroleum Resources and the recently formed Department of Electricity and Energy about the continuing dominance of a coal-based production future (The Africa Report, 2021; https://www.miningmx.com/news/energy/57440-ramokgopa-to-speed-shift-from-coal-to-renewables/, 2024).
- Secondly, this industry sector has been mired in high levels of corruption and state capture which produced a preferred option for coal against the expansion of state investment in alternative energy. The impact of state capture and other sustained large-

scale corruption activities has been debilitating (Cotterill, 2023; Cohen, 2023; Rose, 2024).

- Thirdly, the state's poor management of infrastructure over three decades has resulted in high levels of dysfunctionality producing the crisis of what is euphemistically known as load-shedding. While this has partly to do with what has been a stagnant economy since the economic crisis of 2008-2009, it is also a sign of dysfunctional governance (Bhorat et al., 2017; Baker and Phillips, 2019; Lawrence, 2020).
- Fourthly, even as the state began to pivot towards decentralised power plants the levels of bureaucracy and patronage debilitated the potential of this shift (African Development Bank, 2019). The decision to remove the licensing cap threshold which was set at 100MW produced significant private-sector investment in production.
- Fifthly, has been a dismal failure of leadership and management both at the governmental level and at the level of the state-owned enterprise to produce a clearly shaped plan for the transition. This is aptly described by Lawrence (2020) as the result of local policymakers' reluctance to embrace a rapid transition to renewable energy generation, which stems not only from a lack of understanding of its immediate and long-term benefits but also from their prolonged resistance to this option.
- Sixthly, the interviews in this study of South African companies and energy experts show that the role of Industry 4.0 technologies has not been envisaged as something to be interwoven into the fabric of the industry sector, resulting in its piecemeal deployment. In South Africa, company representatives and experts interviewed explained that the adoption of Industry 4.0 technologies in the energy sector is hindered by excessive costs and a lack of political will, and not by inadequacies in engineering and technological skills (Chapter 4, Bhagwan & Evans, 2024).

The Presidential Commission on 4IR addresses some of these challenges but whether it translates into a much more coherent policy infrastructure remains to be seen (Presidential Commission on the Fourth Industrial Revolution, 2020).

Regarding China and Germany, as was pointed out in Chapter 1 and Chapter 4, the role of the Industry 4.0 technologies in the energy sector are driven by well-defined policy frameworks for the future of the energy sector and of their importance to society. Germany's energy system is highly decentralised, it uses Industry 4.0 technologies to produce an integrated system, still a project in motion. It is a bottom-up approach with many thousands of producers Burger & Weinmann, 2013; Beermann & Tews, 2017). On the other hand, China has a very centralised system, and it uses Industry 4.0 technologies to ensure that that top-down approach meets the needs of its society (Lo & Mah, 2024; Lees & Chen, 2016). There are other challenges that face China and Germany. For example, there are difficulties experienced with standardising these technologies or products due to inadequate industry planning and standards linked to 4IR technologies in the sector. Inadequate empirical scientific research on digitalisation in the energy sector, which Massel (2018) and Alekseev et al., (2019) attribute to limited and inconsistent data collection, has also hindered the implementation of Industry 4.0 technologies in Germany and China. Without baseline, empirical data demonstrating the positive impact of Industry 4.0 technologies in energy production, energy companies across South Africa, Germany, and China will remain cautious about investing in these technologies.

Notwithstanding the fact that some progress has been made in terms of the Presidential Commission on 4IR, the absence of a coherent, national policy plan for South Africa's energy industry and, in particular, a vision for the strategic adoption of Industry 4.0 technologies may lead to the danger of their piecemeal use. This also places the energy sector at risk, and at the mercy of the energy companies that do work for Eskom, further fragmenting the sector.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1. Introduction

Across the globe, a shift towards adopting new technologies can be observed in most sectors. This includes advancements in Artificial Intelligence, Robotics, Machine-Human Integration, the Internet of Things, and the ability to access and analyse Big, Real-Time Data. The energy sector is no exception to this trend. As an industrial powerhouse in Africa, South Africa relies on energy efficiency to drive economic development. It aims to make energy more sustainable by ensuring it is accessible, reliable, and minimally harmful to the environment. Nevertheless, South Africa’s progress in increasing the share of renewable energy within its electricity generation programme has been slow. It was also uncertain whether these technologies are being used in South Africa and, if so, to what extent they are being used to improve efficiency and sustainability across the energy sector. The rationale for this study was grounded in the global energy crisis, coinciding with the world’s strong push into Industry 4.0, to assess the extent of Industry 4.0 technology adoption in South Africa's energy sector as a means to enhance efficiency and sustainability. The sophisticated technologies that have emerged in this era may offer solutions to the energy crisis. However, it was essential to understand if and how these technologies are being adopted within the energy value chain and whether they are helping to create a more effective energy system. Germany and China are at the forefront of transforming their energy sectors. Considering South Africa’s own energy crisis, it was crucial to determine how its energy sector compares to those of countries already making ground in the Industry 4.0 energy space. This study's findings could potentially significantly impact the energy sector, providing valuable insights into the adoption and effectiveness of Industry 4.0 technologies.

This PhD study aimed to determine the extent of the uptake of Industry 4.0 technologies by the South African energy sector, how such usage compares to China and Germany, and whether the nature of their uptake of in South Africa could exacerbate challenges facing the sector.

Chapter 6 presents a synthesis of the key findings of this PhD study, originating from the literature review in Chapter 2, the survey paper in Chapter 3, and the interview paper in Chapter 4. It is organised around the three research objectives. The study's limitations are described, followed by a set of recommendations for future research.

6.2. Key Findings

6.2.1. Research gaps related to the deployment of Industry 4.0 technologies in the energy sectors of Germany, China and South Africa

As explained in Chapter 2, a literature review was carried out using a Scopus search from 2018 to 2022 as the reference point. Beginning at a broader, global level, publications on using Industry 4.0 technologies across the subjects of engineering, computer science and energy were identified. The search was then tightened to the five categories of Industry 4.0 technologies applied in this study (Big, Real-Time Data and data analysis, the Internet of Things, Artificial Intelligence, Robotics, and Machine-Human Integration) in the energy sector, and finally, only for energy production. First, data was gathered for nine countries, based on their economic status, including China, Germany, South Africa, the United States, Brazil, Russia, India, Mexico, and Nigeria. Next, this was narrowed down to South Africa, China, and Germany, the countries selected for this PhD study.

Key findings emerged from this review of the literature. First and foremost, research on the impact of Industry 4.0 technologies on the energy sector, and especially energy production, is limited. Second, emerging economies such as South Africa, Nigeria, Brazil, and Mexico lag developed nations such as the United States and Germany and newly industrialised countries, particularly China and Russia, in the number of publications on the deployment of Industry 4.0 technologies in the energy sector. South Africa performed poorly, compared to the number of publications produced by other BRICS countries. Germany is spearheading the integration of Industry 4.0 technology across various sectors via its "Energiewende" initiative, even though it produces fewer publications than China. Meanwhile, under its "Made in China 2025" strategy, China has actively promoted and incentivised research, innovation in the energy sector, and the local production of Industry 4.0 technologies.

If the volume of publications on specific Industry 4.0 technologies in the energy sector serves as a measure of their adoption (Chapter 2, Bhagwan & Evans, 2023), then the greater number of studies focused on Big Data, Real-Time Data, IoT, and AI—each representing 24%—suggests that these technologies are more widely utilized in global energy production. In contrast, Robotics, which accounts for only 7% of publications, and Machine-Human Integration, with just 1%, appear to have a significantly lower level of adoption. At the level of impact, empirical data on using Industry 4.0 technologies in energy production was scant, particularly regarding their contribution to increased productivity at energy plants.

6.2.2. Comparing and contrasting the importance and use of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa

Research objective 2, incorporated into Chapter 3 of this thesis, was about comparing and contrasting the use of Industry 4.0 technologies within the German, South African, and Chinese energy sectors. To meet this objective, an online survey was administered to 26 companies operating in the energy sector across the three countries. Quantitative analysis using Cronbach Alpha, Kruskal-Wallis and Mann-Whitney testing produced interesting results, the first focusing on understanding how these companies conceptualised Industry 4.0. A consensus was reached on defining Industry 4.0 and its relevance to the energy sector. Definitions encompassed the interactions between humans and machines to enhance industrial productivity, the creation of technology for global connectivity, the development and application of Artificial Intelligence in industry, and the innovation of new technologies to improve efficiencies. After defining Industry 4.0, companies were requested to assess their role within Industry 4.0. Most of these energy companies (85%) perceived themselves as playing a significant role in the Fourth Industrial Revolution. The survey proceeded to interrogate the value placed on these technologies by Chinese, German, and South African energy firms according to their perceived impact on local and global energy sectors. A key finding was that Chinese companies placed more value on the importance of Industry 4.0 technologies in energy than Germany and South Africa.

Regarding technology types, surveyed firms highlighted technologies enabling access to and analysis of Big, Real-Time Data as the most crucial for the global energy sector and local company operations. Conversely, Machine-Human Integration technologies were deemed the least important, with robotics closely behind. At the country level, South African energy companies were found to be integrating technologies for accessing and analysing Big, Real-Time Data, but not those using Artificial Intelligence, Robotics, and Machine-Human Integration. For efficiency, reliability, and seamless integration across the energy system, technologies that enabled access to Big, Real-Time Data and its processing and analysis were highly valued across China, Germany, and South Africa. The Internet of Things was ranked as the third most important 4IR technology, as it facilitated the storage and transmission of data to multiple devices in real time. In contrast, Artificial Intelligence and Machine-Human Integration were considered less reliable, less efficient, and less integrated, by all surveyed firms.

6.2.3. To establish the extent to which the level of uptake of such technologies could exacerbate the challenges facing the South African energy sector

Chapter 4 of this PhD study centred on fulfilling the third research objective, the focus of which was to ascertain the extent to which Chinese, German, and South African energy companies leverage Industry 4.0 technologies to create efficiencies for energy production. For this qualitative component of the PhD study, interviews were held with representatives from 10 South African, Chinese, and German energy producers and technology companies, as well as with six experts in the energy field in South Africa. The interviews investigated views on Industry 4.0 technologies, examined the categories utilised or developed, assessed the added value created, and identified challenges in accessing and implementing the technology. A thematic analysis guided by predetermined themes was then applied. Several key findings transpired. Technologies enabling access to, and analysis of big, real-time data and the Internet of Things are all being leveraged by South African, German, and Chinese energy companies. Moreover, these technologies are helping to enhance efficiency and reliability within energy production, by reducing plant running costs through predictive maintenance and reduced downtime.

Artificial intelligence is far more prominent among German and Chinese energy companies. The uptake has largely been used for Chinese companies to enhance plant operations and safety, and to better manage demand and supply across the energy system. Germany uses artificial intelligence for smart grids, coordinating local, decentralised energy sources efficiently. South African companies are not using artificial intelligence in energy production. Surprisingly, South African experts see the use of Industry 4.0 technologies as an enhancement of existing technologies rather than as being novel and transformative. South African energy companies encounter barriers such as inflated costs and political challenges, most evidently a lack of political will to drive the implementation of Industry 4.0 technologies, which impedes the widespread adoption of 4IR technologies. In contrast, China and Germany primarily deal with issues related to industry standards in advancing these technologies.

As highlighted in Chapters 1 and 4, the adoption of Industry 4.0 technologies in the energy sectors of China and Germany is guided by well-structured policy frameworks that outline the future of the industry and emphasize its significance to society. Germany's energy system is highly decentralized and leverages Industry 4.0 technologies to create an integrated production system. This remains a work in progress. This system follows a bottom-up approach, involving thousands of individual producers. China operates a more centralized energy system, utilizing Industry 4.0 technologies to ensure its top-down approach effectively addresses the needs of society. Both countries are using Industry 4.0 technologies to manage their energy resources more effectively and meet renewable energy targets. South Africa, on the other hand, is caught between the tensions surrounding the need to move away from coal-based power plants, in favour of renewables, the dysfunctionality of an energy system torn apart by mismanagement, corruption, and state capture, both within the government and state-owned enterprises, resulting in the absence of a well-defined energy transition plan. Notwithstanding the progress made through the work of the Presidential Commission on 4IR, what is urgent is the creating of a strategic roadmap for the adoption of Industry 4.0 technologies across the energy sector. Failure to achieve this, risks further fragmentation of the sector.

6.3. Study limitations

The timing of this study coincided with the COVID-19 pandemic, which created a set of unique challenges. Country-wide lockdowns and the economic hardships that ensued made access to energy and technology companies difficult, reducing the anticipated survey and interview sample size, although still producing statistically significant results. The Chinese embassy in Johannesburg assisted with contacting their constituencies and distributing the online survey. There were also delays in securing researchers fluent in Mandarin and German to translate the research instruments into these languages, conduct the survey and interviews amongst Chinese and German energy and technology companies, and then translate these transcripts back into English. Language barriers were also noticeable with some national policy documents, with most Chinese documents not available in English. In such cases, other academic references citing these sources were used. Given their complexity, policies such as the Made in China 2025 strategy and China's five-year energy plan were not conducive to Google Translate tools.

The literature review study contained in Chapter 2 uses percentages of keyword occurrences within a Scopus search, for the years 2018 to 2022, to argue the perceived importance of 4IR technologies implemented across the energy sectors of South Africa, Germany, and China. While this is seen as a limitation, the percentages are based on the count of the number of papers listed in Chapter 2. Whilst it is accepted that frequency of mention does not necessarily indicate significance of Industry 4.0 technology usage, it does suggest interest in such technologies, be it on the part of individual, self-funded research or large, state-level or company-financed research. This is the first step towards recognising differences in the perceived importance and value of these technologies within South Africa, and in countries such as China and Germany who are promoting Industry 4.0 technologies across their energy sectors.

While the literature review looked at the use of Industry 4.0 technologies on all aspects of the energy industry, this study focused primarily on the production side. The decision to study energy production and how this is affected by Industry 4.0 technologies, was informed by the apparent gap in the literature in this part of the energy value chain. Further investigation of the usage and impact of Industry 4.0 technologies across the energy pipeline is important.

6.4. Recommendations

It is recommended that South Africa engage with and embrace Industry 4.0 technologies to a greater extent to remain competitive in the global energy sector. Research reflected in this paper indicates that South African companies value 4IR technologies as tools to enhance efficiency, reliability, and integration within energy production and distribution systems. A higher value is placed on access to and analysis of Big, Real-Time Data and the Internet of Things. However, survey results show that other Industry 4.0 technologies are not widely applied in the South African energy sector. This is despite literature suggesting significant potential for Artificial Intelligence, Robotics, and Machine- Human Integration to advance the energy sector.

It is recommended that the adoption of Industry 4.0 technologies be led by a national policy process that adopts a systemic approach to avoid their piecemeal, truncated use which could in the long-term lead to higher levels of fragmentation. While this study focused on the production side, it would be important that this policy process covers all aspects of the value: production, transmission and consumption.

Over the past decade, energy research in South Africa has predominantly focused on expanding Eskom's capacity. However, research needs to expand into how Industry 4.0 technologies may be leveraged at different parts of the production, distribution and consumption systems to boost efficiency, reliability, and integration. Countries such as China and Germany, which are already effectively utilising these technologies, offer valuable lessons.

Empirical data on the impact of Industry 4.0 technologies in energy production, particularly their contribution to increasing productivity at energy plants, and improving grid distribution, remains limited. Collecting this data could involve various indicators, such as measuring costs beyond maintenance, the time required to implement new technologies, productivity changes based on optimal production quantity and quality, the ability to use Industry 4.0 technologies for simulating and forecasting changing conditions, and the subsequent adaptation using these technologies, as well as the returns on technology investment.

REFERENCES

The Africa Report. (2021, October 26). South Africa: Gwede Mantashe not a 'fossil fuel dinosaur' but 'King Coal'. The Africa Report. https://www.theafricareport.com/363754/south-africa-gwede-mantashe-not-a-fossil-fuel-dinosaur-but-king-coal/

African Development Bank. (2019). Unlocking the potential of the Fourth Industrial Revolution in South Africa: Country case study. African Development Bank. https://4irpotential.afdb.org/

Ahmad, T., Zhang, D., Huang, C., Zhang, H., Dai, N., Song, Y., et al., (2021). Artificial intelligence in sustainable energy industry: Status quo, challenges and opportunities. Journal of Cleaner Production, 289. Elsevier Ltd

Ahmed, K & Khan, B. (2024). China's post-pandemic energy rebound and climate targets under the current regulations and green innovation capacity, Energy, Volume 302, 2024,131829, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2024.131829. https://www.sciencedirect.com/science/article/pii/S0360544224016025

Alekseev, A. N., Lobova, S. V., Bogoviz, A. V., & Ragulina, Y. V. (2019). Digitalization of the Russian energy sector: State-of-the-art and potential for future research. International Journal of Energy Economics and Policy, 9(5), 274-280

Alsaleh, M., & Abdul-Rahim, A. S. (2021). The pathway toward bioenergy growth: Does information and communication technology development make a difference in EU economies? Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-021- 01933-9

Alsaleh, M., & Rahim, A. S. (2019). Cost efficiency of bioenergy industry and its economic determinants in EU-28: A tobit model based on DEA efficiency scores. International Journal of Management and Sustainability, 8(2), 79-87

AlSkaif, T., Lampropoulos, I., van den Broek, M., & van Sark, W. (2018). Gamification- based framework for engagement of residential customers in energy applications. Energy Research & Social Science, 44, 187-195. Elsevier

Ardito, L., Petruzzelli, A. M., Panniello, U., & Garavelli, A. C. (2019). Towards Industry 4.0: Mapping digital technologies for supply chain management–marketing integration. Business Process Management Journal, 25(2), 323–346. https://doi.org/10.1108/BPMJ-04-2017-0088

Aspen Institute. (2019). Future of Work Initiative State Policy Agenda. Aspen Institute Future of Work Initiative. Washington, DC

B. Smith (Eds.), Reaching Net Zero (pp. 9-17). Elsevier. https://doi.org/10.1016/B978-0- 12-823366-5.00002-6

Baker and Phillips. (2019). Tensions in the transition: The politics of electricity distribution in South Africa. Environment and Planning C: Politics and Space 2019, Vol. 37(1) 177–196. DOI: 10.1177/2399654418778590 Accessed: December 8th, 2024. Available at: https://oro.open.ac.uk/94337/1/94337.pdf

Bamati, N., & Raoofi, A. (2020). Development level and the impact of technological factors on renewable energy production. Renewable Energy, 151, 946–955

Beebe, J. (1995). Basic concepts and techniques of rapid appraisal. Human Organization, 54(1), 42–51

Beermann, J., & Tews, K. (2017). Decentralised laboratories in the German energy transition: Why local renewable energy initiatives must reinvent themselves. Journal of Cleaner Production, 169, 125–134. https://doi.org/10.1016/j.jclepro.2016.08.130

Beier, G., Niehoff, S., Ziems, T., & Xue, B. (2017). Sustainability aspects of a digitalized industry – A comparative study from China and Germany. International Journal of Precision Engineering and Manufacturing-Green Technology, 4(2), 227-234

Bhagwan, N., & Evans, M. (2022). A comparative analysis of the application of Fourth Industrial Revolution technologies in the energy sector: A case study of South Africa, Germany, and China. Journal of Energy in Southern Africa, 33(2)

Bhagwan, N., & Evans, M. (2023). A review of Industry 4.0 technologies used in the production of energy in China, Germany, and South Africa. Renewable and Sustainable Energy Reviews, 173, 113075. https://doi.org/10.1016/j.rser.2022.113075

Bhagwan, N. and Evans, M. 2024. Understanding the contribution of Industry 4.0 technologies to Chinese, German, and South African energy companies. Submitted to Renewable and Sustainable Energy Reviews on July 19th, 2023. (under review)

Bhorat, H., Buthelezi, M., Chipkin, I., Duma, S., Mondi, L., Peter, C., Qobo, M., Swilling, M., & Friedenstein, H. (2017). Betrayal of the Promise: How South Africa Is Being Stolen. Johannesburg: Public Affairs Research Institute (PARI)

Blondeel, M., Bradshaw, M. J., Bridge, G., & Kuzemko, C. (2021). The geopolitics of energy system transformation: A review. Geography Compass, e12580. https://doi.org/10.1111/gec3.12580

Braun, V. & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), pp.77–101

Borowski, P. F. (2021). The role of digital technologies in the development of renewable energy: A review. Energies, 14(9), 2358. https://doi.org/10.3390/en14092358

Boudet, H. S. (2019). Public perceptions of and responses to new energy technologies. Nature Energy, 4, 446-455. https://doi.org/10.1038/s41560-019-0399-x

Brown, G., Ventura, N., & Mwangama, J. (2020, January). A software defined approach for improving resilience in smart distribution grids. In 2020 International SAUPEC/RobMech/PRASA Conference (pp. 1-6). IEEE

Bruland, K. (2004). Industrialisation and technological change. In R. Floud & P. Johnson (Eds.), The Cambridge Economic History of Modern Britain (pp. 117–146). Cambridge University Press

Burger, C., & Weinmann, J. (2013). The Decentralized Energy Revolution: Business Strategies for a New Paradigm. Palgrave Macmillan. ISBN: 978-1-137-27069-6

Burger, C., Froggatt, A., Mitchell, C., & Weinmann, J. (2020). Decentralised energy – A global game changer. Ubiquity Press. London

Castro-Hermosa, S. (2020). Perovskite photovoltaics on roll-to-roll coated ultra-thin glass as flexible high-efficiency indoor power generators. Cell Reports Physical Science, 1(5)

Centre for Economics and Business Research. (2017). Impact of automation: A report for Redwood Software [Internet]. Melbourne. Available from: https://apo.org.au/node/218266

Chang, V., Chen, Y., Zhang, Z. (J.), Xu, Q. A., Baudier, P., & Liu, B. S. C. (2021). The market challenge of wind turbine industry-renewable energy in PR China and Germany. Technological Forecasting and Social Change, 166, 120631 https://doi.org/10.1016/j.techfore.2021.120631

Chen, H.-Q., Wang, X., He, L., Chen, P., Wan, Y., Yang, L., & Jiang, S. (2016). Chinese energy and fuels research priorities and trend: A bibliometric analysis. Renewable and Sustainable Energy Reviews, 58, 966-975. https://doi.org/10.1016/j.rser.2015.12.239

Chen, C., Wang, J., Qiu, F., & Zhao, D. (2016). Resilient distribution system by microgrids formation after natural disasters. IEEE Transactions on Smart Grid, 7(2), 958-966

Chen, J. (2017). Reviving vibration energy harvesting and self-powered sensing by a triboelectric nanogenerator. Joule, 6(38), 480-521

Cheng, G., Zhao, C., Iqbal, N., Gülmez, O., Işık, H., & Kirikkaleli, D. (2021). Does energy productivity and public-private investment in energy achieve the carbon neutrality target of China? Journal of Environmental Management, 298

Choy, T. H. (2018). Enhanced output power of a freestanding ball-based triboelectric generator through the electrophorus effect. Journal of Materials Chemistry A, 6(38), 18518-18524

Cohen, M. (2023). Why South Africa is mired in an electricity crisis: QuickTake. Bloomberg. Retrieved from https://www.bloomberg.com/news/articles/2023-12-13/why- south-africa-is-mired-in-an-electricity-crisis-quicktake?embedded-checkout=true

Cotterill, J. (2023, April 5). South Africa backtracks on Eskom state of disaster. Financial Times. Accessed on 21 June 2024

Crafts, N. F. R. (1996). The first industrial revolution: A guided tour for growth economists. The American Economic Review, 86(2), 197-201

Creswell, J. W., & Plano Clark, V. L. (2018). Designing and Conducting Mixed Methods Research (3rd ed.). Thousand Oaks, CA: SAGE

Creswell, J.W. (2014). Research design: Qualitative, quantitative, and mixed methods approaches. 4th ed. Thousand Oaks, CA: Sage Publications

CSIR.(2025).https://www.csir.co.za/development-power-system-operator-model-short-term-variable-renewable-energy-forecasting. Accessed: January 3, 2025

Cui, Y. (2020). Research of ubiquitous power Internet of Things security authentication method based on CPK and RFID. In 2020 IEEE 4th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC) (pp. 1-6). Chongqing: IEEE

Deane, P. (1965). The First Industrial Revolution. Cambridge University Press

Deutsche Energie-Agentur (DENA: German Energy Agency). (2019). Survey: Artificial Intelligence in the energy industry. Berlin: Deutsche Energie-Agentur. Available at: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9237_Survey_Artificial_Intelligence_in_the_energy_industry.pdf Downloaded on 17 August 2023

Deutsche Energie-Agentur (DENA: German Energy Agency). (2024). Project EnerKI – UsingAI to optimise the energy system. Available at: https://www.dena.de/en/topics/projects/project-enerki-using-ai-to-optimise-the-energy- system/
Downloaded on 29 June 2024

Dong, B. (2021). Technology evolution from self-powered sensors to AIoT-enabled smart homes. Nano Energy, 79, 105414

Dong, F., Zhang, S., Zhu, J., & Sun, J. (2021). The impact of the integrated development of AI and energy industry on regional energy industry: A case of China. International Journal of Environmental Research and Public Health, 18(17)

Doyle, L., Brady, A.-M., & Byrne, G. (2009). An overview of mixed methods research. Journal of Research in Nursing, 14(2), 175–185. https://doi.org/10.1177/1744987108093962

Energize. September 4, 2023. Vodacom, Eskom sign historic first virtual wheeling agreement. https://www.energize.co.za/article/vodacom-eskom-sign-historic-first-virtual-wheeling-agreement

Energy and Water Sector Education and Training Authority. (2021). Sector skills plan. 2022-2023.

Energy Foundation China. (2022, September 5). The plan targets a 50% reduction in China's incremental electricity and energy. Available at: https://www.efchina.org/Blog- en/blog-20220905

Energy Newsletter. January 25, (2024). Vodacom's independent power plans taking shape. Available at: https://mybroadband.co.za/news/energy/522851-vodacoms-independent-power-plans-taking-shape.html

Engineering News. August 30, (2023). Vodacom, Eskom sign historic first virtual wheeling agreement. Available at: https://www.engineeringnews.co.za/article/vodacom-eskom-sign-historic-first-virtual-wheeling-agreement-2023-08-30

Ember Report. (2024). Available at: https://ember-climate.org/countries-and-regions/countries/south-africa/ Downloaded on 25 June 2024

Eskom Media Statement. (July 15, 2024). https://www.eskom.co.za/koeberg-operating-licence-extended-for-further-20-years/

Eskom. (2023). Virtual Wheeling Platform. Eskom Holdings SOC Ltd. Retrieved from https://www.eskom.co.za/distribution/wp-content/uploads/2023/07/20230710_-9553-Virtual-Wheeling-Digital-Brochure-FINAL.pdf

ESI Africa. (2018). How to survive the 4th industrial revolution. ESI Africa: Africa's Power Journal, Issue (4). South Africa

Fan, X. (2020). Triboelectric-electromagnetic hybrid nanogenerator driven by wind for self-powered wireless transmission in the Internet of Things and self-powered wind speed sensor. Nano Energy, 68, 104319

Fletcher, W. D., & Smith, C. B. (2020). Addressing global warming. In W. D. Fletcher & C.

Forbes, N., & Mahon, B. (2014). Faraday, Maxwell, and the Electromagnetic Field: How Two Men Revolutionized Physics. Prometheus Books

Forum of China-Africa Cooperation. (2024). http://www.focac.org.cn/eng/

Ganopolski, A. (2019). Climate change models. In B. Fath (Ed.), Encyclopaedia of Ecology (2nd ed., pp. 48-57). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.11166-2

Gao, M. (2021). Power generation for wearable systems. Energy & Environmental Science, 14(4), 2114-2157

Gao, Y., He, X., & Ai, Q. (2021). Multi agent coordinated optimal control strategy for smart microgrid based on digital twin drive. Power System Technology, 45(07), 2483-2491

Ge, S. (2020). Classification system and key technology of coal mine robot. China Coal Society, 45, 455-463

Ghayoor, F., Swanson, A., & Sibanda, M. (2021). Optimal sizing for a grid-connected hybrid renewable energy system: A case study of the residential sector in Durban, South Africa. Journal of Energy in Southern Africa, 32(4), 1–12. https://doi.org/10.17159/2413-3051/2021/v32i4a10356
Ge, S. (2020). Classification system and key technology of coal mine robot. China Coal Society, 45,455-463

German Federal Ministry for Energy and Economic Affairs. (2016). "Plattform Industrie 4.0" in Industrie 4.0 im international en Kontext. VDE-Verlag GmbH: 134-137

German Federal Ministry for Economic Affairs and Energy. (2020). Germany's Energy Efficiency Strategy 2050 [Internet]. Berlin. Available from: www.bmwi.de. Downloaded on 13 June 2024

Ghenai, C., Alhaj Husein, L., Al Nahlawi, M., Hamid, A. K., & Bettayeb, M. (2022). Recent trends of digital twin technologies in the energy sector: A comprehensive review. Sustainable Energy Technologies and Assessments, 54, 102837. https://doi.org/10.1016/j.seta.2022.102837

Gotz M. (2018). Energy management concepts for wireless sensor nodes. Energy harvesting for wireless sensor networks: technology, components, and system design.
DeGruyter 2018: 65–100

Govender, D., Moodley, J., & Balmahoon, R. (2021). Augmented and mixed reality-based decision support tool for the integrated resource plan. In IECON Proceedings (Industrial Electronics Conference). IEEE Computer Society

Grabchak, E. P., & MEVI. (2018). How to make digitalization successful. Energy Policy, 5, 25-29

Hanto, J., Schroth, A., Krawielicki, L., Oei, P.-Y., & Burton, J. (2022). South Africa's energy transition – Unravelling its political economy. Energy for Sustainable Development, 69, 164-178. https://doi.org/10.1016/j.esd.2022.06.006

Hao, H., Wang, Y., Shi, Y., Li, Z., Wu, Y., & Li, C. (2019, October). IoT-G: a low-latency and high-reliability private power wireless communication architecture for smart grid. In 2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm) (pp. 1-6). IEEE

Harlan, T., & Baka, J. (2024). Stacked energyscapes: Conceptualizing fossil fuel and renewable energy entanglements in low-carbon transitions. Energy Research & Social Science, 115, 103648. https://doi.org/10.1016/j.erss.2024.103648

He, P., & Ni, X. (2022). Renewable energy sources in the era of the fourth industrial revolution: A perspective of civilization development. Journal of Physics: Conference Series, 2301, 012030. https://doi.org/10.1088/1742-6596/2301/1/012030

Holkin, D. V. C. I. (2018). Digital transition in Russian power engineering: In search of meaning. Energy Policy, 5, 7-16

Holmberg, J., & Sandbrook, R. (1992). Sustainable development: What is to be done? In J. Holmberg (Ed.), Policies for a small planet (pp. 19–38). Earthscan Publications

Horbach, J., & Rammer, C. (2018). Energy transition in Germany and regional spill-overs: The diffusion of renewable energy in firms. Energy Policy, 121, 404-414

Human Sciences Research Council (HSRC). (2018). The Fourth Industrial Revolution: A Framework for South Africa. HSRC. https://hsrc.ac.za/uploads/pageContent/10155/4IR%20Framework%20Report_Final_lowres.pdf

Institute for Security and Development Policy. (2015). Made in China 2025. Institute for Security and Development Policy. Washington

International Energy Agency. (2018). World Energy Outlook 2018. OECD Publishing. Retrieved from https://www.iea.org/reports/world-energy-outlook-2018

International Energy Agency. (2023). South Africa: Energy System Overview. Retrieved from https://www.iea.org/countries/south-africa

International Energy Agency. (2023a). Available at: https://www.iea.org/countries/germany# Downloaded on 28 June 2024

International Energy Agency. (2023b). Available at: https://www.iea.org/countries/china Downloaded on 28 June 2024

International Energy Agency. (2023c). Available at: https://www.iea.org/countries/south- africa Downloaded on 28 June 2024

International Energy Agency. (2019). Key energy statistics [Internet]. Available from: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics

International Energy Agency. (2020). Special report on clean energy innovation energy technology perspectives [Internet]. Paris. Available from: https://iea.blob.core.windows.net/assets/04dc5d08-4e45-447d-a0c1d76b5ac43987/Energy_Technology_Perspectives_2020_-Special_Report_on_Clean_Energy_Innovation.pdf. Downloaded on 13 March 2024

International Energy Agency. (2021). Energy sector roadmap to carbon neutrality in China: IEA country report [Internet]. Paris. Available from: https://www.iea.org/reports/an-energy- sector-roadmap-to-carbon-neutrality-in-china. Downloaded on 12 April 2024

International Energy Agency. (2021). World Energy Outlook 2021. Retrieved from https://www.iea.org/reports/world-energy-outlook-2021. Downloaded on 12 April 2024

International Energy Agency. (2020. Global Energy Review: The impacts of the Covid-19 crisis on global energy demand and CO2 emissions. IEA, April. https://www.iea.org/reports/globalenergy-review-2020

International Energy Agency. (2022). China Energy Profile: Key Energy Statistics. Retrieved from https://www.iea.org/countries/china. Downloaded on 12 April 2024

International Monetary Fund. (2022). World Economic Outlook: Countering the cost-of-living crisis. Retrieved from https://www.imf.org/en/Publications/WEO/Issues/2022/10/11/world-economic-outlook-october-2022

International Monetary Fund. (2024). Available from: https://www.imf.org/external/datamapper/NGDPD@WEO/AFQ/ZAF/NGA/EGY?year=2024

International Renewable Energy Agency (IRENA). Renewable Energy Patents Evolution. https://www.irena.org/Data/View-data-by-topic/Innovation-and-Technology/Patents-Evolution\. Accessed: January 25, 2025

IoT.nxt. (Jul 27, 2023). https://www.iotnxt.com/the-potential-for-iot-technology-in-managing-the-energy-crisis-in-south-africa/

Jha, S. K., Bilalovic, J., Jha, A., Patel, N., & Zhang, H. (2017). Renewable energy: Present research and future scope of artificial intelligence. Renewable & Sustainable Energy Reviews, 77, 297-317

Jiang, A., Yuan, H., Li, D., & Tian, J. (2019). Key technologies of ubiquitous power Internet of Things-aided smart grid. Journal of Renewable and Sustainable Energy, 11(6)

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a definition of mixed methods research. Journal of Mixed Methods Research, 1(2), 112–133. https://doi.org/10.1177/1558689806298224

Jordaan, G., Malekian, N., & Malekian, R. (2019). Internet of Things and 5G solutions for the development of smart cities and connected systems. Communications of the CCISA, 25(2)

Kander, A., Malanima, P., & Warde, P. (2014). Power to the people: Energy in Europe over the last five centuries. Princeton University Press

Kafle, Y. R., Mahmud, K., Morsalin, S., & Town, G. (2016). Towards an internet of energy. Conference Paper. September 2016. Powercon

Kasza, J. (2019). Fourth industrial revolution (4IR): Digital disruption of cyber-physical systems. World Scientific News [Internet], 134(2), 118-147. Available from: www.worldscientificnews.com. Downloaded on 7 April 2023

Knieps, G. (2017). Internet of Things and the Economics of Microgrids in Innovation and Disruption at the Grid's Edge. Elsevier Inc, 241-258

Kober, T., Schiffer, H. W., Densing, M., & Panos, E. (2020). Global energy perspectives to 2060 – WEC's World Energy Scenarios 2019. Energy Strategy Reviews, 31, 100523. https://doi.org/10.1016/j.esr.2020.100523. Downloaded on 19 February 2022. Available at: https://www.sciencedirect.com/science/article/pii/S2211467X20300766

Kramm, L. (2012). The German Nuclear Phase-Out After Fukushima: A Peculiar Path or an Example for Others? Renewable Energy Law and Policy Review, 3(4), 251–262. http://www.jstor.org/stable/24324663. Downloaded on 26 July 2024

Kravchenko, A., & Kyzymenko, I. (2019). The Fourth Industrial Revolution: New Paradigm of Society Development or Posthumanist Manifesto. Philosophy and Cosmology, 22, 120–128

Kuittinen, H., & Velte, D. (2018). Germany's commitment to Industry 4.0 and renewable energy: Policies and strategies for achieving climate neutrality by 2050. Energy Policy Journal, 123, 127-139. https://doi.org/10.1016/j.enpol.2018.09.002 Downloaded on 22 June 2023

Kuittinen, H., & Velte, D. (2018). Mission-oriented R&I policies: In-depth case studies. Case Study Report Energiewende. https://op.europa.eu/en/publication-detail/-/publication/5e774d98-2351-11e8-ac73-01aa75ed71a1/language-en Downloaded on 19 March 2024

Kuhlmann, S., Stegmaier, P., & Konrad, K. (2019). The tentative governance of emerging science and technology—A conceptual introduction. Research Policy, 48(5), 1091-1097

Kühnbach, M, Pisula, S, Bekk, A, Weidlich, A. (2020). How much energy autonomy can decentralised photovoltaic generation provide? A case study for Southern Germany, Applied Energy, Volume 280, 2020, 115947, ISSN 0306-2619,
https://doi.org/10.1016/j.apenergy.2020.115947
https://www.sciencedirect.com/science/article/pii/S0306261920314033

Liao, Y., Deschamps, F., Loures, E. de F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0—a systematic literature review and research agenda proposal. International Journal of Production Research, 55(12), 3609–3629

Lawrence, A. (2020). Eskom and the dual character of the South African state. In South Africa's energy transition. Progressive Energy Policy (pp. 59-83). Cham: Palgrave Pivot. https://doi.org/10.1007/978-3-030-18903-7_3

Lees, C & Chen, G. (2016). 'Growing China's renewables sector: a developmental state approach', New Political Economy, vol. 21, no. 6, pp. 574-586. https://doi.org/10.1080/13563467.2016.1183113

Li, W., & Han, M. (2023). Mapping renewable energy transition worldwide: Gravity trajectory, contribution decomposition and income levels. Renewable Energy, 206, 1265- 1274. https://doi.org/10.1016/j.renene.2023.02.119

Liao, X., Wang, H., Niu, J., Xiao, J., & Liu, C. (2019). Research on simulation training system of immersive substation based on virtual reality. IOP Conference Series: Materials Science and Engineering, 486(1), 12112

Lin, B., & Zhu, J. (2019). Determinants of renewable energy technological innovation in China under CO.sub.2 emissions constraint. Journal of Environmental Management, 247, 662

Limpopo Economic Development Agency. (2019). Musina-Machado special economic zone development: Final Scoping Report. Informa UK Limited

Lincoln, Y.S. & Guba, E.G. (1985). Naturalistic inquiry. Newbury Park, CA: Sage Publications.

Li, Q., & Zhang, L. (2024). The Impact of AI on the Energy Sector in China. IAEE Energy Forum, Second Quarter, 5–7

Liu, S. (2016). Innovation design: Made in China 2025. DMI [Internet], 27(1), 51-58. Available from: https://www.researchgate.net/publication/323869484. Downloaded on 5 February 2022

Liu, Y., Zheng, F., Guo, R., Wang, J., Nie, Q., Wang, X., & Wang, Z. (2018). Robot intelligence for real-world applications. Chinese Journal of Electronics, 27(3), 446-458

Liu, Z., Zheng, W., Qi, F., Wang, L., Zou, B., Wen, F., & Xue, Y. (2018). Optimal dispatch of a virtual power plant considering demand response and carbon trading. Energies, 11(6), 1488

Lo, K & Mah, D. (2024). State capitalism, fragmented authoritarianism, and the politics of energy policymaking: Policy networks and electricity market liberalization in Guangdong, China, Energy Research & Social Science, Volume 107,2024,103348, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2023.103348. https://www.sciencedirect.com/science/article/pii/S2214629623004085

Lu, W., Sun, Y., Li, B., & Chang, L. (2021, April). Research and Application of “Source- Network-Load-Storage” Coordination Optimisation Technology Based on Cloud Platform. In 2021 4th International Conference on Energy, Electrical and Power Engineering (CEEPE) (pp. 813-818). IEEE

Lund, H., Østergaard, P. A., Connolly, D., & Mathiesen, B. V. (2017). Smart energy and smart energy systems. Energy (Oxford), 137, 556-565

Lyu, W., & Liu, J. (2021). Artificial intelligence and emerging digital technologies in the energy sector. Applied Energy, 303, 117615

Ma, C., Wang, R., Tetik, H., Gao, S., Wu, M., Tang, Z., ... & Wu, W. (2019). Hybrid nanomanufacturing of mixed-dimensional manganese oxide/graphene aerogel macroporous hierarchy for ultralight efficient supercapacitor electrodes in self-powered ubiquitous nanosystems. Nano Energy, 66, 104124

Mabunda, M. V., Mukonza, R. M., & Mudzanani, L. R. (2023). The effects of loadshedding on small and medium enterprises in the Collins Chabane local municipality. Journal of Innovation and Entrepreneurship, 12(1), 57

Makala, B., & Bakovic, T. (2020). Artificial intelligence in the power sector [Internet]. International Finance Corporation, World Bank. Available from: https://www.researchgate.net/publication/343624277. Downloaded on 4 November 2022

Massel, L. V. (2018). Methods and intelligent technologies for scientific substantiation of strategic solutions on the digital transformation of the energy industry. Energeticheskaya Polit, 5, 30-42

Meceda, A. M. V. N. (2018). The singular economy: End of the digital/physical divide. STI Policy Review, 9(1), 133-157

Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). Qualitative data analysis: A methods sourcebook (3rd ed.). SAGE Publications

Mokyr, J. (2009). Intellectual property rights, the Industrial Revolution, and the beginnings of modern economic growth. American Economic Review, 99(2), 349–355

Monyei, C. G., & Akpeji, K. O. (2020). Repurposing electricity access research for the global south: A tale of many disconnects. Joule, 4(2), 278-281

Morrar, R., Arman, H., & Mousa, S. (2017). The fourth industrial revolution (Industry 4.0): A social innovation perspective. Technology Innovation Management Review, 7(11), 12–20

Müller, J. M., & Voigt, K. I. (2018). Sustainable industrial value creation in SMEs: A comparison between Industry 4.0 and Made in China 2025. International Journal of Precision Engineering and Manufacturing-Green Technology, 5(5), 659–670. https://doi.org/10.1007/s40684-018-0056-z

MyBroadband. (2023, August 30). Vodacom signs first “virtual wheeling” deal with Eskom. Retrieved from https://mybroadband.co.za/news/cellular/506168-vodacom-signs-first-virtual-wheeling-deal-with-eskom.html

Narayan, A., Krueger, C., Goering, A., Babazadeh, D., Harre, M. C., Wortelen, B., ... & Lehnhoff, S. (2019, May). Towards future SCADA systems for ICT-reliant energy systems. In International ETG-Congress 2019; ETG Symposium (pp. 1-7). VDE

Narges, B., & Ali, R. (2020). Development level and the impact of technological factor on renewable energy production. Renewable Energy, 151, 946-955. https://doi.org/10.1016/j.renene.2020.07.062

Nel, A. J. H., Vosloo, J. C., & Mathews, M. J. (2018). Financial model for energy efficiency projects in the mining industry. Energy (Oxford), 163, 546-554.

Neshat, M., Nezhad, M. M., Abbasnejad, E., Mirjalili, S., Groppi, D., Heydari, A., Tjernberg, L. B., Astiaso Garcia, D., Alexander, B., Shi, Q., & Wagner, M. (2021). Wind turbine power output prediction using a new hybrid neuro-evolutionary method. Energy, 229

Neu, J. (2021). Design and characterization of polymeric domes as biasing elements for dielectric elastomer membrane actuators. In ACTUATOR: International Conference and Exhibition on New Actuator Systems and Applications (pp. 1–4). VDE

Neshat, M., Nezhad, M.M., Abbasnejad, E., Mirjalili, S., Groppi, D., Heydari, A., Tjernberg, L.B., Astiaso Garcia, D., Alexander, B., Shi, Q. & Wagner, M. (2021). Wind turbine power output prediction using a new hybrid neuro- evolutionary method. Energy, 229

Ng, T. C., & Ghobakhloo, M. (2020). Energy sustainability and Industry 4.0. In IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing

Noble, H. & Smith, J. (2015). Issues of validity and reliability in qualitative research. Evidence-BasedNursing, 18(2), pp.34–35

Nowell, L.S., Norris, J.M., White, D.E. & Moules, N.J. (2017). Thematic analysis: Striving to meet the trustworthiness criteria. International Journal of Qualitative Methods, 16(1), pp.1–13

O’Reilly, J., Ranft, F., & Neufeind, M. (2018). Identifying the challenges for work in the digital age in Work in the digital age: Challenges of the fourth industrial revolution. Rowman & Littlefield International. London

Obiora, C. N., Ali, A., & Hasan, A. N. (2020). Estimation of hourly global solar radiation using deep learning algorithms. Conference Paper: 11th International Renewable Energy Congress (IREC)

Oláh, J., Aburumman, N., Popp, J., Khan, M. A., Haddad, H., & Kitukutha, N. (2020). Impact of Industry 4.0 on environmental sustainability. Sustainability, 12(11), 4674. https://doi.org/10.3390/su12114674

Ozoegwu, C. G. (2018). The solar energy assessment methods for Nigeria: The current status, the future directions, and a neural time series method. Renewable & Sustainable Energy Reviews, 92, 146-159

Paiho, S., Kiljander, J., Sarala, R., Siikavirta, H., Kilkki, O., Bajpai, A., et al., (2021). Towards cross-commodity energy-sharing communities – A review of the market, regulatory, and technical situation. Renewable and Sustainable Energy Reviews, 151, 111568

Pallant, J. (2007). SPSS Survival Manual: A Step-by-Step Guide to Data Analysis using SPSS for Windows. Open University Press. London

Pandey, A., Kumar, N., & Kaushik, N. (2023). Digitalization in the energy sector: Opportunities and challenges for transition to sustainable energy systems. Renewable and Sustainable Energy Reviews, 152, 111675
https://doi.org/10.1016/j.rser.2021.111675

Patel, L. (2015). Social Welfare and Social Development in South Africa. Oxford University Press

Penprase, B. E. (2018). The fourth industrial revolution and higher education. In Gleason, N. W. (Eds.), Higher Education in the Era of the Fourth Industrial Revolution (pp. xx-xx). Springer. Singapore

Pfeiffer, S. (2017). The vision of “Industrie 4.0” in the making—a case of future told, tamed, and traded. NanoEthics, 11(1), 107-121

Pinheiro, M. D. O., & Lucas, C. A. (2019). Industry 4.0 and industrial revolutions: An assessment based on complexity. Sustainability, 11(20), 5729. https://doi.org/10.3390/su11205729

Potts, S., & Walwyn, D. R. (2020). An exploratory study of the South African concentrated solar power sector using the technological innovation systems framework. Journal of Energy in Southern Africa, 31(2), 1–13. https://doi.org/10.17159/2413-3051/2020/v31i2a7745

Presidency of South Africa. (2012). National Development Plan 2012. SA Presidency. Pretoria

Presidential Commission on the Fourth Industrial Revolution. (2020). Report of the Presidential Commission on the Fourth Industrial Revolution. The Presidency, Republic of South Africa

Pretorius, R., & Kotze, B. J. (2021). South African Universities Power Engineering Conference. Conference. IEEE. South Africa

Rahaman, S. A., Urmee, T., & Parlevliet, D. A. (2020). PV system defects identification using remotely piloted aircraft (RPA) based infrared (IR) imaging: A review. Solar Energy, 206, 579-595

Ritchie, H., & Rosado, P. (2020). Electricity mix. OurWorldInData.org. Downloaded on 27 July 2024 from https://ourworldindata.org/electricity-mix

Rifkin, J. (2013). A new economic narrative: Industrial Revolution 3.0. Our World, United Nations University. Available at: https://ourworld.unu.edu/en/a-new-economic-narrative-industrial-revolution-3-0 Downloaded on 5 November 2024

Rose, R. (2024, March 12). South Africa sets an ambitious timeline to end rolling blackouts. Financial Times. Available at: https://www.ft.com/content/362c08c3-518f-48c1- 922d-e15dfeb36899 Downloaded on 20 July 2024

Roth, L., Lowitzsch, J., Yildiz, Ö., & Hashani, A. (2018). Does (co-)ownership in renewables matter for an electricity consumer's demand flexibility? Empirical evidence from Germany. Energy Research and Social Science, 46, 169-182

Schalk Burger, S. (June 11, 2024). Published by Creamer Media Senior Deputy Editor https://www.miningweekly.com/article/eskom-arrests-suspected-coal-swapping-thief-2024-06-11

Scheffran, J., Felkers, M., & Froese, R. (2020). Economic growth and the global energy demand. In G. Kaynak & T. A. Winston (Eds.), Green energy to sustainability: Strategies for global industries (pp. 1-44)

Schroeder, W. (2016). Germany's Industrie 4.0 strategy: Rhine Capitalism in the age of Digitalisation. Friedrich Ebert Stiftung. London

Schwab, K. (2017). The fourth industrial revolution. Portfolio Penguin. London. Published: 05/01/2017. ISBN: 9780241300756

Seeleib-Kaiser, M. (2016). Welfare State Transformations and Inequality in OECD Countries. Social Policy & Administration, 50(4), 482–503

Sewnarain, S., Onunka, C., & Akindeji, K. (2020). Assessment of tidal energy as alternative energy. IEEE Xplore. https://doi.org/10.1109/ACCESS.2020.3007531

Shapsough, S., Takrouri, M., Dhaouadi, R., & Zualkernan, I. (2020). An IoT-based remote IV tracing system for analysis of city-wide solar power facilities. Sustainable Cities and Society, 57, 102041

Sharma, G. (2017). Pros and cons of different sampling techniques. International Journal of Applied Research, 3(7), 749–752

Shenzhen Municipality. (2023). Shenzhen Digital Energy White Paper: Creating a Green Future with Digital Energy. Development and Reform Commission of Shenzhen Municipality. China. Downloaded on 2 June 2024 from: https://www.siat.ac.cn/zhxw2016/202311/P020240311373658498224.pdf

Sigwadi, L. (2020). Data Science and the Fourth Industrial Revolution (4IR). University of the Western Cape. Cape Town. 1-3

Sima, V., Gheorghe, I. G., Subić, J., & Nancu, D. (2020). Influences of the Industry 4.0 revolution on human capital development and consumer behavior: A systematic review. Sustainability, 12(10)

Sino-German Energy Partnership. (2021). About Us. Downloaded on 1 June 2023 from https://energypartnership.cn/about-us/

Sino-German Energy Partnership. (2023). The German energy transition and impulses for China to achieve carbon peaking and carbon neutrality – Targets, status, and prospects. Beijing: Sino-German Energy Partnership, p. 8

Sino-German Energy Transition Project. (2020). China Energy Transition Status Report. Beijing: Sino-German Energy Transition Project. Downloaded on 1 June 2023 from https://www.energypartnership.cn/fileadmin/user_upload/china-energy-transition-status-report.pdf

Spalding-Fecher, R., Williams, A., & Van Horen, C. (2000). Energy and environment in South Africa: Charting a course to sustainability. Energy for Sustainable Development, 4(4), 8–17

Staff Writer. (2024, July 9). Ramokgopa to speed shift from coal to renewables. Miningmx. Retrieved from: https://www.miningmx.com/news/energy/57440-ramokgopa-to-speed-shift-from-coal-to-renewables/

South African - German Energy Partnership. https://energypartnership.org.za. Accessed: 10 December 2024

South Africa Department of Energy. (2019). The South African energy sector. Report [Internet]. Available from: http://www.energy.gov

South Africa Integrated Resource Plan 2019 [Internet]. (2019). Pretoria: South African Department of Mineral Resources and Energy. Downloaded on 14 April 2022 from http://www.energy.gov.za/IRP/2019/IRP-2019.pdf.

South African Department of Minerals and Energy. (2024). South African Renewable Energy Masterplan (SAREM)

South African Department of Minerals and Energy. (2024). Draft Integrated Energy Plan 2023

South Africa Presidency. (2012). South Africa - National Development Plan 2030 [Internet]. Pretoria. Downloaded on 18 October 2022 from: https://www.gov.za/sites/default/files/gcis_document/201409/ndp-2030-our-future-make-itworkr.pdf.

South African Local Government Association. (2018). SALGA 2018 Energy Summit Discussion Documents: Defining the Energy Future of Local Government. SALGA. Pretoria. South Africa

South African Qualifications Authority. (2021). The South African National Qualifications Framework and the Fourth Industrial Revolution. Johannesburg

Statista. (2024). Downloaded on 17 July from https://www.statista.com/statistics/263616/gross-domestic-product-gdp-growth-rate-inChina/#:~:text=In%202023%2C%20the%20growth%20of,rate%20of%20around%20five%20percent

Stewart, A., & Stanford, J. (2017). Regulating work in the gig economy: What are the options? The Economic and Labour Relations Review, 28(3), 420-437

Sun, C. (2019). Self-powered multifunctional monitoring system using hybrid integrated triboelectric nanogenerators and piezoelectric microsensors. Nano Energy, 58, 612-623

Sutherland, E. (2020). The Fourth industrial revolution–the case of South Africa. Politikon, 47(2), 233-252

The State Council of China. (2020). White Paper on Energy in China's New Era. Available at: https://english.mee.gov.cn/Resources/publications/Whitep/202012/t20201222_814160.shtml

The State Council of China. (2024). China's Energy Transition. Foreign Languages Press Co. Ltd, Beijing, China, 2024. ISBN 978-7-119-14016-2

Tymoshenko, M., Redko, K., Serbov, M., Shashyna, M., & Slavkova, O. (2022). The impact of industry 4.0 on modeling energy scenarios of developing economies. Journal on Innovation and Sustainability RISUS, 13(4), 158–173. https://doi.org/10.23925/2179- 3565.2022v13i4p158-173

United Nations. (2020). Sustainable Development Report 2020. New York: United Nations Publications

United Nations Industrial Development Organisation. (2018). Low-Carbon and Climate Resilient Industrial Development in Africa. Impact LCCR Report. Downloaded on 29 September 2022 from: https://www.unido.org/sites/default/files/files/2018-12/LCCR- Impact-Report.pdf

United Nations Industrial Development Organization. (2025). China-Africa Development Fund and its impact on Africa's energy sector. Retrieved from https://www.unido.org/node/84747 on January 8, 2025

United Nations Framework Convention on Climate Change. (2015). Paris Agreement. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

United Nations. (2016). Sustainable Development Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all. Retrieved from https://sdgs.un.org/goals/goal7

Urban, B. (2018). Effectuation and opportunity recognition in the renewable energy sector in South Africa: A focus on environmental dynamism and hostility. Journal of Developmental Entrepreneurship, 23(2)

Viétor, B., Hoppe, T., & Clancy, J. S. (2015). Decentralised combined heat and power in the German Ruhr Valley; assessment of factors blocking uptake and integration. Energy, Sustainability and Society, 5(1), 1-16

Voropai, N. (2018). Problems of vulnerability and survivability of cyber-physical and electric power systems. Energy Policy, 5, 53-61

Voyant, C., Notton, G., Kalogirou, S., Nivet, M., Paoli, C., Motte, F., & Fouilloy, A. (2017). Machine learning methods for solar radiation forecasting: A review. Renewable Energy, 105, 569-582

Wang, Q., Liu, Y., Huang, Y., Liu, C., Chen, G., & Liu, J. Y. (2020). Congestion management of urban power grid considering demand response of data center. Power System Technology, 44(8), 3129-3138

Wang, Y., Zou, R., Liu, F., Zhang, L., & Liu, Q. (2021). A review of wind speed and wind power forecasting with deep neural networks. Applied Energy, 304, 117766

Wang, J., Ma, X., Zhang, J., & Zhao, X. (2022). Impacts of digital technology on energy sustainability: China case study. Applied Energy, 323, 119329. https://doi.org/10.1016/j.apenergy.2022.119329

Weigel, P., & Fischedick, M. (2019). Review and categorization of digital applications in the energy sector, vol. 9. Applied Sciences. MDPI AG

Winkler, H. (2024). South Africa’s electricity crisis: What political parties say in their election manifestos about solving it. The Conversation. Downloaded on 11 June 2024 from https://theconversation.com/south-africas-electricity-crisis-what-political-parties-say- in-their-election-manifestos-about-solving-it-226518

Wired. (2024, August 22). The Green Economy Is Hungry for Copper—and People Are Stealing, Fighting, and Dying to Feed It. Retrieved from https://www.wired.com/story/power-metal-green-economy-is-hungry-for-copper

World Bank Group. (2021). Climate Change Action Plan 2021-2025. Available from: www.worldbank.org

World Bank. (2019). An analysis of issues shaping Africa's economic future. Africa’s pulse. April 2019 (19). World Bank Group. Washington DC

World Bank. https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=ZA-CN. Accessed: December 12, 2024

World Economic Forum. (2017). The future of jobs and skills in Africa: Preparing the region for the Fourth Industrial Revolution. Executive Briefing

World Intellectual Property Organization. (2021). China's leading role in renewable energy technologies: Patents and innovation. Downloaded on 5 July 2024 from https://www.wipo.int/wipo_magazine/en/2020/01/article_0008.html

Wu, Z., & Chu, W. (2021, August). Sampling strategy analysis of machine learning models for energy consumption prediction. In 2021 IEEE 9th International Conference on Smart Energy Grid Engineering (SEGE) (pp. 77-81). IEEE

Wübbeke, J., Meissner, M., Zenglein, M. J., & Ives, J. (2016). Made in China 2025: The making of a high-tech superpower and consequences for industrial countries. MERICS. China

Xiaojing Zhang, Khalid Khan, Xuefeng Shao, Camelia Oprean-Stan, Qian Zhang. (2024). The rising role of artificial intelligence in renewable energy development in China, Energy Economics, Volume 132, 2024, 107489, ISSN 0140-9883, https://doi.org/10.1016/j.eneco.2024.107489. https://www.sciencedirect.com/science/article/pii/S014098832400197X

Xie, S.-P. (2024). Global warming: Thermodynamic effects. In S.-P. Xie (Ed.), Coupled Atmosphere-Ocean Dynamics (pp. 339-366). Elsevier. https://doi.org/10.1016/B978-0- 323-95490-7.00013-8

Yan X, Tian X, Li H and Guo H (2024), Research on technical cooperation path of renewable energy between China and South Africa Front. Energy Res. 12:1411546.
doi: 10.3389/fenrg.2024.1411546

Yang, F., & Gu, S. (2021). Industry 4.0, a revolution that requires technology and national strategies. Complex & Intelligent Systems, 7(8), 1311–1325

Yin, E., Zeyl, T., Saab, R., Hu, D., Zhou, Z., & Chau, T. (2016). An auditory-tactile visual saccade-independent P300 brain–computer interface. International Journal of Neural Systems, 26(1), 1650001

Yuen, S. C., Yaoyuneyong, G., & Johnson, E. (2011). Augmented Reality: An Overview and Five Directions for AR in Education. Journal of Educational Technology Development and Exchange (JETDE), 4(1). https://doi.org/10.18785/jetde.0401.10

Yunfeng, Z., & Mingming, P. (2019). Application and prospect of human-machine interaction in power system. Journal of Physics: Conference Series, 1345(3), 032094

Zeng, S., Tanveer, A., Fu, X., Gu, Y., & Irfan, M. (2022). Modelling the influence of critical factors on the adoption of green energy technologies. Renewable and Sustainable Energy Reviews, 168, 112817

Zhang, S., & Andrews-Speed, P. (2020). State versus market in China's low-carbon energy transition: An institutional perspective. Energy Research & Social Science, 66

Zhang, Y. (2018). A big data driven analytical framework for energy-intensive manufacturing industries. Journal of Cleaner Production, 197(1), 57-72

Zhou, R. (2019). Research on situational sensing method of grid cyber-physical system under network attack. In 2019 IEEE Sustainable Power and Energy Conference (iSPEC) (pp. 454-458). Beijing: IEEE

Zhou, X., Zhou, D., Wang, Q., & Su, B. (2020). Who shapes China's carbon intensity and how? A demand-side decomposition analysis. Energy Economics, 85, 104573. https://doi.org/10.1016/j.eneco.2019.104573

Zmolek, M. A. (2013). Rethinking the Industrial Revolution: Five Centuries of Transition from Agrarian to Industrial Capitalism in England. Brill

Zou, C., Zhao, Q., Zhang, G., & Xiong, B. (2023). Future energy transition: Mechanisms and models. Petroleum Exploration and Development, 47(1), 1-9. https://doi.org/10.1016/S1876-3804(20)60002-3

APPENDIX A

Interview Information sheet, interview schedule

RESEARCH PARTICIPANT INFORMATION SHEET

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Dear Madam/Sir

My name is Nadya Bhagwan (Ms), a lecturer in education at the University of Johannesburg and a PhD candidate at the School of Geography, Archaeology and Environmental Studies at the University of the Witwatersrand. The title of my PhD study is “An evaluation of the extent to which South African energy companies leverage Industry 4.0 technologies to improve efficiencies in comparison with China and Germany.” This PhD study aims to ascertain whether and to what extent South African energy companies are leveraging 4IR technologies, compare this usage with that of China and Germany and evaluate the extent to which these technologies enhance efficiency in energy production. The rationale of the study is underpinned by the global energy crisis at a time when the world has begun to forcefully navigate itself within a Fourth Industrial Revolution (4IR). Sophisticated technologies that have emerged may be used to address the energy crisis but, to do so, one needs to understand if and where in the energy production chain these technologies are being adopted and, the extent to which they are contributing to more efficient processes in energy.

As part of this study, I would like to invite you to take part in an interview. I have chosen you to be part of this study because of your knowledge and expertise in the energy sector in South Africa. This activity will involve your personal understanding of the Fourth Industrial Revolution (4IR), in the context of the energy sector, and if you are part of a company, the extent to which you believe your company is leveraging 4IR technologies to advance its position in the energy sector. The objectives of my study are to:

1. To identify research gaps relating to the uptake of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa by technology type and impact.
2. To compare the importance and use of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa.

3. To determine the extent to which the level of uptake of such technologies could exacerbate challenges facing the South African energy sector.

The interview comprises between 6 to 8 questions and will take approximately 45 minutes. With your permission, I would also like to record the interview. Although you will not receive any direct benefits from participating in this study, you will play an important and valuable role in contributing to the knowledge that is produced because of the research. You may withdraw at any time or not answer any question if you do not want to. The interview will be completely confidential and anonymous as I will not be asking for your name or any identifying information, and the information you give to me will be held securely and not disclosed to anyone else. I will be using a pseudonym (false name) to represent your participation in my final research report. In cases where you are speaking on behalf of the company, and if agreed to by yourself and or the relevant company representative, permission may be requested to use the name of the company. I have received ethics approval from the University of the Witwatersrand and my ethics number is H190706.

If you have any questions during or afterwards about this research, feel free to contact me on the details listed below. This study will be written up as a research report which will be available online through the university library website. If you wish to receive a summary of this report, I will be happy to send it to you. If you have any concerns or complaints regarding the ethical procedures of this study, you are welcome to contact the: University Human Research Ethics Committee (Non-Medical)

Tel: +27(11)-717-1408, email hrec-medical.researchoffice@wits.ac.za

Thank you very much for your help.

NBhagwan

Researcher: N. Bhagwan	Supervisor: Prof. Mary Evans
nadyab@uj.ac.za	Mary.evans@wits.ac.za
084-786 1008	011-717 6582

Company Interview Questions

1. Describe your company type and provide some background information on how the company fits into the broader energy sector.
2. Define the Fourth Industrial Revolution and associated Industry 4.0 technologies.
3. Does your company develop or use Industry 4.0 technologies? How?
4. What is the value-add of the above Industry 4.0 technologies?
5. How is this value-add measured?
6. Are these Industry 4.0 technologies new technologies, or are they enhancements to existing technologies? Explain.
7. What are some of your company's “missing” Industry 4.0 technologies? Provide reasons for why these technologies may be missing.
8. Rank the following technologies in order of importance to the energy sector: Big, Real-Time Data, the Internet of Things, Artificial Intelligence, Robotics, and Machine-Human Integration.

Academic / Industry Expert Interview Questions

1. What is your main area of expertise/research within the energy sector?

2. What do you understand by Industry 4.0 technologies/technology components?

3. Are renewable energy companies using Industry 4.0 technologies/components?

4. How do 4IR technologies/components add value to the energy sector?

5. Rank the following Industry 4.0 technologies from 1 to 5 in order of importance to the energy sector: Big, Real-Time Data, the Internet of Things, Artificial Intelligence, Robotics, and Machine-Human Integration.

6. Are you familiar with the energy sectors in China and Germany? If so, which country should South Africa model, and how best should this be done?

APPENDIX B

Survey information sheet, survey, ethics clearance certificate

RESEARCH PARTICIPANT INFORMATION SHEET FOR SURVEY

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Dear Madam/Sir

My name is Nadya Bhagwan (Ms), a lecturer in education at the University of Johannesburg and a PhD candidate at the School of Geography, Archaeology and Environmental Studies at the University of the Witwatersrand. The title of my study is "An evaluation of the extent to which South African energy companies leverage Industry 4.0 technologies to improve efficiencies in comparison with China and Germany." I would sincerely appreciate it if you could send me an email address for the person involved in strategic development as well as technology development. This PhD study aims to ascertain whether and to what extent South African energy companies are leveraging 4IR technologies, compare this usage with that of China and Germany and evaluate the extent to which these technologies enhance efficiency in energy production. To meet this aim, the following objectives will need to be met:

1. To identify research gaps relating to the uptake of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa by technology type and impact.
2. To compare the importance and use of Industry 4.0 technologies in the energy sectors of Germany, China, and South Africa.
3. To determine the extent to which the level of uptake of such technologies could exacerbate challenges facing the South African energy sector.

As part of this study, I invite you to participate in an online survey. I have chosen you to be part of this study because of your knowledge and expertise in the energy sector in South Africa. This activity will involve your personal understanding of the Fourth Industrial Revolution (4IR), in the context of the energy sector, the extent to which you believe your company has been a part of the 4IR, and what is needed to advance your company within 4IR. The online survey comprises 14 questions and will take approximately 20 minutes. Although you will not receive any direct benefits from participating in this study, you will play an important and valuable role in contributing to the body of knowledge that is produced as a result of the research. The survey will be kept completely confidential and anonymous as I will not be asking for your name or any identifying information, and the information you give to me will be held securely and not disclosed to anyone else. I have received ethics approval from the University of the Witwatersrand and my ethics number is H190706.

If you have any questions during or afterwards about this research, feel free to contact me on the details listed below. This study will be written up as a research report which will be available online through the university library website. If you wish to receive a summary of this report, I will be happy to send it to you.

If you have any concerns or complaints regarding the ethical procedures of this study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone: +27(11)-717-1408, email: hrec-medical.researchoffice@wits.ac.za

Thank you very much for your help.
Yours sincerely,

Researcher: N. Bhagwan
nadyab@uj.ac.za
011-559-2679

Supervisor: Prof. Mary Evans
Mary.evans@wits.ac.za
011-717-6582

Leveraging 4IR technologies to advance the energy sector

Dear Madam/Sir

My name is Nadya Bhagwan (Ms). I am a lecturer at the University of Johannesburg. I am also a PhD candidate at the School of Geography, Archaeology and Environmental Studies at the University of the Witwatersrand. The title of my study is "Leveraging 4IR technologies to advance the energy sector in South Africa."

The aim of this research is to determine the extent to which the South African energy sector is using 4IR technologies and to create a benchmarking instrument that may be used by energy companies to measure their performance within 4IR.The aim of this research is multipronged. Firstly, it will seek to identify key technology driven components of the Fourth Industrial Revolution that impact directly on the production and distribution of energy. Secondly, the research will create real-life scenarios for different energy sectors representative of different climatic conditions, environmental policy commitments, economic conditions, energy policy, knowledge of and access to 4IR technologies and, energy demand and supply characteristics and or statistics. Finally, the study will aim to compare the energy sector in South Africa globally.

As part of this study, I would like to invite you to take part in an online survey. I have chosen you to be part of this study because of your knowledge and expertise in the energy sector in South Africa. This activity will involve your personal understanding of the 4IR in the context of the energy sector, the extent to which you believe your company has been a part of the 4IR and why this is the case. The online survey comprises 14 short questions and will take approximately 5-10 minutes. Although you will not receive any direct benefits from participating in this study, you will play an important and valuable role in contributing to the body of knowledge that is produced as a result of the research.

The survey will be kept completely confidential and anonymous as I will not be asking for your name or any identifying information, and the information you give to me will be held securely and not disclosed to anyone else. I have received ethics approval from the University of the Witwatersrand and my ethics number is H190706.

Thank you for your valuable contribution to this important study.

* Required

Email address *

Your email

WITS PhD study

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Emerging technologies in 4IR

1. Which statement best describes the Fourth Industrial Revolution (4IR) for you? *

- ◯ 4IR is about the interactions between human and machines to improve productivity in industry
- ◯ 4IR is about creating technology to connect globally
- ◯ 4IR is about the development and use of Artificial Intelligence (AI) in industry
- ◯ All of the above
- ◯ None of the above

2. If you answered "None of the Above" to question 1, please explain why.

Your answer

3. How important are 4IR technologies for the global energy sector? *

- Very important
- Important
- Somewhat important
- Not important

4. Rank each 4IR technology in order of how important it is for the global energy sector, with 1 being the most important and 7 the least important. *

Each number rank may only be used once.

	I Most important	Column 2	3	4	5	6	7 Least important
Big data	☐	☐	☐	☐	☐	☐	☐
Reall–time,, live data	☐	☐	☐	☐	☐	☐	☐
Big and real-- time data analysis	☐	☐	☐	☐	☐	☐	☐
Artificial intelligence	☐	☐	☐	☐	☐	☐	☐
Robotics	☐	☐	☐	☐	☐	☐	☐
Machine-- human interaction (augmented reality)	☐	☐	☐	☐	☐	☐	☐
Internet of Things (IoT)	☐	☐	☐	☐	☐	☐	☐

5. Do you consider your company to be part of the 4IR? *

Choose

6. In which country is your company located? *

Your answer

7. In which sub-sector is your company located? Tick the most appropriate option. *

- [ ] Non-renewable energy (eg. coal)
- [ ] Renewable energy (eg. solar, wind, tidal, biomass)
- [ ] Both renewable and non-renewable
- [ ] Non-Energy

8. Is your company using 4IR technologies?8 *

Choose

9. From your understanding of 4IR technologies, list the ones that your company is using.

Your answer

10. How would you describe your company's use of 4IR technologies? *

Choose

11. Rank in order of how importance from 1 to 7, which 4IR technologies in the list below are used in your company, with 1 being the most important and 7 the least important.

Each number rank may only be used once.

	I Most important	2	3	4	5	6	7 Least important
Big data	☐	☐	☐	☐	☐	☐	☐
Reall–time, data	☐	☐	☐	☐	☐	☐	☐
Big and real– time data analysis	☐	☐	☐	☐	☐	☐	☐
Artificial intelligence (AI)	☐	☐	☐	☐	☐	☐	☐
Robotics	☐	☐	☐	☐	☐	☐	☐
Machine-- human interaction (augmented reality)	☐	☐	☐	☐	☐	☐	☐
Internet of Things (IoT)	☐	☐	☐	☐	☐	☐	☐

12. How efficient are these 4IR technologies that are used in your company?

	Very efficient	Somewhat efficient	Not efficient
Big, real-time data	☐	☐	☐
Data analysis	☐	☐	☐
Artificial Intelligence	☐	☐	☐
Machine--human integration	☐	☐	☐
Internet of Things	☐	☐	☐

13. How reliable are these 4IR technologies that are used in your company?

	Very reliable	Somewhat reliable	Not reliable
Big, real-time data	☐	☐	☐
Data analysis	☐	☐	☐
Artificial Intelligence	☐	☐	☐
Machine--human integration	☐	☐	☐
Internet of Things	☐	☐	☐

14. How integrated are these 4IR technologies in your company?

	Completely integrated	Somewhat integrated	Not integrated
Big, real-time data	☐	☐	☐
Datta analysis	☐	☐	☐
Artificial Intelligence	☐	☐	☐
Machine--human integration	☐	☐	☐
Internet off Things	☐	☐	☐

15. What are the names of the 4IR technologies that you ranked in the top 3 above and which country does each come from?

Your answer

16. If your company is NOT using 4IR technologies tick the reason for this.

Choose

A copy of your responses will be emailed to the address you provided.

Submit

UNIVERSITY OF THE
WITWATERSRAND.
JOHANNESBURG

Research Office

HUMAN RESEARCH ETHICS COMMITTEE (NON–MEDICAL)
R14/49 Bhagwan

CLEARANCE CERTIFICATE	**PROTOCOL NUMBER: H19(07/06**
PROJECT TITLE	Leveraging 4IR technologies to advance the energy sector in South Africa
INVESTIGATOR(S)	Ms N Bhagwan
SCHOOL/DEPARTMENT	Geography Archaeology and Environmental
DATE CONSIDERED	Studies/ 19 July 2019
DECISION OF THE COMMITTEE	Approved Permission letters required before data collection can commence
EXPIRY DATE	04 September 2022

05 September 2019 **CHAIRPERSON** J. Knight
(Professor J Knight)

cc: Supervisor: Professor M Evans

DECLARATION OF INVESTIGATOR(S}

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10004, 10th Floor, Senate House, University. Unreported changes to the application may invalidate the clearance given by the HREC (Non-Medical)

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. **I agree to completion of a yearly progress report.**

Date: 6/9/2019

Signature: Nadya Bhagwan

APPENDIX C

Chapter 2 Figures Enlarged

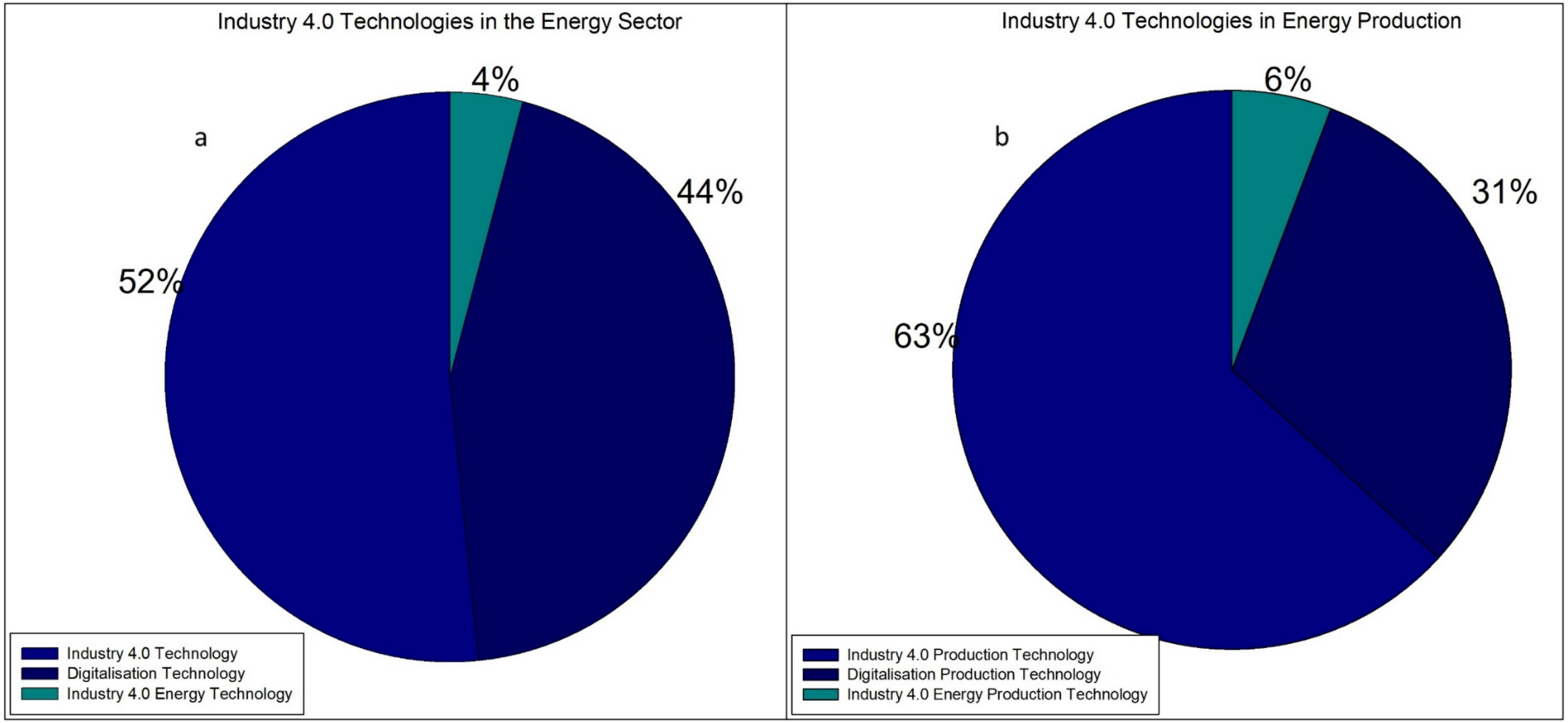

Fig. 1. The number of publications focused on Industry 4.0 technologies in (a) the global energy sector and (b) energy production only.

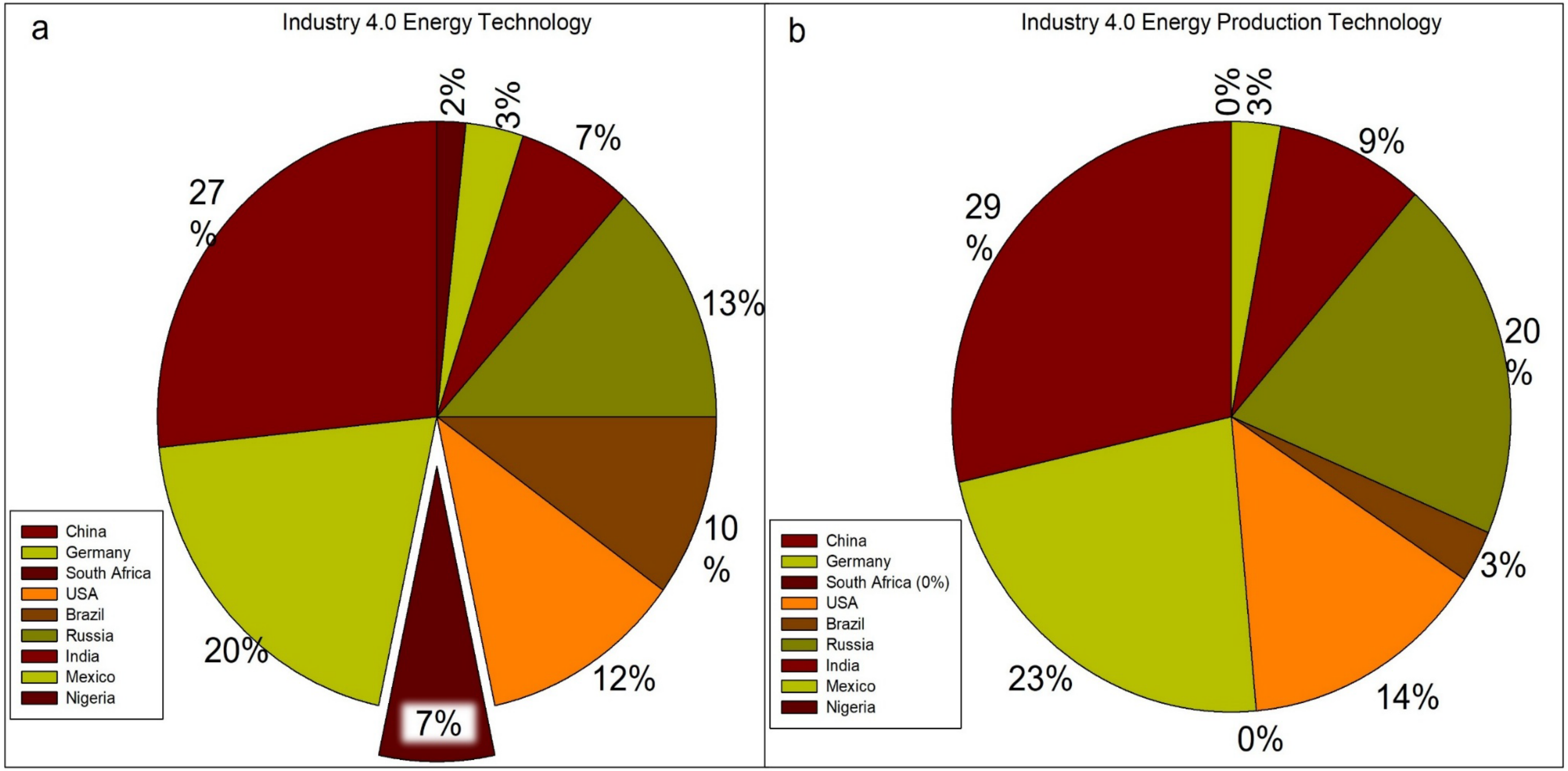

Fig. 2. The number of publications produced per country in (a) energy technology and (b) energy production technology. South Africa accounts for 7% of publications on energy technologies.

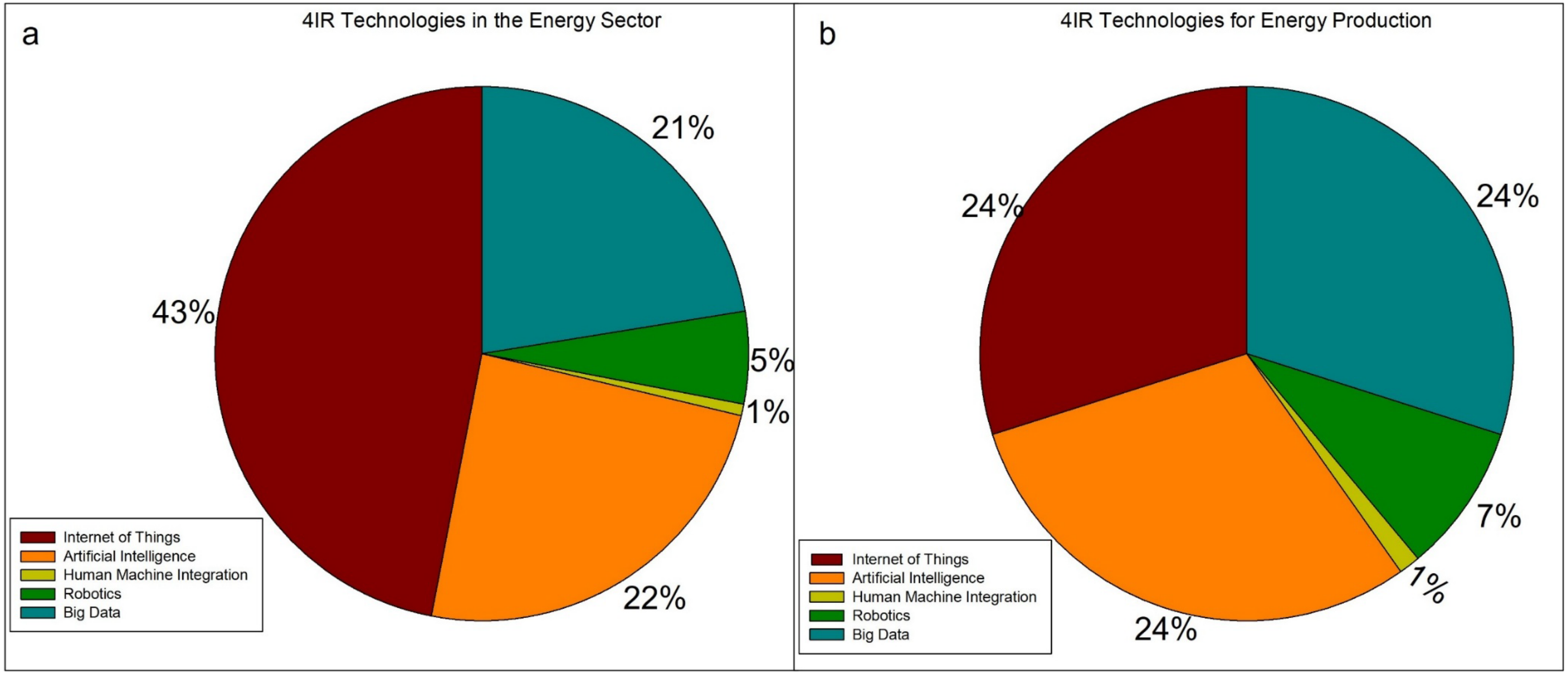

Fig. 3. The number of global publications globally per Industry 4.0 technology category in a) the overall energy sector and (b) energy production only.

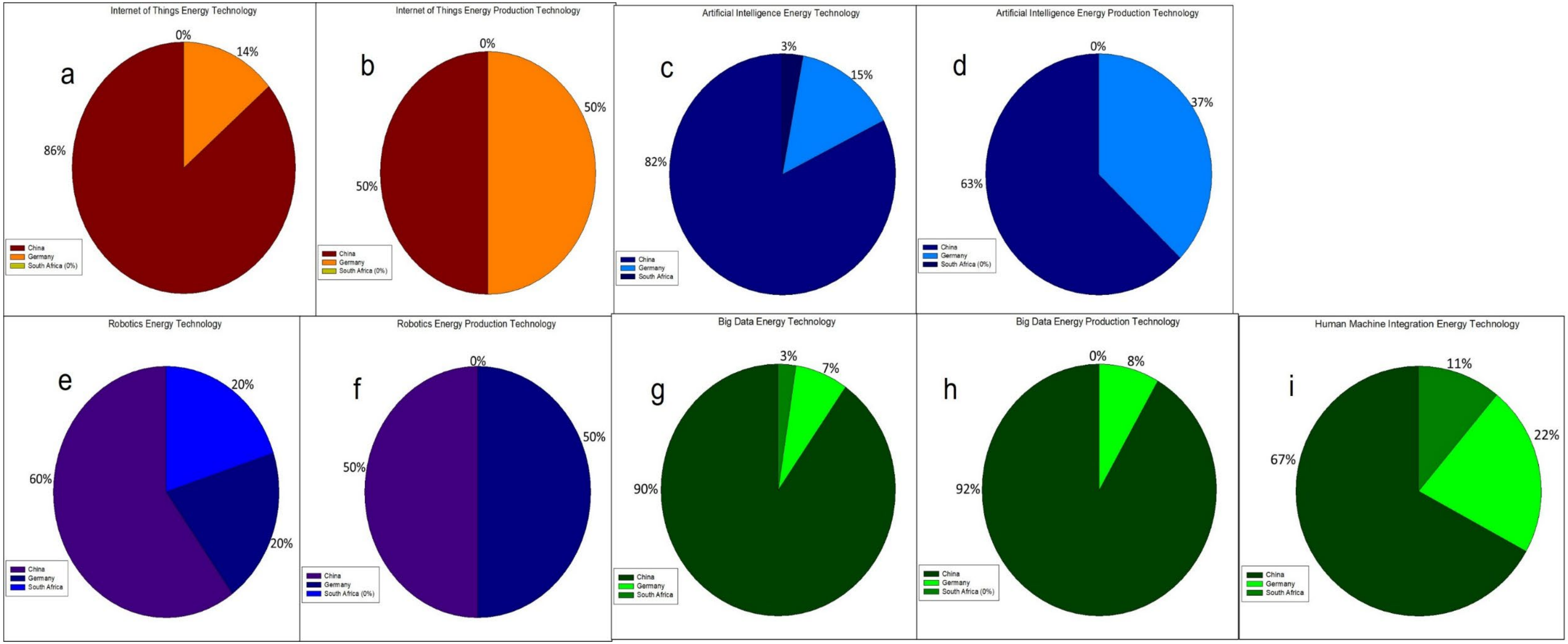

Fig. 4: Total number of publications in each technology category for China, Germany and South Africa in energy overall and energy production.