Sustainable Energy Consumption in the Industry 4.0 era

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Abstract

Worsening environmental degradation, depletion of fossil fuels reserves, and fuel price volatility have led to increased concerns about getting adequate energy to power the rapidly growing industrial sector and other uses. The cost of energy is a major contributor to the rising cost of production and a source of worry to both the producers and consumers alike. Investigation into devising sustainable, accessible, and affordable energy sources to power the manufacturing sector and other consumers has engaged the attention of researchers and other stakeholders in recent decades. The current research, therefore, investigates techniques for ensuring sustainable energy consumption in the Industry 4.0 era. Results show that effective implementation of energy saving, cost reduction, and green manufacturing measures will lower energy costs, benefit the environment and result in a high return on invested capital. The application of novel intelligent technologies like cyber-physical systems, industrial internet of things, artificial intelligence, big data, cloud computing, smart metering, and other components of Industry 4.0 will contribute to achieving sustainable energy utilization in the manufacturing sector. Going forward, more targeted investigations are required to cultivate realistic and implementable models for achieving affordable, environmentally benign, and sustainable energy for the manufacturing sector.

Keywords
Industry 4.0, sustainable energy, cost-saving, green manufacturing, intelligent technologies.

1. Introduction
The perceived depletion of fossil oil reserves, worsening environmental concerns, and the high and erratic cost of fossil-based fuels have made the continuous search for sustainable and environmentally friendly energy alternatives more imperative. The global industrial energy consumption that was 238.9 quadrillion British thermal units (Btu) in 2018 became 240.2 quadrillions Btu in 2020 and has been predicted to become 257.5 quadrillions Btu, 283.4 quadrillions Btu, and 316.7 quadrillion Btu by 2030, 2040, and 2050 respectively (Statista 2021) (Figure 1). The industrial sector, comprising iron and steel, chemical and petrochemicals, food and tobacco, paper and pulp, machinery, emitted 24.2 % of the global greenhouse gas (GHG) emission of 49.4 billion tonnes CO_{2eq} in 2016 (Ritchie and Roser 2020) (Figure 2). In 2018, the industrial sector consumed 37 % (157 EJ) of total global final energy and emitted 24 % of global emissions (8.5 $GtCO_2$) despite the deployment of renewable fuels and other low-carbon processes pathways (IEA 2020). In the United States, an industrialized

nation, the manufacturing sector accounted for about 36 % of the total energy utilization and 33 % of the total energy consumption. The bulk of the energy is from natural gas, petroleum, electricity, coal, and renewable sources (EIA 2020). With an increment in industrial activities, energy consumption and GHG emissions are predicted to increase unless some drastic actions are taken to arrest the trend. The advent of Industry 4.0 is projected to ensure a reduction in energy utilization and subsequent GHG emissions.

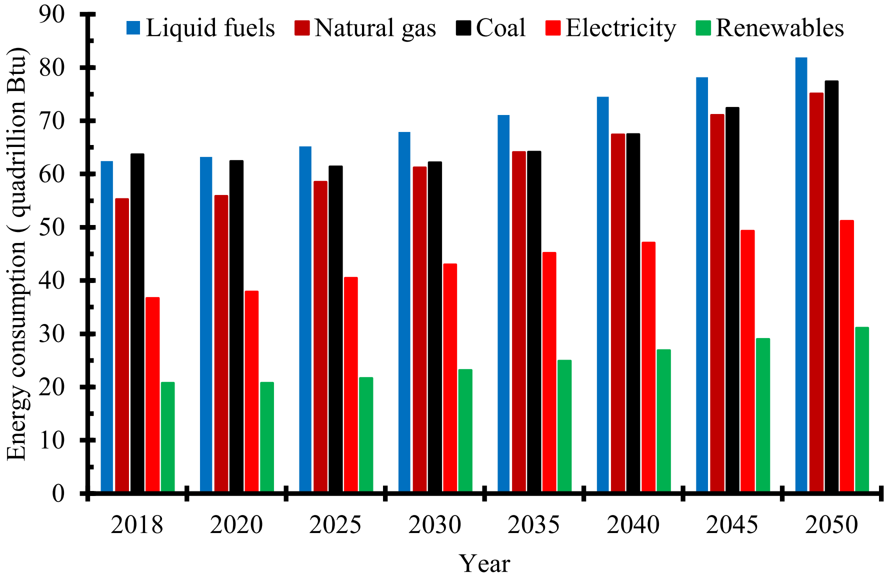

Figure 1. Global industrial sector energy consumption, by source 2018-2050 (Statista 2021)

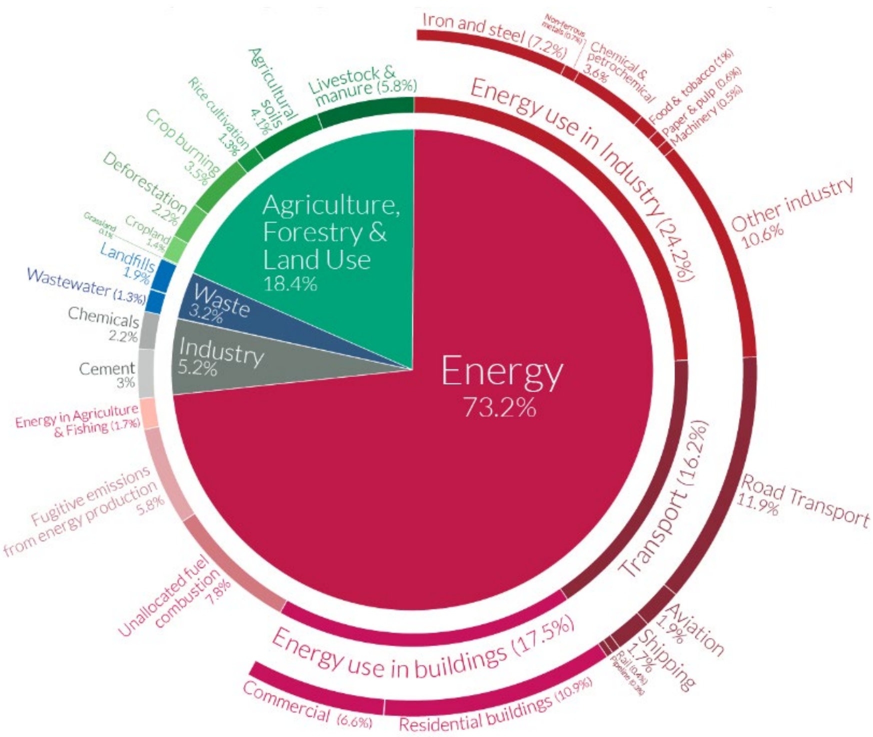

Figure 2. Global greenhouse gas emissions by sector, 2016 (Ritchie and Roser 2020).

The world has witnessed three industrial revolutions since the eighteenth century. Figure 3 shows the main features of the four Industrial Revolutions witnessed so far. The Fourth Industrial Revolution, otherwise known as Industry 4.0, is characterized by modern digital technologies including Cyber-Physical Systems (CPS), Artificial Intelligence (AI), Big Data, Cloud computing, Augment and Virtual Reality (AVR), and Industrial Internet of Things (IIoT) (Ng and Ghobakhloo 2020). Industry 4.0 aims to adopt smart manufacturing to improve productivity at the lowest cost possible by the implementation of processes, techniques, and technologies that optimize systems, reduce risks and maximize profit. Industry 4.0 allows for automation of the production systems, provides self-decision processes by minimizing human intervention and real-time control and manipulation of equipment and machinery (Alcácer and Cruz-Machado 2019, Awogbemi and Kallon 2021).

Energy consumption in the industries is principally for production, lighting, and other supplementary business, including cooling, heating, in the manufacturing industries. This energy must be used sustainably to ensure value for money and the preservation of the environment. Paper, primary metal, petroleum and coal products, chemical, wood products, food and non-metallic mineral products manufacturers consumed 27.2 %, 23.2 %, 14 %, 12 %, 6.4 %, 5 % and 4.6 % respectively in 2019 (Statcan 2020).

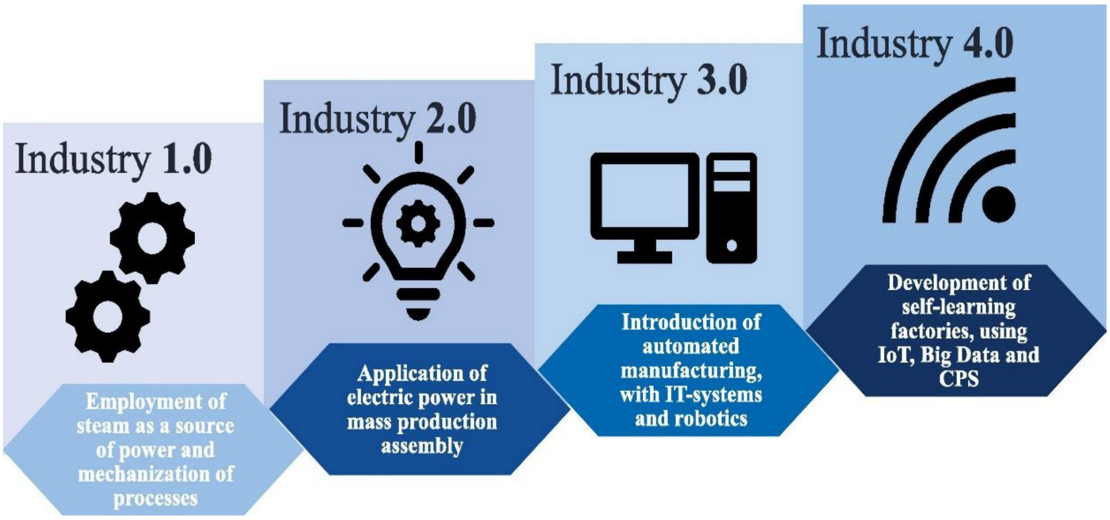

Figure 3. Industrial revolutions and their major features (Tesch da Silva et al. 2020)

2. Literature Review

The subject of the energy required for driving the revolutions in the industrial sector has attracted the attention of scholars in recent years. In research, (Ng and Ghobakhloo 2020) looked at energy utilization, energy efficiency, and energy sustainability in Industry 4.0 and concluded that energy sector transformation, smart energy management system, and making an informed decision on the choice of energy are key to sustainable energy utilization in the new industrial revolution era. According to them the digitization of the entire value chain, from retailers to the manufacturers and up to the consumers, and the digital conversion of the energy industry is needed to ensure a sustainable energy system for the new industrial revolution. Similarly, (Mohamed et al. 2019) discussed the strategies aimed at improving the energy efficiency in smart factories in the industry 4.0 era. They emphasized the need to adapt strategies and technologies that favour minimization of production cost, prevent energy wastages, and reduction on greenhouse gas emissions. According to them, environmental sustainability should not be sacrificed on the altar of increased production capacity. In their work, (Scharl and Praktiknjo 2019), (Hidayatno et al. 2019) and (Oláh et al. 2020) suggested the use of energy systems that meet the affordability, availability, and environmental sustainability requirements to drive the new industrial revolution.

2.1 Objectives

Despite the aforementioned intervention by various researchers, the pertinent question to ask, which constitutes the motivation for the current intervention is whether the utilization and consumption of energy in the Industry 4.0 era has been fully interrogated and adequate solutions provided. The object of this work is to interrogate sustainable energy consumption in Industry 4.0 era. Specifically, strategies and technologies to ensure energy savings, energy cost reduction, green manufacturing, energy peak load, energy balance and prevent energy breakdown are discussed to come up with a sustainable energy system for Industry 4.0. The current effort is, however, limited to desktop analysis and without any experimental data.

3. Strategies and Technologies for Sustainable Energy Consumption

One of the principal goals of Industry 4.0 is to minimize energy consumption during manufacturing. This is achievable when appropriate strategies and technologies are implemented to ensure energy savings, smart use of energy, and sustainable energy utilization. Appropriate use of energy can contribute to cost reduction, profit maximization, and attainment of smart manufacturing. The following are some of the strategies to achieve sustainable energy consumption during Industry 4.0 era.

3.1 Energy savings

With the enormity of energy used in the production process and the consequent GHG emission emanating from the consumption of such energy, it is imperative to adopt energy saving measures to minimize energy consumption during manufacturing. To mitigate the impact of rising energy costs, the environmental effect of CO_2 emissions, and improvement of energy efficiency, manufacturing outfits are forced to adopt energy management measures. One of such measures is energy saving (Kamara, et al. 2021) and (Shandu and Kallon, 2021).

The first stage in the implementation of the energy saving measures is to undertake an aggressive awareness campaign to sensitive stakeholders on the imperative of the process. There must also be a technological requirement for energy awareness to gain insight into the energy consumption pattern and identify areas of possible reduction. The use of smart meters based on the IIoT paradigm is key in metering real-time energy consumption data and monitoring the energy consumption pattern (Shrouf et al. 2017). This will lead to the implementation of energy saving initiatives to minimize energy consumption and emissions. Table 1 shows some of the strategies for achieving energy savings in manufacturing.

Table 1. Strategies for energy saving

Energy saving measures	Practical steps
Reduce energy consumption	• Use energy-efficient products like LEDs • Maintain and repair equipment regularly • Reduce the impact of harmonic currents • Ensure supply the appropriate voltage and current • Check for air compressor leaks • Install waste heat recovery systems
Optimize energy usage patterns	• Use lighting controls • Schedule your energy usage at off-peak times • Optimize appliances • Turn off appliances when not in use
Maintenance	• Undertake timely maintenance • Clean and maintain electrical and mechanical appliances • Check air conditioning lines • Reduce closing door delays • Ensure proper insulation • Equipment upgrade
Technologies	• Deploy modern low-energy consumption technologies • Install new heating and cooling systems • Novel energy management strategies • Employ proper metering and smart grid • Use cogeneration, micro-cogeneration, and trigeneration • Use cheaper renewable energy sources
Behavioral change	• Educate and collaborate with the employee • Secure employee support on better energy management • Use natural airflow instead of air conditioning or heater, where practicable

3.2 Energy cost reduction

The fact that the industrial sector uses about one-third of the total global energy indicates the high cost of energy in running the industrial sector, globally. The Manufacturers Association of Nigeria (MAN) reported that about 38 % of the total production cost was spent on energy production in 2019 while in Belgium 47 % of the production cost goes to energy (Gong et al. 2015). The cost of energy in most industries in South Africa has been put at between 15- 50 % of total operating costs (Adenuga et al. 2019). For the manufacturing industries to remain competitive and produce goods that are affordable to the consumers, the cost of energy must be drastically reduced. Table 2 summarizes some measures that can lead to cost saving in manufacturing, reduce the cost of production, guarantee a return on investments without compromising standards.

Table 2. Cost reduction measures in manufacturing

Cost saving measure	Strategies for implementation
Intelligent technologies	• Industry 4.0 technologies like AI, IIoT, big data, etc. • Embrace Lean Manufacturing • Work smarter through robotics and automation • Invest in smart metering and energy audit • Deploy energy-efficient technologies
Reduce energy consumption	• Use low energy consumption equipment and lighting • Maintain efficient energy management team • Overhaul/replace obsolete heating and cooling systems • Eliminate avenues of energy loss and leakage • Work during off-peak periods
Renewable energy	• Invest in renewable energy technologies • Waste and heat conversion and utilization • Proper energy conservation strategies
Maintenance	• Regular preventive and predictive maintenance • Reduce machine and personnel downtime • Adequate lubrication • Timely replacement of worn parts and equipment • Regular technical cleaning and sanitation • Ensure proper insulation • Prompt detection and correction of vibration anomalies in rotating equipment
Behavioral change	• Sensitize employees on energy cost saving measures • Build energy management team • Motivate employees to embrace energy saving • Switch off lighting during the day • Reward employees who obey energy cost reduction measures • Encourage energy-efficient behaviours

3.3 Green manufacturing

Green Manufacturing (GM) is an evolving paradigm in industries to achieve eco-friendly and sustainable conversion of raw materials into finished products. GM is the development and deployment of various techniques and strategies to ensure waste minimization, cost reduction, pollution eradication, resources conservation for economic growth, and return on investment. It involves strategies and techniques targeted at the reduction of environmental impacts of manufacturing, maximum utilization of resources through various integrated approaches to achieve sustainable production (Pang and Zhang 2019, Singh and Deepak 2022). The concept of green manufacturing seeks to achieve minimum energy consumption, reduce GHGs emissions, sustainable production, and consumption strategies, and improve industrial production at affordable cost. Major advantages of the deployment of GM include energy sustainability, emission reduction, improved productivity, prompt management of risk, and safety measures, among others (Dalmarco et al. 2019, Kerin and Pham 2019, Ghobakhloo 2020). Table 3 summarizes some of the benefits and strategies for achieving GM.

Table 3. Benefits and strategies for achieving GM

GM benefits	Strategies for achieving GM
Energy sustainability	• Embrace improved digital tools like robotics, additive manufacturing, IIoT, and smart metering • Introduce efficient production systems • Digitization of energy systems • Deploy smart material planning and allocation • Real-time decentralization and horizontal/vertical integration
Emission reduction	• IIoT and AI-based production system • Implement mass customization and product individualization • Novel environmental and social sustainability measures • Waste reduction and conversion • Minimize carbon emission
Environmental sustainability	• Deploy IIoT, robots, and cloud big data to ensure compliance with environmental standards • Adopt environmental-friendly practices • Efficient waste and emission reduction
Increased productivity	• Deploy IIoT, CPS, and other intelligent technologies • Digitize manufacturing system • Development and implementation of a hybrid lean-agile manufacturing system • Use industrial automation to reduce human intervention, risk, and injury
Risk and safety management	• Use of IIoT, CPS, AI, machine learning, cloud data, and data analytics • Deployment of intelligent cameras, smart sensors, smart safety wearables, and AI-based location awareness systems • Identify potential hazards and avert them • Implement advanced built-in safety measures
Cost reduction	• Adaptation of improved technologies • Streamlined procurement processes • Real-time monitoring and accident prevention • Waste reduction and utilization • Energy efficiency • Reduction of human errors through automation • Intelligent decision-making
Production modularity	• Application of smart digital technologies like data mining, data analytics, AI, IIoT • Process digitization • Waste reduction • Higher productivity and product customizability.

4. Conclusion

Evolving inexpensive and ecologically benign energy to power the manufacturing sector is a task that must be accomplished to the benefit of social and economic development. In this study, we have established the inevitability of low cost and readily available energy for the manufacturing sector, especially in the Industry 4.0 era. To have adequate and sustainable energy for the industrial sector, energy saving, energy cost reduction and the deployment of green manufacturing techniques are paramount. The application of energy management, energy sustainability, waste reduction and conversion, reduction in energy consumption, energy audit, emission reduction, and behavioural change are key issues to achieve sustainable energy for the manufacturing sector. The deployment of AI, AVR, CPS, IIoT, data analytics, robotics, cloud computing, smart metering, and other intelligent technologies to back up the infrastructure for Industry 4.0 will enhance this process.

Advanced manufacturing techniques such as additive manufacturing, lean manufacturing, green manufacturing, rapid prototyping manufacturing, and nanomaterials should be employed and implemented. Employees must be encouraged and motivated to embrace energy conservation measures and key into other energy saving techniques to complement the management vision for energy sufficiency. Going forward, more targeted investigations are needed on the adaptation and deployment of more intelligent technologies and other practices that will ensure the availability of energy for the industrial sector.

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Biographies

Omojola Awogbemi obtained PhD in Mechanical Engineering from the University of KwaZulu-Natal, South Africa in 2020. He had earlier graduated with a Higher National Diploma in Mechanical Engineering from Yaba College of Technology, Lagos, Nigeria in 1998, Post Graduate Diploma in Mechanical Engineering from University of Ado Ekiti (now Ekiti State University), Nigeria in 2004, and Master of Engineering degree in Mechanical Engineering from Ekiti State University, Ado Ekiti, Nigeria in 2014. Dr. Awogbemi is a registered Engineer with the Council for the Regulation of Engineering in Nigeria and an active member of Nigerian Society of Engineers, South African Institution of Mechanical Engineering, among other professional bodies. He has published widely in peer reviewed journals, and presented papers in local and international conferences. His research interest includes Renewable Energy, Bioenergy, Waste to Energy, Biomass Conversion, Biofuel generation and utilization, and Engineering Education.

Daramy Vandi Von Kallon is a Sierra Leonean holder of a PhD degree obtained from the University of Cape Town (UCT) in 2013. He holds a year-long experience as a Postdoctoral researcher at UCT. At the start of 2014 Dr Kallon was formally employed by the Centre for Minerals Research (CMR) at UCT as a Scientific Officer. In May 2014 he transferred to the University of Johannesburg as a full-time Lecturer and later a Senior Lecturer in the Department of Mechanical and Industrial Engineering Technology (DMIET). Dr Kallon has more than twelve (12) years of experience in research and six (6) years of teaching at University level, with industry-based collaborations. He is widely published, has supervised students from Master to Postdoctoral levels and has graduated seven (7) Masters Candidates. His primary research areas are Acoustics Technologies, Mathematical Analysis and Optimization, Vibration Analysis, Water Research and Engineering Education.

Adefemi O. Owoputi is a Nigerian-born academic researcher based in South Africa. Adefemi obtained his Bachelor degree in Materials and Metallurgical Engineering from the Federal University of Technology, Akure, Nigeria, after which he proceeded to University of KwaZulu-Natal, South Africa for his Master degree in Mechanical Engineering where he focused on power generation from renewable sources. He graduated with a *cum laude* and his research dissertation has been published into a book. Adefemi recently completed his PhD study on materials development for engineering for engineering application. During his Doctoral study, he developed functionally graded metal matrix composites for automobile engine component, using a combination of unique fabrication processes. His research interests are in, but not limited to, material engineering development, renewable energy, additive manufacture, and project management and has authored several academic journal articles stemming from his research. He is currently a lecturer in the Information Systems department at the Durban University of Technology, South Africa.

Kelleh G. Mansaray is a Professor, engineer, educator, and one of the leading pioneers in the development and promotion of various renewable technologies in Sierra Leone. He has taught and conducted research in a range of disciplines, and published several papers in scholarly journals. Prof. Mansaray holds a BSc Degree in Physics, an MSc Degree in Energy Engineering, and a PhD degree in Bioenergy Engineering. He is a member of the International Association for Solar Energy Education (IASEE), a member of the Professional Engineers Registration Council of Sierra Leone (PEng) and a Fellow of the Sierra Leone Institution of Engineers (FSLIE).