Chapter 18

Green Software Engineering Development Paradigm:

An Approach to a Sustainable Renewable Energy Future

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ABSTRACT

A major software engineering process of the twenty-first century is green software engineering (GSE), which represents a complete paradigm shift in the software development process. Previously, software engineers were primarily concerned with developing hardware and software, with little attention paid to sustainability, or to the technical, economic, environmental, social, and individual aspects of environmental sustainability. It is necessary to determine the elements that affect the sustainability of GSE on an individual basis as well as how they interact with team and organizational practices, policies, and decisions. The fundamental goal is to create best practices and recommendations that have been experimentally established for measuring, enhancing, and preserving sustainability from the standpoint of the software engineers. It is anticipated that these steps will guarantee engineers' sustainable approach to the software engineering profession and facilitate regular, high-quality software development towards carbon emission reduction.

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1. INTRODUCTION

The creation of useful and user-friendly software is just one aspect of software engineering development process; that focused on the environmental sustainability that track and manage consumption and compute related carbon emissions by processing environmental data on energy, transportation, waste, water, and fugitive gasses(Da Fonseca-Soares, Eliziário, Galvinicio, & Ramos-Ridao, 2023). Green software engineering(GSE), also known as sustainable software, maximizes energy efficiency and reduces its negative effects on the environment throughout the course of its lifetime(Lorincz, Capone, & Wu, 2019). This kind of software considers the environment during its design, development, and implementation. A fundamental set of skills that can assist in defining, developing, and implementing sustainable software applications are the principles of sustainable software engineering, which must be adhered to in order to produce sustainable software. Aspects like data, testing, deployment, operations, architecture, design, code, infrastructure, and monitoring are all covered by these concepts(Raturi, Tomlinson, & Richardson, 2015). The ability and duty to produce software that is sustainable and can lessen the environmental impact of an organization's goods and services falls on software developers and architects. In order to lessen the information technology (IT) industry's environmental impact with relation to its practice of contributing to toxic waste and global warming, GSE is essential(Almusaed, Almssad, Alasadi, Yitmen, & Al-Samaraee, 2023). Software can be made to use less energy and hardware resources by implementing modern application architectures, such as serverless computing or functions-as-a-service (FaaS) architecture, localizing computer processing, optimizing logical constructs, and reducing data exchanges and service calls. Software engineers may design systems that are responsible, resource-efficient, and energy-efficient by implementing sustainable software engineering techniques into software development practice(Heithoff, Hellwig, Michael, & Rumpe, 2023).

The objective of green software engineering is to minimize greenhouse gas emissions and lower an organization's carbon footprint. Software that emits the least amount of carbon is considered green software, or carbon-efficient software(Schmidt et al., 2023). Energy efficiency, carbon awareness, and hardware efficiency are the only three actions that lower software's carbon emissions. Organizations can achieve environmental, social, and governance compliance by making the most of their current resources and developing green software(Wu & Tham, 2023). Corporate performance evaluation criteria evaluate a company's ability to oversee its social and environmental impacts and how well its governance mechanisms are in place. The field of software engineering has grown to be vital to society's professional aspirations, and as its use has grown, so too have the demands on energy and resources. IT finds more effective software solutions to solve environmental issues, which helps to promote sustainability. The GSE takes into account the needs for computer hardware and software in order to solve sustainability's environmental implications(Jiang, Ni, Ni, & Guo, 2023). In an IT system, hardware and software are meaningless without the application layer that integrate it with other cyber physical systems and Internet of Things (IoT) infrastructures. Operating on hardware, the software offers features like paperless workplaces, smart heating, smart lighting, and smart logistics. Because software development is a human endeavor, sustainability ought to be taken into account.

The environmental and energy aspects of software engineering sustainability have received the majority of research attention. There are several reasons why adopting a GSE approach is imperative.

i. **Cost Reduction:** Software product operation and maintenance costs can be decreased with the use of GSE techniques, such as resource optimization.

ii. **Enhanced Usability:** Due to its increased speed and dependability, software that is made with sustainability and efficiency in mind can offer a better user experience.
iii. **Accountability for Ethics:** It is crucial for software developers to think about how their work will affect society at large and make decisions that will lead to a more sustainable future.
iv. **Advantage over competitors:** Businesses that use GSE techniques can stand out from the competition and show their dedication to sustainability, giving them a competitive edge.

2. THE OVERALL STUDY OBJECTIVE

i. To give a summary of the many technology gateway, architectures, infrastructural methods that are used in implementing GSE initiatives.
ii. To designate the fundamental architectural designs for GSE that supported energy conservation, reuse, sustainable energy sources, and environmental safety considerations.
iii. On the account that many businesses already have a strong commitment to sustainability, it's critical to align the GSE design process with current environmental or climate management protocols and to make the outcomes of the process widely available, particularly through sustainability reports.
iv. GSE incorporates best practices for environmentally friendly applications since it is centered on hardware and how it operates in IT. The emphasis is on practical approaches, trustworthy data, instruments, and methods that enhances both the environmental impact and sustainability.
v. All facets of sustainable software design are integrated into GSE design, including scope, specification, architecture, design, and implementation. The following aspects of the usage phase are also taken into account: maintainability, modest user hardware needs, and CO2 reduction through software uses.

3. THEORETICAL FRAMEWORK

The GSE is a code paradigm that synthesizes software as a service (SaaS), platform as a service(PaaS) and code driven infrastructures as a service ((IaaS) and execute them with intention of minimizing energy usage and minimizing its impact on the environmental ecosystem sustainability(Franco, Graña, Flacher, & Rikap, 2023). Climate change, electrical markets, hardware and data center design, software practices, and software architecture are all taken into account in green software engineering. A company's carbon footprint is also intended to be decreased through the usage of green software engineering(Voumik, Ridwan, Rahman, & Raihan, 2023). Companies are committing to becoming carbon neutral or even negative in order to combat the global climate devastation. Using green software computing strategies, the public cloud provider manages all of the hardware and traditional software, such as middleware, application software, and security(Onyebuchi et al., 2022). The SaaS clients have the ability to construct, grow, and upgrade business solutions more quickly, predict total cost of ownership more precisely, and do it at a substantially lower cost compared to managing on-premises systems and software. For the past several years, software vendors have been hammering home to IT specialists and business executives the advantages of cloud computing infrastructures. Along with improved performance and efficiency, the cloud infrastructures also helps organizations reduce IT expenditures, as it offers greater flexibility and reliability Additionally, it enhances innovation, enabling businesses to deploy AI and machine learning use cases into computational strategies and accelerate time to market and overall energy business automation(Ohabuiro, Matthew, Umar, Tonga, & Onyebuchi, 2022)s.

Given the importance of innovation in the digital era, companies want to leverage the most recent advancements in software engineering to create a friendly environment. Cloud computing addresses resource and energy consumption, enabling IT businesses to implement green software engineering computing(Katal, Dahiya, & Choudhury, 2023). The Green Software Foundation was founded in May 2021 by Microsoft, Thoughtworks, Accenture, GitHub, Joint Development Foundation Projects LLC, and Linux Foundation(Peters, 2023), as a nonprofit organization with the goal of creating a network of people, standards, tooling and best practices for green software. A few of these businesses have also committed to taking individual action to address the climate crisis through effective green computing schemes. As a matter of fact, Microsoft is pushing all software engineers, developers, and others to design, create, and implement sustainable applications in addition to doing so themselves. Microsoft suggests that in order to become more energy-efficient and lower their carbon emissions, businesses should shift their workloads to the cloud and make coding, architectural, and other modifications that will lower carbon emissions(Buyya, Ilager, & Arroba, 2024). Over 70,000 of Accenture's engineers have received training in GSE techniques, and the corporation claims that it has created its own green software tools, framework, and best practices by moving 95% of its applications to the public cloud. Technology from Thoughtworks, including its green cloud service, might help cut carbon emissions directly, the company claims. Since 2019, all platform usage and development on Microsoft-owned GitHub have been carbon neutral. VMware, which became a member of the Green Software Foundation in January 2022, is utilizing more energy-efficient IT infrastructure in an effort to lower the overall energy consumption of workloads(Venters et al., 2023).

Energy-efficient data centers, multi-tenancy, virtualization, and other techniques allow cloud computing to lower energy consumption and carbon emissions, motivating companies to embrace the computing architecture(Gupta et al., 2022). It is no longer necessary to have energy-intensive data centers when using cloud computing. Additionally, edge computing enables cost-saving redistribution of processing close to users. It enables the construction of smaller data centers, which require less energy and money for upkeep. Parallel computing also contributes to lower energy usage by allowing several small-scale computations or functions to execute concurrently on numerous processors that communicate with each other through shared memory(Jin et al., 2017), as opposed to using more power while operating on separate hardware. The convergence of cloud computing, IoT technology, and artificial intelligence (AI) has significantly transformed software engineering development methods, opening the door to a disruptive technological era of insights and solutions(Alahi et al., 2023). IoT technologies offer real-time data streams that track critical parameters in environmental monitoring, reveal complicated correlations in ecological sensing, and reveal intricate connections in forest monitoring. IoT sensors provide insights on carbon cycles and coral health in a variety of habitats, including peatlands and coral reefs. With built-in analytics and a comprehensive perspective of the entire organization, a modern SaaS suite may enable better business decisions, facilitate faster innovation, and provide improved customer experiences in response to these competitive challenges. Using a network of sensors to collect data is one of the core components of IoT-based environmental monitoring(Hernández-Morales, Luna-Rivera, & Perez-Jimenez, 2022). More broad coverage and better granularity of data are now possible with monitoring systems due to their enlarged scope and scalability brought about by advancements in energy efficiency, wireless connectivity, and sensor downsizing. In order to combine real-time responsiveness with effective data management, edge and cloud computing integration has emerged as a key technique for handling the massive amounts of data produced by IoT-based environmental monitoring systems(Khanh et al., 2023).

4. RESEARCH METHODOLOGY

The concern for GSE initiative, sometimes referred to as sustainable software, green computing, or green coding, has been around for a while, with emphasis on meaningful and sustainable preservation of the environment and limiting environmental pollution. Software must be created and used effectively and efficiently with minimal to no impact on the environment as green coding can be a significant factor in reducing carbon emissions and enhancing sustainability initiatives in small, medium, and big enterprises. The current study made use of secondary data gathered from the archive of International Energy Agency (IEA) that quantified the amount of carbon emission from various industries around the world. In order to generate forecasts on energy consumption, energy-related to CO_2 emissions, and other greenhouse gas emissions throughout time, the IEA examines a variety of reliable statistics sources. The latest information is derived from national government statistics and real-time data from power system operators across the globe. A wide range of topics are covered in the IEA Market Report series, such as electricity, natural gas, coal, oil, and renewable energy. Another approach is the most recent monthly data that was sent to the IEA Energy Data Center. In the absence of monthly or annual information, estimates are utilized. In addition to emissions from industrial operations like the manufacturing of cement, iron and steel, and chemicals, the scope of CO2 emissions in this report encompasses emissions from all uses of fossil fuels for energy purposes, including the combustion of non-renewable waste. The most recent production data for aluminum, chemicals, iron and steel, and cement clinker are used to estimate emissions from industrial processes.

A comprehensive view of greenhouse gas emissions connected to energy is given by CO2 emissions(Kazaure, Matthew, & Nwamouh, 2022). The current study observed that despite the disruptions brought on by the global energy crisis, the rate of increase in emissions worldwide was not as high as some had initially anticipated(Hoang et al., 2021). In addition to providing data on methane and nitrous oxide emissions connected to energy, this most recent release compiles the IEA's most recent analysis and calculates CO2 emissions from all energy sources and industrial processes. As part of the IEA's support for the Paris Agreement, this research is being conducted in the lead-up to COP28, the just concluded UN Climate Change Conference, which was scheduled at the end of 2023. Estimates of the greenhouse gasses associated with energy in the world also include emissions of CO2 from the burning of flared gases. Fugitive emissions, or the deliberate and unwanted release, leakage, or discharge of gases or vapors from pressure-containing machinery or facilities, such as oil, gas, and coal supplies, are examples of non-CO2 greenhouse gas emissions. Based on the normal emissions factors for the appropriate end uses and areas, methane and nitrous oxide emissions associated with energy combustion are also investigated. The term "global warming" refers to the slow, long-term rise in earth's atmospheric average temperature caused by the greenhouse effect, which occurs when heat from solar radiation is trapped in gases from various human activities, such as burning fossil fuels. The majority of scientists worldwide concur that global warming is a real issue that, if ignored, could have disastrous consequences for humanity, despite differing views on the matter. Humans are the primary cause of this issue, according to more than 99% of peer-reviewed scientific studies(Lynas, Houlton, & Perry, 2021). The overabundance of greenhouse

Table 1. Global carbon dioxide emissions from 2010 to 2022, by sector (in million metric tons of carbon dioxide)

Year	Power industry	Transportation	Buildings	Industrial combustion	Industrial processes	Fuel exploitation	Other sectors
2010	12,512.60	7,010.90	3,330.10	6,080.70	2,503.20	2,271.40	139.50
2011	13,112.60	7,128.40	3,262.80	6,311.10	2,655.20	2,294.50	146.70
2012	13,393.90	7,187.50	3,229	6,332	2,741.30	2,346.90	149.40
2013	13,626.20	7,373.90	3,348.50	6,358.80	2,823.70	2,380	155.50
2014	13,686.20	7,497.30	3,290.90	6,425.30	2,886	2,353.50	151.10
2015	13,387.10	7,732.10	3,316.80	6,286.60	2,857.70	2,423.20	155.40
2016	13,441.60	7,879.20	3,350.90	6,130.90	2,961.50	2,337.20	154.70
2017	13,754	8,078.30	3,417.50	6,067.80	3,024.50	2,395.40	152.70
2018	14,203.60	8,271.80	3,438.80	6,206.70	3,107.40	2,450.30	153.20
2019	14,084	8,269.90	3,354.10	6,210.70	3,179.20	2,568.60	158.30
2020	13,584.10	7,101.10	3,276.60	6,181	3,219.70	2,417.10	164.90
2021	14,533.30	7,610.50	3,439.70	6,497.60	3,321.20	2,512.60	167.20
2022	14,669.30	7,967.60	3,421.60	6,537.50	3,226.30	2,531.90	167.80

Global CO_2 emissions 2010-2022, by sector, Published by Ian Tiseo, Sep 18, 2023, https://www.statista.com/statistics/276480/world-carbon-dioxide-emissions-by-sector/

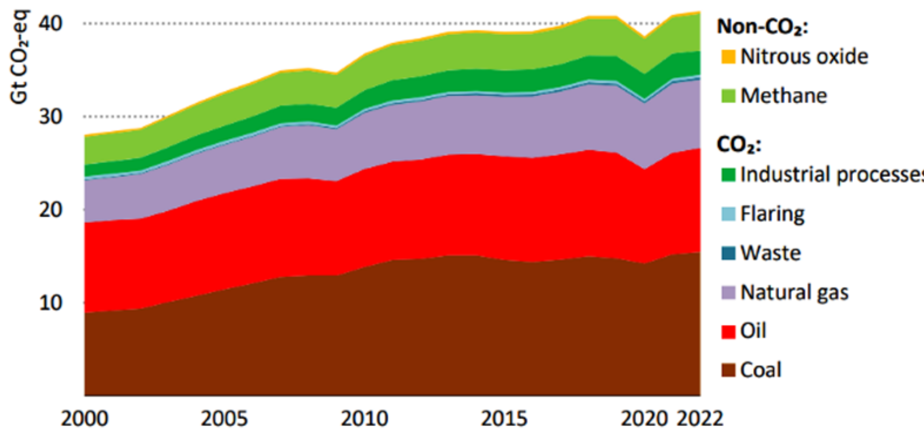
gases such as carbon dioxide (CO2), nitrous oxide (N2O), and methane (CH4) in the earth's atmosphere, is commonly blamed for global warming.

The **table 1** above illustrated the world's emissions of CO2 from industrial processes, power industry, transportation, building, industrial combustion, fuel exploitation, and other sector of the economy. The most recent official national statistics as well as openly accessible information on energy consumption, economic indicators, and meteorological data are combined with the IEA's comprehensive analysis, which is based on a region-by-region and fuel-by-fuel breakdown. The rise in emissions connected to energy was the result of two years of extraordinary fluctuations. As a result of the Covid-19 pandemic reducing energy demand, emissions decreased by more than 5% in 2020. Emissions increased more than 6% in 2021 in response to the introduction of vaccines and economic stimulus, surpassing pre-pandemic levels when the global economy returned to growth.

4.1 IoT Data Handling in GSE Design for Environmental Sustainability

This study examined the top 10 Sustainable Cloud Companied and role of investments in sustainable infrastructure in GSE with focus on renewable energy system that targeted carbon reduction through software energy paradigm shift, with the global goal of implementing more environmentally friendly cloud services. Modern technologies are designed to maximize resource efficiency and minimize their negative effects on the environment without sacrificing performance. To ensure that technology does not contribute to global warming, the major organizations have a responsibility to share their knowledge and development budgets in order to reshape the world in both a digital and sustainable way. This endeavor includes identifying the technological footprint as well as prioritizing actions to stop awkward computing mechanization. The ten cloud providers under investigation are changing the digital environment and

Figure 1. The global energy-related greenhouse gas emissions from 2000-2022
Source: The IEA's analysis of flaring emissions, derived from the World Bank's Global Gas Flaring Reduction Programme.



creating the interconnected world of the future by making significant investments in sustainable data centers and ethical cloud services.

The **Figure 2** illustrates the basic architecture of the layers that handle, fuse, and analyze IoT sensor data in the environmental handling. The primary constituents of the IoT sensor data layer are multiple IoT sensors, each of which is capable of measuring the physical surroundings and logging environmental changes in real time(Paredes-Baños, Molina-Garcia, Mateo-Aroca, & López-Cascales, 2024). Among the commonly used IoT sensors are thermometers, humidity, level, pressure, accelerometers, gas, gyroscopes, motion sensors, optical sensors, infrared (IR) and RFID sensors, and others. Wi-Fi communication interfaces, microprocessors, storage, control, and power systems are the main components to which IoT sensors are attached. There are limits to IoT sensor devices in terms of size, computing power, memory, networking, and storage capacity(Majid et al., 2022). Near Frequency connection (NFC), Bluetooth, Wi-Fi, Zig Bee, and LTE/4G mobile technologies are commonly used wireless communication protocols for IoT sensor device connectivity(Theissen, Kern, Hartmann, & Clausen, 2023). Most IoT sensor data are analyzed in real time for use in industrial, scientific, and environmental applications. To improve understanding and decision-making, it is essential to filter these sensed data to eliminate any ambiguities before assessing them further. In light of this, the data processing layer focuses on several tasks, including data aggregation, data denoising, data outlier detection, and data repair for missing values. The data fusion layer is in charge of managing the various sensor data issues that arise from multiple heterogeneous sensor devices. Data fusion is used to combine actual sensor data from several IoT sensor devices. Next, for effective knowledge creation and decision-making, the integrated data from several sources is transmitted to the data analysis layer. Direct sensor data fusion from various sensor devices is the main method of data fusion. Data fusion comes after the first stage of feature extraction. Cloud, fog, and edge computing have all seen revolutionary changes in recent years as a result of the adoption of developing technologies, leading to the analysis of IoT sensor data(Krishnamurthi et al., 2020).

The ubiquitous, dependable, and practical platform offered by these enabling technologies allows for the management of the dynam ic and diverse character of IoT sensor data. In order to handle a wide range of IoT-based applications, the data analytic layer thus strives to build intelligent capabilities. Reduced computing and storage costs, increased network transmission reliability, decreased network latency,

Table 2. Cloud infrastructure for renewable energy sustainability

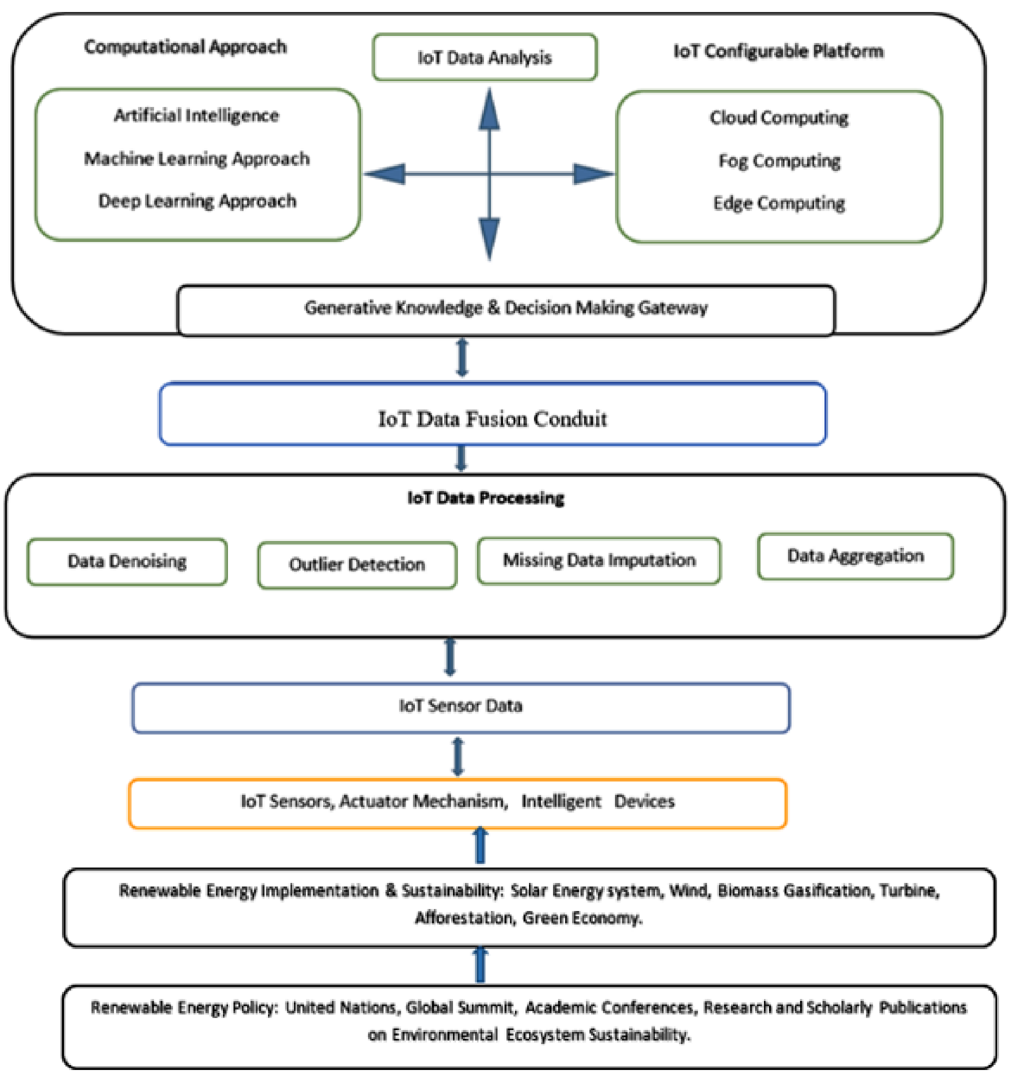
Company	Significant Cloud Service for Renewable Energy Initiative	IT Investment/ Infrastructure Worth as at January 2024
Akamai	The adaptive network design of Akamai optimizes data routing while lowering transaction power usage. By supporting more environmentally friendly renewable energy sources and digital infrastructure, this strategy exemplifies Akamai's dedication to the environmental ecosystem sustainability.	$17.77 billion
DigitalOcean	The data centers of DigitalOcean are purposefully engineered to maximize energy efficiency and comply with stringent environmental regulations, with a focus on conscientious e-waste disposal and recycling.	$3.01 billion
OVHcloud	By utilizing cutting-edge cooling methods like drawing air from outside sources, OVHcloud dramatically lowers the energy required for cooling systems. In an effort to lessen their carbon footprint, they also make investments in renewable energy sources. OVHcloud's commitment to the circular economy is demonstrated by their recycling and repurposing of server components, which emphasizes their environmental responsibilities.	$28.927 Million
HPE Greenlake	Utilizing state-of-the-art technologies for energy conservation and carbon footprint reduction in conjunction with renewable energy sources and environmentally friendly materials is part of HPE GreenLake's focus on data center efficiency. With the help of HPE's solutions, customers can efficiently track and manage their environmental impact.	$8.3 billion
Oracle Cloud	Carbon emissions and power usage are greatly decreased by using energy-efficient data center technologies. In an effort to provide more environmentally friendly cloud services, Oracle Cloud aggressively invests in sustainable infrastructure and renewable energy sources. Cutting-edge technologies are optimized to maximize resource efficiency and minimize environmental impact while preserving high performance.	$282.12 billion
IBM Cloud	By incorporating environmentally friendly practices into its cloud services, IBM Cloud, along with the entire organization, exhibits a strong commitment to sustainability. IBM is focused on running data centers with little energy consumption and using renewable energy to power its buildings. IBM's performance in resource optimization is further enhanced by its use of analytics and AI.	$5 billion
Alibaba Cloud	Being a well-known player in the technology industry, Alibaba Cloud prioritizes sustainability in renewable. Energy-saving solutions installed in its data centers result in notable drops in energy consumption and carbon emissions from data center operations. Alibaba Cloud goes on top of and above by using analytics driven by AI to maximize resource efficiency and minimize waste.	$41-$60 billion
Google Cloud	With the use of advanced cooling technologies and clever resource management, Google Cloud excels in energy efficiency within its data center operations. Adopting renewable energy is a crucial component of Google Cloud's strategy, which it has been actively pursuing since 2017. The corporation significantly lessens its environmental effect by running carbon-neutral data centers.	$225 billion
Microsoft Azure	Microsoft Azure prioritizes water conservation and uses cutting-edge cooling techniques to cut down on water usage. With the audacious aim of achieving carbon-negative operations by 2030, Microsoft Azure is also actively involved in efforts to reduce carbon emissions.	$646.55 Billion
AWS, or Amazon Web Services	Along with reducing water use, AWS is investing in large-scale solar and wind projects. Amazon is a leader in environmentally friendly cloud services because of its sustainable approach, which strikes a balance between technological innovation and ecological responsibility in the ever-changing, more connected digital ecosystem.	$8.07 Billion

improved IoT network security and privacy, guaranteed scalability, and the ability to implement failsafe and risk-free IoT solutions are the goals of these platforms. Future developments in the Internet of Things will enable interaction between virtual and physical computer entities through context-awareness, which encompasses environment sensing, network connectivity, and data processing techniques. Advanced Internet of things applications enabled by advancements include intelligent healthcare, smart building systems, smart energy, and smart transportation. The intelligent IoT-based application services and the underlying IoT sensor networks are a component of the IoT networks' cohesive design. Predictions from Gartner indicate that the global IoT industry will have 5.8 billion IoT-based applications by 2020, a 21% increase from 2019. Also, the worldwide IoT market is expanding due to the use of cutting-edge technologies like cloud computing and wireless networking which had already permitted the sustainability of GSE development paradigm(Allioui & Mourdi, 2023).

5. RESULTS

A global paradigm from the use of fossil fuels toward sustainable, renewable energy sources has been forced by the need to create a new energy mix for the digital economy of the twenty-first century(Kazaure

Figure 2. Modified Framework of GSE
(Krishnamurthi, Kumar, Gopinathan, Nayyar, & Qureshi, 2020)



s/n	Global Protocol on Renewable Energy & Environmental Ecosystem Sustainability	Performance Effect
1.	The 26th United Nations Climate Change Conference (COP26) held at Glasgow 2021(Stoddart, Tindall, Brockhaus, & Kammerer, 2023).	Achieving worldwide net zero carbon emissions, maintaining the 1.50C temperature increase goal in order to safeguard environmental ecosystems, and mobilizing resources.
2.	The Renewable Energy Policy Network for the 21st Century(REN21) programme(Burrett et al., 2009).	In order to develop frameworks and analyze trends in the renewable energy market, industry, and policy, REN21 worked with a number of stakeholders, including the World Bank, the G20, and the International Renewable Energy Agency (IRENA) to renegotiate renewable energy future.
3.	The 2015 Paris Agreement on environmental protection, a legally binding international treaty on climate change, adopted by 196 Parties at the UN Climate Change Conference (COP21)(Zangerolame Taroco & Sabbá Colares, 2019).	A global discussions concerning the mitigation of the impacts of climate change.
4.	The Kyoto Protocol, an international agreement that expanded the United Nations Framework Convention on Climate Change (UNFCCC) established in 1992(Harrould-Kolieb, 2019).	Article 2 of the Framework Convention states that stabilizing greenhouse gas concentrations in the atmosphere at a level that would preclude harmful anthropogenic interaction with the climate system is the ultimate goal of the convention.
5.	The 28th session of the United Nations Climate Change Conference (COP28) held from 30 November to 12 December, 2023 in Dubai, the United Arab Emirates(Locke, Dsilva, & Zarmukhambetova, 2023).	In order to guarantee that food production is not jeopardized, to allow ecosystems to naturally adapt to climate change, and to facilitate sustainable economic development, the treaty called for regular meetings, negotiations, and future policy agreements.
6.	South African International Renewable Energy Conference, 2015.	South Africa hosted its first-ever International Renewable Energy Conference (IREC) in October 2015, making it the first African continent’s sixth host nation overall. IREC is a high-level political conference series hosted by a national government, organized by the Renewable Energy Policy Network for the 21st Century (REN21). Previously, the event has been hosted in Bonn, Germany (2004), Beijing, China (2005), Washington, USA (2008), Delhi, India (2010), and Abu Dhabi, United Arab Emirates (2013). Government ministers, senior decision-makers, experts, specialists, and thought leaders, as well as members of the private sector and civil society, had a global platform to discuss and exchange ideas, experiences, and solutions to speed up the global scale-up of renewable energy at the South African International Renewable Energy Conference (SAIREC 2015).

et al., 2022). The 197 signatories, who included representatives from businesses, government agencies, and environmental advocacy groups, reaffirmed the objectives of the 2015 Paris Agreement on environmental protection with the proposed measures for securing global net zero carbon emissions, maintaining the 1.50C temperature increase target, and mobilizing resources. The information in table 3 showed the global commitment to the renewable energy projection and environmental sustainability.

The ability to develop environmentally friendly software while taking into account the requirements of the process of green and sustainable software engineering will require government, industries and citizens commitment. Optimizing software for energy efficiency, use sustainable coding practices, and leverage cloud technologies to lessen environmental effect. In the area of GSE research and worldwide practice, the following results are anticipated from the current project, which will also contribute to the body of knowledge. Reducing energy use, carbon emissions, and waste output are the goals of GSE. This is accomplished by using a variety of tactics, including:

i. The first result is the development of awareness regarding the relationship between the sustainability of software engineers and their duties and obligations towards a more environmentally friendly software engineering community.
ii. The second output is a taxonomy of the factors that, at the individual, group, and organizational levels, influence the sustainability of green software and how they interact with choices, procedures, and guidelines. The taxonomy can be employed by practitioners to operationalize software sustainability concepts in decision-making processes related to the software development process.
iii. Thirdly, to make sure that GSE is sustainable, a set of scientifically supported protocols, rules, and practices have been developed. The recommendations presented here may be used by practitioners to significantly modify software engineering development processes or organizational norms and procedures for clean society.

6. CONCLUSION

With its increased sophistication in data processing, data fusion, and sensor data analytics, the green software engineering paradigm has evolved into a sustainable environmental ecosystem that uses cloud, fog, and edge computing. The present research aimed to give an overview of several data processing approaches used in green software engineering with a focus on investments in renewable energy. Using sustainable practices at each level of the software development lifecycle is part of the process of integrating sustainability into software engineering. This covers the stages of development, deployment, maintenance, and design. It necessitates a comprehensive strategy that takes into account the software's energy efficiency as well as the resources used in its creation and any possible environmental effects of its implementation. Creating software that is energy-efficient is one of the main tactics of sustainable software engineering. To do this, the software's code must be optimized to use less energy when running. Software engineering and programmers can create software that makes better use of hardware resources or employ methods that demand less processing power. Taking into account how the software's distribution may affect the environment is another aspect of sustainable software engineering. This covers the electrical energy used by data centers hosting the software as well as the electronic trash produced by outdated hardware. Software engineers can utilize techniques like cloud computing, which enables more effective use of hardware resources, and lifecycle management, which entails organizing for the recycling or disposal of hardware at the end of its useful life, to lessen these effects.

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REFERENCES

Alahi, M. E. E., Sukkuea, A., Tina, F. W., Nag, A., Kurdthongmee, W., Suwannarat, K., & Mukhopadhyay, S. C. (2023). Integration of IoT-Enabled Technologies and Artificial Intelligence (AI) for Smart City Scenario: Recent Advancements and Future Trends. *Sensors (Basel)*, *23*(11), 5206. doi:10.3390/s23115206 PMID:37299934

Allioui, H., & Mourdi, Y. (2023). Exploring the Full Potentials of IoT for Better Financial Growth and Stability: A Comprehensive Survey. *Sensors (Basel)*, *23*(19), 8015. doi:10.3390/s23198015 PMID:37836845

Almusaed, A., Almssad, A., Alasadi, A., Yitmen, I., & Al-Samaraee, S. (2023). Assessing the Role and Efficiency of Thermal Insulation by the "BIO-GREEN PANEL" in Enhancing Sustainability in a Built Environment. *Sustainability (Basel)*, *15*(13), 10418. doi:10.3390/su151310418

Burrett, R., Clini, C., Dixon, R., Eckhart, M., El-Ashry, M., Gupta, D., & House, C. (2009). Renewable energy policy network for the 21st century. *REN21 Renewables Global Status Report*.

Buyya, R., Ilager, S., & Arroba, P. (2024). Energy-efficiency and sustainability in new generation cloud computing: A vision and directions for integrated management of data centre resources and workloads. *Software, Practice & Experience*, *54*(1), 24–38. doi:10.1002/spe.3248

Da Fonseca-Soares, D., Eliziário, S. A., Galvinicio, J. D., & Ramos-Ridao, A. F. (2023). Life-Cycle Greenhouse Gas (GHG) Emissions Calculation for Urban Rail Transit Systems: The Case of Pernambuco Metro. *Applied Sciences (Basel, Switzerland)*, *13*(15), 8965. doi:10.3390/app13158965

Franco, S. F., Graña, J. M., Flacher, D., & Rikap, C. (2023). Producing and using artificial intelligence: What can Europe learn from Siemens's experience? *Competition & Change*, *27*(2), 302–331. doi:10.1177/10245294221097066

Gupta, A., Singh, P., Jain, D., Sharma, A. K., Vats, P., & Sharma, V. P. (2022). A sustainable green approach to the virtualized environment in cloud computing *Smart Trends in Computing and Communications* [Springer.]. *Proceedings of SmartCom*, *2022*, 751–760.

Harrould-Kolieb, E. R. (2019). (Re) Framing ocean acidification in the context of the United Nations Framework Convention on climate change (UNFCCC) and Paris Agreement. *Climate Policy*, *19*(10), 1225–1238. doi:10.1080/14693062.2019.1649994

Heithoff, M., Hellwig, A., Michael, J., & Rumpe, B. (2023). *Digital twins for sustainable software systems. Paper presented at the 2023 IEEE/ACM 7th International Workshop on Green And Sustainable Software (GREENS).* IEEE. 10.1109/GREENS59328.2023.00010

Hernández-Morales, C. A., Luna-Rivera, J., & Perez-Jimenez, R. (2022). Design and deployment of a practical IoT-based monitoring system for protected cultivations. *Computer Communications*, *186*, 51–64. doi:10.1016/j.comcom.2022.01.009

Hoang, A. T., Nižetić, S., Olcer, A. I., Ong, H. C., Chen, W.-H., Chong, C. T., & Nguyen, X. P. (2021). Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: Opportunities, challenges, and policy implications. *Energy Policy*, *154*, 112322. doi:10.1016/j.enpol.2021.112322 PMID:34566236

Jiang, Y., Ni, H., Ni, Y., & Guo, X. (2023). Assessing environmental, social, and governance performance and natural resource management policies in China's dual carbon era for a green economy. *Resources Policy*, *85*, 104050. doi:10.1016/j.resourpol.2023.104050

Jin, C., de Supinski, B. R., Abramson, D., Poxon, H., DeRose, L., Dinh, M. N., Endrei, M., & Jessup, E. R. (2017). A survey on software methods to improve the energy efficiency of parallel computing. *International Journal of High Performance Computing Applications*, *31*(6), 517–549. doi:10.1177/1094342016665471

Katal, A., Dahiya, S., & Choudhury, T. (2023). Energy efficiency in cloud computing data centers: A survey on software technologies. *Cluster Computing*, *26*(3), 1845–1875. doi:10.1007/s10586-022-03713-0 PMID:36060618

Kazaure, J. S., Matthew, U. O., & Nwamouh, U. C. (2022). Performance of a Gasifier Coupled to Internal Combustion Engine and Fired Using Corn Cob Feedstock in Biomass Energy Production. *Energy*, *11*(2), 35–46.

Khanh, Q. V., Nguyen, V.-H., Minh, Q. N., Van, A. D., Le Anh, N., & Chehri, A. (2023). An efficient edge computing management mechanism for sustainable smart cities. *Sustainable Computing : Informatics and Systems*, *38*, 100867. doi:10.1016/j.suscom.2023.100867

Krishnamurthi, R., Kumar, A., Gopinathan, D., Nayyar, A., & Qureshi, B. (2020). An overview of IoT sensor data processing, fusion, and analysis techniques. *Sensors (Basel)*, *20*(21), 6076. doi:10.3390/s20216076 PMID:33114594

Locke, J., Dsilva, J., & Zarmukhambetova, S. (2023). Decarbonization strategies in the UAE built environment: An evidence-based analysis using COP26 and COP27 recommendations. *Sustainability (Basel)*, *15*(15), 11603. doi:10.3390/su151511603

Lorincz, J., Capone, A., & Wu, J. (2019). *Greener, energy-efficient and sustainable networks: State-of-the-art and new trends* (Vol. 19). MDPI.

Lynas, M., Houlton, B. Z., & Perry, S. (2021). Greater than 99% consensus on human caused climate change in the peer-reviewed scientific literature. *Environmental Research Letters*, *16*(11), 114005. doi:10.1088/1748-9326/ac2966

Majid, M., Habib, S., Javed, A. R., Rizwan, M., Srivastava, G., Gadekallu, T. R., & Lin, J. C.-W. (2022). Applications of wireless sensor networks and internet of things frameworks in the industry revolution 4.0: A systematic literature review. *Sensors (Basel)*, *22*(6), 2087. doi:10.3390/s22062087 PMID:35336261

Ohabuiro, J., Matthew, U. O., Umar, S., Tonga, D. A., & Onyebuchi, A. (2022). Global Solar Radiation Modelling using an Artificial Neural Network for Kazaure, Jigawa State, Nigeria. *Journal of Electrical Engineering*, *4*(4), 316–331.

Onyebuchi, A., Matthew, U. O., Kazaure, J. S., Okafor, N. U., Okey, O. D., Okochi, P. I., Taiwo, J. F., & Matthew, A. O. (2022). Business demand for a cloud enterprise data warehouse in electronic healthcare computing: Issues and developments in e-healthcare cloud computing. [IJCAC]. *International Journal of Cloud Applications and Computing*, *12*(1), 1–22. doi:10.4018/IJCAC.297098

Paredes-Baños, A. B., Molina-Garcia, A., Mateo-Aroca, A., & López-Cascales, J. J. (2024). Scalable and Multi-Channel Real-Time Low Cost Monitoring System for PEM Electrolyzers Based on IoT Applications. *Electronics (Basel)*, *13*(2), 296. doi:10.3390/electronics13020296

Peters, M. (2023). *Exploring the market potential for sustainable steam to electricity generation within the United States*.

Raturi, A., Tomlinson, B., & Richardson, D. (2015). Green software engineering environments. *Green in Software Engineering*, 31-59.

Schmidt, A., Stock, G., Ohs, R., Gerhorst, L., Herzog, B., & Hönig, T. (2023). *carbond: An Operating-System Daemon for Carbon Awareness.* Paper presented at the Proceedings of the 2nd Workshop on Sustainable Computer Systems. ACM. 10.1145/3604930.3605707

Stoddart, M. C., Tindall, D. B., Brockhaus, M., & Kammerer, M. (2023). Conference of the Parties Meetings as Regularly Scheduled Critical Events for Global Climate Governance: Reflecting on COP 26 and the Glasgow Climate Pact. *Society & Natural Resources*, *36*(4), 442–450. doi:10.1080/08941920.2023.2175284

Theissen, M., Kern, L., Hartmann, T., & Clausen, E. (2023). Use-Case-Oriented Evaluation of Wireless Communication Technologies for Advanced Underground Mining Operations. *Sensors (Basel)*, *23*(7), 3537. doi:10.3390/s23073537 PMID:37050603

Venters, C. C., Capilla, R., Nakagawa, E. Y., Betz, S., Penzenstadler, B., Crick, T., & Brooks, I. (2023). Sustainable software engineering: Reflections on advances in research and practice. *Information and Software Technology*, *164*, 107316. doi:10.1016/j.infsof.2023.107316

Voumik, L. C., Ridwan, M., Rahman, M. H., & Raihan, A. (2023). An investigation into the primary causes of carbon dioxide releases in Kenya: Does renewable energy matter to reduce carbon emission? *Renewable Energy Focus*, *47*, 100491. doi:10.1016/j.ref.2023.100491

Wu, Y., & Tham, J. (2023). The impact of environmental regulation, Environment, Social and Government Performance, and technological innovation on enterprise resilience under a green recovery. *Heliyon*, *9*(10), e20278. doi:10.1016/j.heliyon.2023.e20278 PMID:37767495

Zangerolame Taroco, L. S., & Sabbá Colares, A. C. (2019). The un framework convention on climate change and the Paris agreement: Challenges of the conference of the parties. *Prolegómenos*, *22*(43), 125–135. doi:10.18359/prole.3449