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RESEARCH ARTICLE

Addressing the Security risk of a Massive Deployment of Photovoltaic Power for Electric Power Systems

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Abstract

Future electric power systems will incorporate a high percentage of Photovoltaic (PV) power generation as a means of mitigating environmental issues including global warming and energy depletion. The author observes that if the increase in uncertainties brought about by the PV penetration cannot be prevented, then it will be difficult to carry out the N-1 security level. To ensure the N-1 security requirement is met despite the uncertainties, paper has suggested a new notion of "robust power system security" along with many conditions to be met. In this research, and offer a model of uncertainties caused by PV generation, and use robust power system security to guide our choice of parameters. Next, simulate the system to learn more about, how PV and load disconnections affect stability, and how Fault Ride Through (FRT) and Dynamic Voltage Support (DVS) influence stability. Finally, it is demonstrated that the massive penetration of PV would significantly raise the complexity of burden jobs in future power system operation planning and real-time operation.

Keywords: Photovoltaic; PV; Solar Energy; DVS; Power System Security; Security Issues

Introduction

Global warming and energy depletion are only two of the many issues that have received attention in recent years. In an effort to address a wide range of environmental issues, the spotlight is now on renewable energy. There will likely be a significant increase in the number of intermittent renewable energy sources integrated into grids in the coming years. In particular, the quantity of photovoltaic (PV) power introduced in 2020 will be multiplied by 20, and will climb to 40 times (about 53 GW) by 2030. The future speedy installation of solar panels is a goal that has been established. Growth is anticipated to continue (1). But when solar radiation levels are high, a lot of PV is added to the grid, and its output varies a lot. the distribution system's voltage regulation and management to dampen output variations It has been noted that there are issues, such as insufficient power and frequency variations (2). in this sense However, the authors believe it is an issue that has not been well explored. Consequently, huge variations in PV production as a result of variations in solar radiation conditions, that is, prediction Increasing unpredictability makes it impossible to guarantee a constant supply of goods and services. Furthermore, the standard N1 confidence scale Create a new log and a system to track how the standard can be kept even in the face of uncertainty. explained their idea of "bust reliability" (5).

This will be effective in the future as uncertainty grows. This is expected to provide guidance for measures to sustain reliability. Following that, it will take a bird's-eye view of the complete system in a more realistic setting. The behaviour of load and PV during system disruption is interesting from several perspectives. Consider how it will impact the system. (1) Consider how load and PV dropouts affect stability. (2) Assuming that PV will be widely adopted in the future, the FRT function will be used to endure low voltage and continue operation, and the Dynamic Voltage Support (DVS) function will be used to maintain voltage. Consider the effect of Then the PV's presence or absence. Summarise the aspects of shedding. (3) load and PV desorption; power system faults may develop as a result of power outages or weather-related PV power generating conditions. The paper present that the complexity of the integration process grows by pointing out that the failure point leading to step-out can change when it occurs. In addition, the future supply and demand outlook is presented in this paper. Regarding future energy policy, however, it is necessary to review existing plans. There are numerous discussions occurring, including situational discussions. In all cases, however, the quantity of PV installed is expected to grow faster than anticipated. enigmatic uncertainty problems and confidence maintenance in uncertain environments In particular, the issue of stability affects not only India but also worldwide.

Future system reliability

Conventional system operation is based on annual, monthly, weekly, and daily time schedules. After securing reliability while gradually increasing accuracy with bread. The resulting load p(t) on the demand side is changes are almost patterned, and the uncertainties that are difficult to predict are not much to consider. Mathematically, this can be expressed as p(t) is the variation parameter value at time t, and the predicted lead time.

The estimation problem for δt can be expressed as follows.

$$p(t) = \hat{p}\ (t|t - \delta t) + \Delta(\delta t) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \ (1)$$

The first term on the right side of equation (1) is the value of p(t) estimated at time t-δt.

is the predicted value, and the second term is the prediction error. The prediction error is at time t-δt is unavoidable uncertainty in tend to increase on the other hand, in the future, a large amount of PV Under the conditions of introduction, the amount of power generated in a specific area is affected by the weather.

Uncertainties corresponding to mispredictions in supply and demand management, such as sudden changes in supply and demand are likely to increase significantly. In statistical planning, system operation planning, and real-time operation, the prediction considerable amount of difficult uncertainty Δ should be considered in analysis and control. In order to express this mathematically, in this paper, Eq. (1)

Based on the above, the existence region Rp(t) of p(t) is defined as follows.

$$Rp(t) = \{p|p = \hat{p}(t) + \Delta, \text{ for all } \Delta \in R\Delta(\delta t)\} \cdots\cdots \ (2)$$

Equation (2) above is called the parameter variation region, and the frequency of the predicted value p0(t) is allow an uncertainty Δ in A conceptual diagram of this is shown in Fig. 1.

where the region RΔ of Δ represents the spread as a function of δt, and multiple system states exist at the same time cross-section. means that it is equivalent to in this paper, the Uncertainty is defined as the difference in PV generation at the demand end (regional weather forecast).

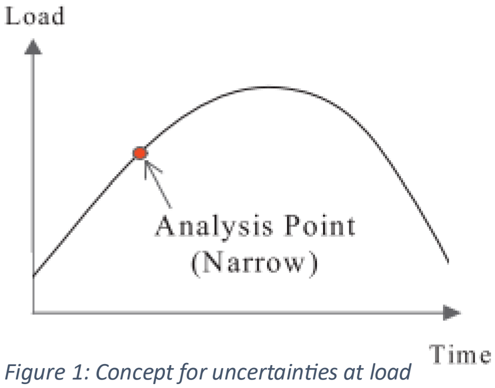

Figure 1: Concept for uncertainties at load

Applying the conventional N-1 reliability criterion in such an uncertain environment i.e., the number of analyses required to identify the most severe accident point. However, there is a risk that it will be difficult to apply due to reasons such as a significant increase. Therefore, system maintain the N-1 reliability criterion in an uncertain environment. Here, organized the conditions for what is suggested. Robust reliability refers to system planning and system operation. At some time before, maintaining the N-1 confidence criterion taking uncertainty into account.

Robust reliability is defined as follows. First, the conventional Control variables such as generator output to satisfy N-1 reliability criteria. The region of u is the static security region (SS region) is defined as follows:

$$u \in SS(p) = SS_0(p) \cap SS_1(p) \cap \cdots \cap SS_N(p)$$

$$SS_n(p) = \{u \mid u_{min} \leq u \leq u_{max},\ f_n = 0,\ g_n \leq 0\} \qquad (3)$$

$$n = 0, \ldots N$$

where $f_n = 0$, $g_n \leq 0$ is n^{th} system constraint, and $SS_n(p)$ is given by the deterministic parameter p in the region u can take while satisfying this constraint. As a system constraint, overloading of lines, etc., is considered against contingency failures. load, voltage value, voltage stability, and transient stability. It mean the intersection area for each of these constraints. The Robust Static Security region (RSS region) is by introducing uncertainties such as PV output, the parameters of Eq. (2). It is defined by the following equation as the intersection area of the SS area for the fluctuation.

Modeling of Future Grids

In this section, it is presenting a model of the 50-Hz system assuming a cross-section in 2035. Simulations using a multi-layer system confirmed the calculations shown in the previous section. In the following, the system used for the study and the desorption of load and PV are described.

Model System Used for the Study

The system is divided into three parts: demand forecast, generation mix, and power system model. The details of each are described below:

Demand Forecast "Long-term Energy Supply and Demand Outlook"

Natural Resources and Energy Agency) (6) shows power generation in 2030 in the current fixed case. For a capacity of 1,359,000 GWh, a case that introduces maximum energy conservation. The power demand reduction rate is calculated from the power generation amount of 964,000 GWh.

29% (= 1 − 96.4/135.9)

On the other hand, the "power demand Long-term Perspective" (Research Committee for Natural Resources and Energy) (7), 2000 Extending the average annual growth rate of 1.35% from 2020 to 2025. The maximum power demand in 2030 without considering energy conservation is 263.9 GW. The reduction rate of power demand of 29% mentioned above is taken into consideration. The maximum nationwide demand in 2030, when energy conservation is introduced to the maximum extent, is 187.4 GW can be assumed. Similarly, the maximum demand of the 50 Hz system is based on the 50 Hz national demand ratio (58.3%), this is the maximum demand of the 50 Hz system model used in the paper is 107.8 GW.

Simulation

In this study, the computer simulations are used to show how unfavourable weather circumstances might be avoided. The impact of determinism on system stability is investigated. First, in this scenario, look at Patterns down:

- **Pattern 0:** When both PV and load remain constant. The influence on stability is then considered when the PV or load drops. As a result, the research is organised into three patterns.
- **Pattern 1:** Only PV declines
- **Pattern 2:** Only when the load lowers
- **Pattern 3:** When both the PV and the load fail

In the rest of this paper will discuss the simulation and present the results.

Conditions for Simulation

The study was carried out under the following prerequisites conditions:

- ✓ Power flow between regions is assumed to be (assuming interconnected lines). It is set at 1 to 3 GW, similar to the power system.
- ✓ The subsystem distributes the PV installation area.
- ✓ The starting voltage of each node must be within 1 0.05 pu.
- ✓ Eight fault spots on the 500-kV main line.
- ✓ Assume a 3-L-G-O (fault clearance time of 0.077 seconds) accident in the starting power flow cross-section of the peak cross section.

- ✓ The generator's operating condition is governor-free operation.

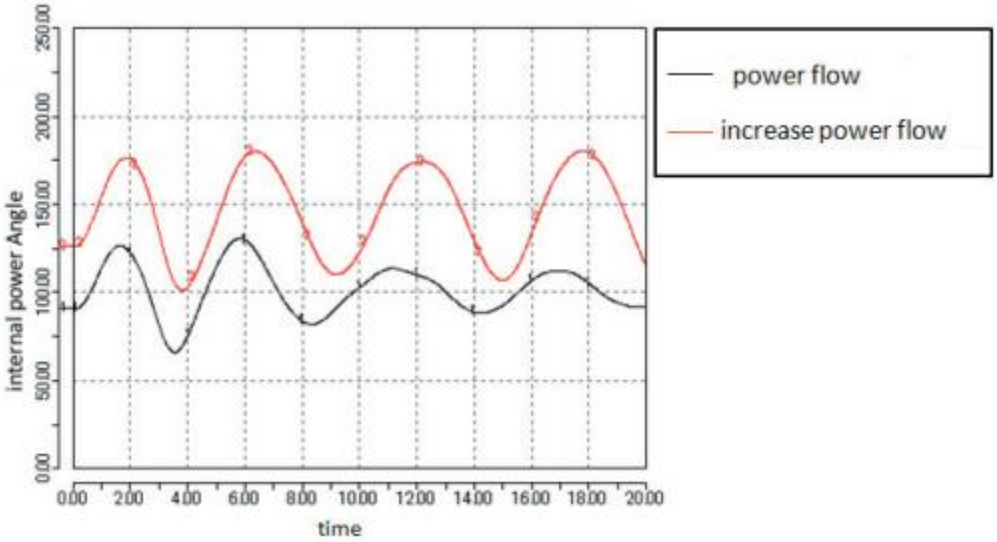

Figure 2:Swing curve at Fault Point with Pattern 0

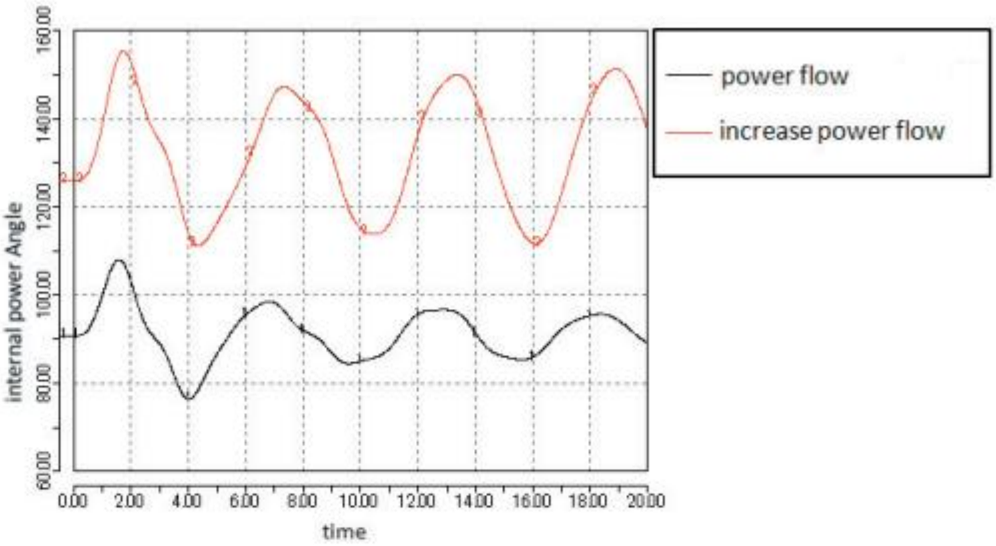

Figure 3: Swing Curve at Fault Point with Pattern 1

Following that, Pattern 1 (PV dropout), the most severe and somewhat severe Pattern 1, is analysed, followed by Pattern 2 (load loss). Pattern 1 (PV dropout) is the most severe because existing power sources, such as thermal internal phase difference angle increases and generator acceleration owing to a system fault, are exacerbated. This is due to the fact that the synchronization force concerning the reference generator is assumed, and there is figure 2,3,4,5 depicts the simulation results discussed above. Pattern 2 (load loss) is less severe because the load is smaller. Because the supply capacity becomes insufficient as a result of the dropping of the group of generators, the output will decline, and finally, the internal phase with the reference generator will be reduced.

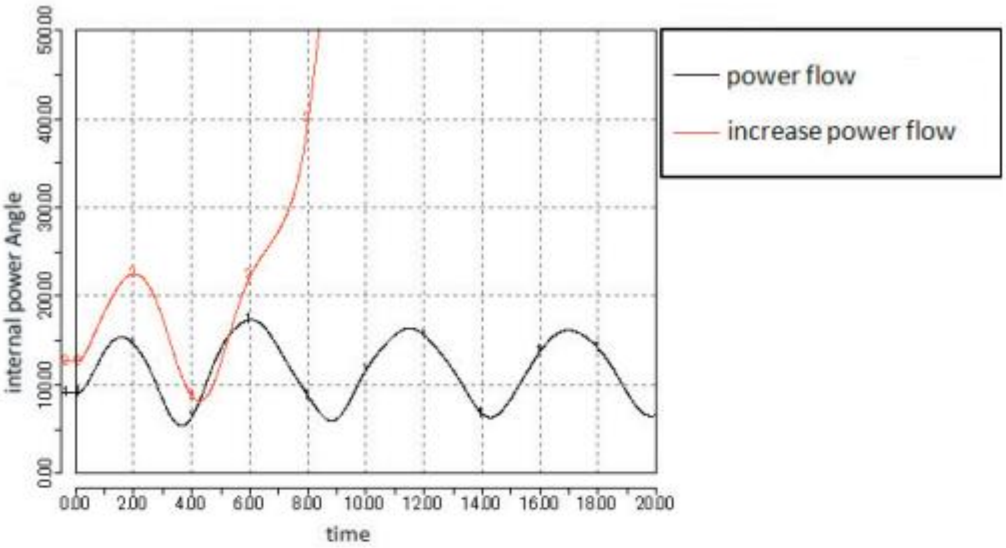

Figure 4: Swing Curve at Fault Point with Pattern 2

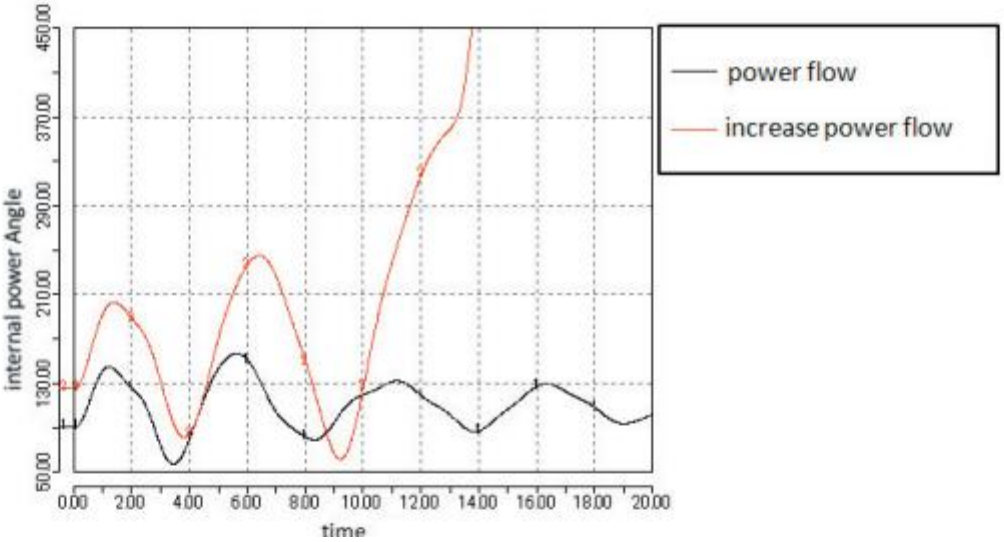

Figure 5: Swing Curve at Fault Point with Pattern 3

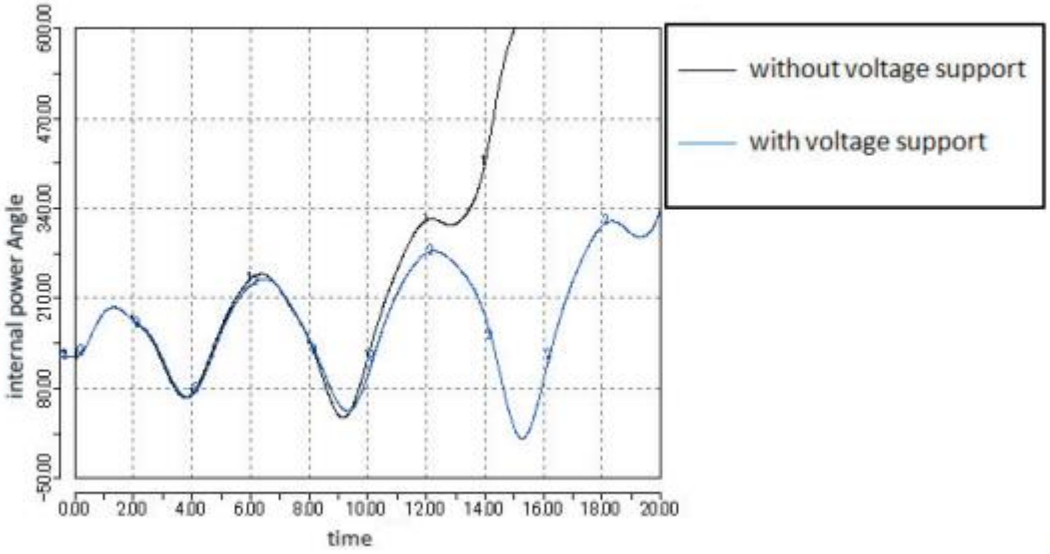

Figure 6: Comparison of Transient Stability with or without DVS

This is assumed to be since it acts in the direction of reducing the differential angle. From the results in Figure 6, it is clear that the PV does not have a DVS function. Even in cases where it becomes stable, it is stable with the DVS function. It can be seen that it contributes in a situation where PV is generating full power in all regions, and the stability is unstable. It has improved from a stable state to a stable state. this is an especially long distance. In the case of a comb system, the voltage drops at the intermediate point due to a system fault is supported by the DVS function of PV, that is, the so-called halftone phase. It is considered that this indicates that the effect is appearing. The power conditioning subsystem of PV is FRT Equipped with a function to continue operation without dropping out in the event of a system disturbance. It is being established technically as far as possible.

Conclusion

The research modeled the uncertainty of PV and proposed a suitable parameter selection strategy based on the concept of robust reliability. This is expected to provide suggestions for effective strategies to sustain reliability. The Effects of Load and PV Dropouts on Oscillatory Divergence Stability In terms of impact, took a bird's-eye view of the complete system in a condition similar to the actual system. Considering future large-scale PV deployment DVS is equipped with functions for constant voltage adjustment and stability maintenance, in addition to the FRT function, which withstands voltage sag and maintains operating.

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Authors contribution: Sole author

Data availability: From the author

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REVIEW ARTICLE

A concise review of technologies for converting forest biomass to bioenergy

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Abstract

The use of biomass is vital in reducing the negative effects of rising fossil fuel consumption. Given its quantity and diversity, forest biomass has garnered a lot of interest among the many kinds of biomass. This study evaluates the various strategies for transforming woody waste into usable biofuels. Carbon dioxide emissions from traditional energy generation systems could be mitigated through the direct utilization of forest biomass. Low energy conversion rates, as well as soot emissions and residues, are some of the problems that come up when directly using forest biomass. The sustainability of direct energy generation from forest biomass is also seriously threatened by the lack of constant access to biomass. Co-combustion with coal and pelletizing biomass is two solutions proposed for this issue. Co-combustion of forest biomass with coal has the potential to lower the process's emissions of carbon monoxide, nitrogen oxides, and sulfides. This article reviews and discusses the biochemical and thermochemical mechanisms that can transform forest biomass into a variety of liquid and gaseous biofuels. Future research using cutting-edge sustainability assessment tools like life cycle assessment, exergy, etc. should investigate the sustainability of forest biomass conversion processes to bioenergy further.

Keywords: Forest; Biomass; Bioenergy; Biodiesel; Biogas

Introduction

The escalating utilization of fossil energy sources is mostly responsible for the generation of greenhouse gases (GHGs) and other detrimental gases, which have emerged as a significant worldwide issue (Ali et al., 2022; Borowski, 2022; Raihan, 2023a; Sultana et al., 2023). GHGs have been widely recognized as a pivotal determinant in the phenomenon of global warming, exerting a significant influence on the intricate dynamics of climate change (Agan & Balcilar, 2023; Raihan, 2023b; Voumik et al., 2023). Numerous studies have demonstrated that the utilization of alternative carbon sources such as biomass has the potential to mitigate these difficulties (Sarwer et al., 2022; Raihan, 2023c). The existing body of literature on the utilization of biomass for energy production encompasses discussions regarding the contentious issue of the relative significance of forest biomass (Plank et al., 2023; Raihan, 2023d). In general, forest biomass can be categorized into two main types: firewood and commercial roundwood (Raihan, 2023e; Siarudin et al., 2023). Fuelwood is obtained from forested areas and is either burned directly to produce usable heat or transformed into bioenergy and biofuels to generate heat and power (Manikandan et al., 2023; Raihan, 2023f). Fuelwood exhibits great potential as a feedstock for several conversion processes, including thermochemical transformation, biological conversion, liquefaction, and gasification, owing to its substantial concentration of macromolecular carbohydrates such as cellulose and organic matter (Manikandan et al., 2023; Raihan, 2023g). Forest biomass has the potential to be utilized either in co-combustion with fossil fuels or as a standalone fuel source in power generation equipment such as boilers (Raihan et al., 2018; Kalak, 2023). In the context of formulating national energy development strategies, there is a considerable emphasis on the efficient usage of forest biomass resources as a means to address environmental crises (Jaafar et al., 2020; Yana et al., 2022; Raihan, 2023h). As an illustration, within the spectrum of energy sources accessible in China, around 54.2% of forest biomass is employed for power generation and fuel production (Cavali et al., 2023).

The energy derived from forest biomass has the potential to meet around 15.4% of the overall global energy demand (Kalak, 2023). From 2004 to 2015, the total power generation derived from forest biomass was around one million kilowatts per year (Fujino & Hashimoto, 2023). This contribution played a significant role in the removal of forest wastes and the attainment of ecological-zero carbon dioxide (CO_2) emissions, as highlighted by Nunes et al. (2018). As an example, the utilization of forest biomass as an alternative to fossil fuels in Australia results in a yearly reduction of around 25 million tons of atmospheric CO_2 emissions (Raihan et al., 2021a). Additionally, according to the contribution played a significant role in the removal of forest wastes and the attainment of ecological-zero CO_2 emissions statistical data from the European Union (EU), there is a discernible upward trajectory in the potential of forest waste to meet human energy demands between 2010 and 2030 (Singh et al., 2022). Table 1 displays the statistical data provided by the EU about energy production derived from various forms of forest biomass in the year 2010, together with projected estimations for the year 2030. Given the considerable importance of forest biomass within the future global energy market, this study seeks to provide a concise overview of diverse approaches for converting forest biomass into bioenergy and biofuel.

Table 1. Energy production is derived from various forms of forest biomass in the EU.

Type of forest biomass	**The potential of biomass (TJ × 10^4)**		**Sources**
	2010	**2030**	
Wood processing	419	427	Searle & Malins (2016)
Forest crops	180-193	427-615	Böttcher & Graichen (2015)
Forest residue	180	163-301	Moiseyev et al. (2014)
Total	**779-792**	**1017-1343**	

The imperative to decrease the burning of fossil fuels has become increasingly apparent to achieve the global objectives for reducing carbon emissions (Begum et al., 2020; Oyebanji & Kirikkaleli, 2022; Raihan, 2023i). Furthermore, it is worth mentioning that fossil fuel reserves are finite resources, and the reserves of coal, oil, and gas are gradually diminishing as a result of excessive use driven by the rapid global population expansion (Raihan, 2023j; Wang et al., 2023). The utilization of forest biomass for bioenergy production has the potential to make significant contributions to the attainment of long-term environmental and economic sustainability objectives (Raihan et al., 2019; Voumik et al., 2022), while also aiding in the mitigation of adverse environmental consequences associated with the utilization of fossil fuels (Isfat & Raihan, 2022; Pramanik et al., 2023; Raihan, 2023k). Bioenergy production plays a crucial role in enhancing both energy efficiency and energy security, while concurrently stimulating economic growth through the creation of new employment opportunities (Tănasie et al., 2022; Raihan & Tuspekova, 2023a). Bioenergy has emerged as a prominent subject within the global discourse on climate change (Raihan & Tuspekova, 2023b). However, there exists a dearth of comprehensive research that offers a comprehensive examination of bioenergy production, specifically focusing on the conversion technologies employed to generate bioenergy from forest biomass (Rocha-Meneses et al., 2023). A notable research deficiency exists within the current body of literature on the process of converting forest biomass into bioenergy (Rani et al., 2023). Hence, the primary objective of this study is to present a comprehensive review of the many methods utilized in the conversion of forest biomass into bioenergy. The current research addresses the existing knowledge gap about the intersection of bioenergy for environmental sustainability and forest-based bioenergy production technologies. This review article provides valuable insights for future endeavors aimed at advancing sustainable bioenergy production from forest biomass and its potential to replace fossil fuels. This research specifically addresses the pressing issues of global warming and climate change by emphasizing the importance of bioenergy production from forest biomass and lowering emissions resulting from the combustion of fossil fuels.

Methodology

This study conducted a systematic literature review to address the potential technologies for converting forest biomass to bioenergy. The systematic literature review is a reliable framework (Benita, 2021). After settling on a research topic, relevant publications were found and downloaded using several research databases including Scopus, Web of Science, and Google Scholar. Multiple search terms were used to find relevant documents, including "forest biomass," "bioenergy," "biodiesel," "biogas," "bioenergy production," "forest biomass to bioenergy," "bioenergy conversion," "bioenergy technology," and so on. At first, there was a great deal of published material returned by the keyword search. Since it's been impossible to read all the found articles since 2020, the literature exhibition has had to be limited in various ways. According to the study's purpose, 429 articles were retrieved from the databases. All of the retrieved publications and papers were evaluated based on a set of encoded measures for insertion and elimination of primary research papers. After reading the titles, abstracts, and entire pieces, it filtered out 282 unrelated publications that had been copied from an earlier search. A number of 147 articles were selected to use in this review based on their relevance to the study's stated objective of "technologies for converting forest biomass to bioenergy." Figure 1 depicts the evolution of review criteria used to choose appropriate documents for analysis.

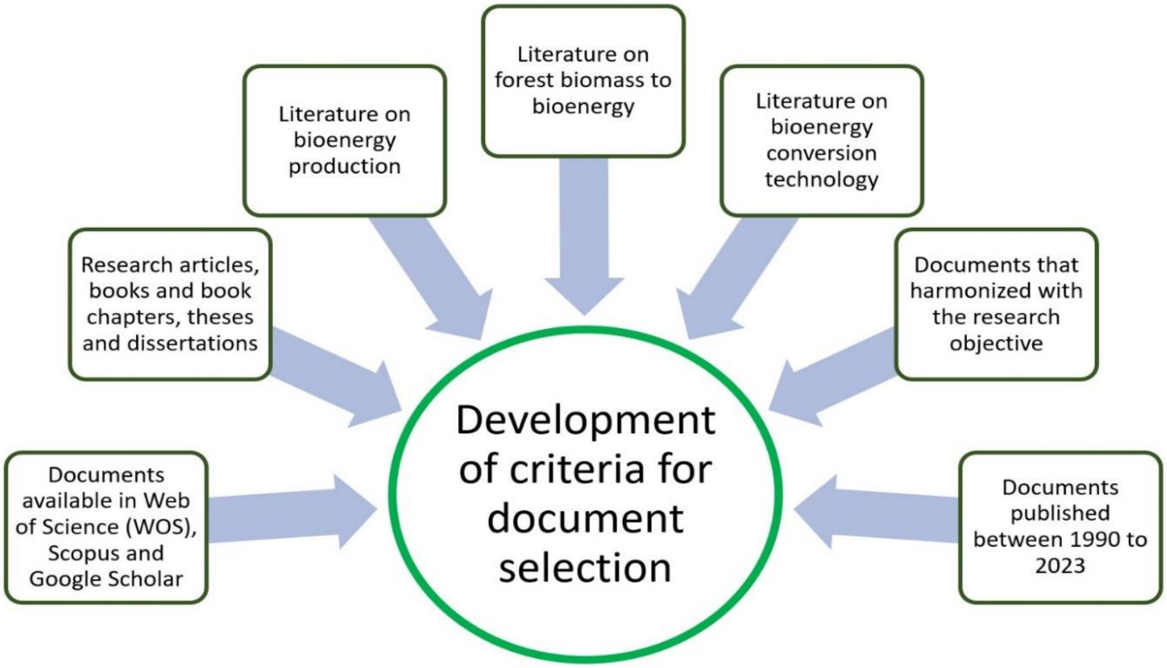

Figure 1. The development of criteria for document selection.

This study solely used research articles published in peer-reviewed journals to assure the quality of the results, which provide a foundation for future research and management considering the conversion of forest biomass to bioenergy. These papers were then reviewed to determine if their primary topic was similar to that of the current investigation. The next step is a systematic review of all 147 papers, wherein the study topics and other features, such as the methodologies, settings, and theoretical frameworks underlying the investigations, are dissected and analyzed. The qualitative and quantitative secondary literature on the production of bioenergy from forest biomass is also discussed. In addition, this study examined interrelated topics, opening up fresh avenues for future study. Comprehending the research outcomes on the conversion of forest biomass to bioenergy, the study also examined future direction prospects and research concerns. Figure 2 depicts the systematic review processes that were employed in the present investigation. Following the selection of the research topic, this study proceeded to identify and locate pertinent articles, conduct an analysis and synthesis of various literature sources, and compile written materials for article review. The synthesis phase involved the gathering of diverse articles that were afterward compiled into conceptual or empirical analyses that were pertinent to the completed research.

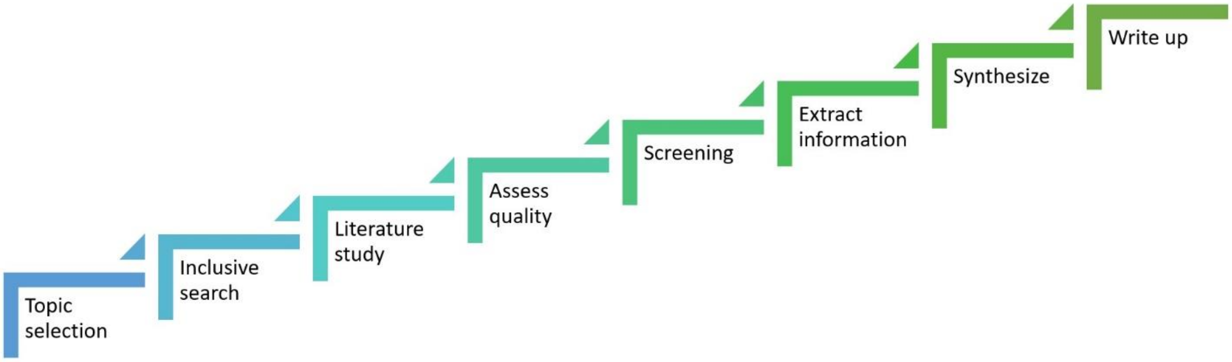

Figure 2. The procedure of systematic review conducted by the study.

Results and Discussion

Direct use of forest biomass

One notable benefit associated with forest biomass is its potential for direct combustion (Borowski, 2022). The direct combustion method is a type of thermochemical procedure in which biomass undergoes combustion in an unconfined environment, resulting in the conversion of the chemical energy contained in the biomass through photosynthesis into thermal energy (Li et al., 2023). While the combustion of forest biomass does result in the release of CO_2, particulate matter (PM2.5), sulfur dioxide (SO_2), and other detrimental compounds, the quantities emitted are comparatively lower than those generated by the combustion of fossil fuels (Arya, 2022; Raihan et al., 2022a). For instance, prior studies have demonstrated that the combustibility of forest biomass yields a 20% reduction in CO_2 emissions compared to the utilization of fossil fuels (Sasaki, 2021). Nevertheless, the utilization of forest biomass is accompanied by specific limitations (Míguez et al., 2021). One of the identified drawbacks is the relatively poor energy conversion rate (Ramos et al., 2022). Additionally, the process of direct combustion results in the formation of soot and debris (He et al., 2021).

The practice of utilizing the direct burning of biomass for electricity generation has persisted since the 1990s (Amalina et al., 2022). According to Chen et al. (2021), biomass-fired combined heat and power (CHP) systems consist of a vibratory grating furnace, condensation steam turbine, and electric generator. The vibratory grating boiler is a type of automated combustion equipment characterized by its simplistic structure and relatively low capacity (Silva et al., 2023). The surface of the grate undergoes vibrations due to alternating inertial forces, which in turn propel biomass forward, facilitating automated combustion (Ciliberti et al., 2022). The combustion of forest biomass generates thermal energy within the boiler, which in turn facilitates the conversion of water into steam through a process known as the steam Rankine cycle (Chen et al., 2022). Following the process of water evaporation within the boiler, steam is subsequently introduced into the turbine to undergo expansion and engage in mechanical activity (Cortazar et al., 2023). Subsequently, the pressure is diminished, leading to the condensation of the steam and its conversion back into water (Hejazi, 2022). It is important to acknowledge that the steam-driven Rankine cycle holds significant importance as a thermodynamic cycle in the realm of energy production (Dincer and Bicer, 2020). The observed rate of conversion of forest biomass to electricity using the Rankine cycle falls within the range of 39-44% (Oyekale et al., 2020). Consequently, the combustion of a single ton of forest biomass yields approximately 4.4 kilowatt-hours (kWh) of electrical energy (Esfilar et al., 2021). An evident benefit associated with the utilization of electric energy is the mitigation of CO_2 emissions derived from the power generation sector, which predominantly relies on fossil fuels (Raihan et al., 2022b). Table 2 presents a comprehensive tabulation of the reductions in CO_2 emissions achieved by power plants that utilize forest biomass as compared to those reliant on fossil fuels.

Table 2. Reductions in CO_2 emissions are achieved by power plants that utilize forest biomass as compared to those reliant on fossil fuels.

Biomass type	Country	Power plant type	Power plant capacity (MW)	Reduction of CO_2 emission (t/yr)	Source
Forest waste (wood chips)	United States	Thermal power plant	70	552,032	Campbell & Mika (2009)
Palm tree waste	Iran	Rankine cycle steam power plant	8	40,500	Mallaki & Fatehi (2014)
Forest waste	Portugal	Thermal power plant	314	1,000,000	Nunes et al. (2014)
Forest waste (woody biomass)	Japan	Thermal power plant	5.7	30,934	Nakano et al. (2015)
Forest waste (wood chips, wood pellets, and black pellets)	Japan	Thermal power plant	500	198,000-252,000	Furubayashi & Nakata (2018)

One notable challenge associated with the utilization of forest biomass to obtain energy generation through direct burning is the geographical distance between these waste materials and industrial as well as residential regions (Yana et al., 2022; Al-Bawwat et al., 2023). In addition, it should be noted that forests encompass extensive areas, and the process of collecting biomass presents intricate challenges (May et al., 2023). Consequently, the absence of consistent availability of biomass is a significant issue in ensuring the long-term viability of utilizing forest biomass for direct energy generation (Al-Bawwat et al., 2023; Raihan & Tuspekova, 2022a). However, it is advisable to establish forest biomass-based companies across a radius of 120 km from forested areas to address this issue (Daneshmandi et al., 2022). However, substantial financial expenditure and considerable storage capacity are required (Saravanakumar et al., 2022).

Furthermore, the utilization of co-combustion presents a viable and uncomplicated approach to address the issues linked to the direct burning of forest biomass (Míguez et al., 2021). These concerns encompass the availability of biomass continuously, the space needed for storage, and the economic challenges involved with transportation and distribution (Zahraee et al., 2022). One notable benefit associated with the co-burning of biomass and coal in comparison to the exclusive combustion of coal is the potential reduction in emissions of carbon monoxide (CO), nitrogen oxides (NOx), and sulfides, while simultaneously maintaining production efficiency (Syrodoy et al., 2022). The burning of forest biomass and coal employs pulverized coal boilers and fluidized bed boilers as the reactor, from a technical standpoint (Ling et al., 2023). The addition of forest biomass in fluidized-bed boiler results in a decrease in the production of nitric oxide (NO) and enhances the efficiency of the combustion process (Żukowski et al., 2023). In contrast to coal, biomass has a higher volatile content, which is a positive characteristic for facilitating quick ignition (Raihan et al., 2022c). Recent research has revealed that the substitution of a single ton of coal by forest biomass in co-combustion processes has the potential to result in a reduction of around 87 tons of CO_2 emissions (Ye et al., 2023). According to Twumasi et al. (2022), there is an anticipated rise in biomass consumption of 450,000 metric tons per year in the year 2030 and beyond. This increase is expected to result in a corresponding decrease of around 395,000 metric tons per year in CO_2 emissions (Chen et al., 2023). In addition, the combustion of biomass can result in the formation of alkaline ash, which has the potential to impede the release of SO2 emissions through coal and mitigate global acidification (Putra et al., 2023).

Co-combustion is regarded as a cost-effective approach for using available biomass resources for power generation, owing to its capacity to mitigate the emission of hazardous gases and enhance the reliability of power generation (Borowski, 2022; Raihan & Tuspekova, 2022b). In light of this information, thermal power plants have the potential to utilize biomass as an environmentally friendly and economically viable combustion co-fuel in conjunction with coal (Srivastava et al., 2023; Raihan & Tuspekova, 2022c). Nevertheless, forest biomass has other notable limitations, including but not limited to inadequate energy density, elevated particle emissions, inconsistent combustion performance, and challenges associated with storage and transportation (Ramos et al., 2022; Sarker et al., 2023). Therefore, future research endeavors must focus on developing effective strategies to address and alleviate these challenges.

Pellets from forest biomass

Numerous methodologies have been devised to enhance the transportation and optimize the conversion efficiency of forest biomass, such as the mechanical treatment of biomass into a granular form known as pellets (Mujtaba et al., 2023). The process of pelleting forest biomass enhances its density and decreases its water content (Ahmed et al., 2022). The combustion efficiency of biomass is significantly influenced by two crucial parameters, namely density and moisture content (Ramos et al., 2022). Therefore, the utilization of pelleted forest residue in combustion by itself or co-combustion with coal has the potential to enhance combustion efficiency (Borowski, 2022; Daba et al., 2023). For example, Ghorashi and Khandelwal (2023) indicated that the effectiveness of boilers utilizing pellets ranged from 5% to 90%, whereas wood-fired boilers exhibited a range of 75% to 85% efficiency. Figure 3 shows the steps of pellets production from forest biomass.

Figure 3. The steps of pellets production from forest biomass (Sarker et al., 2023).

The incorporation of forest biomass with other biomass materials can be employed to augment the collective characteristics of the combination, hence improving its suitability for pellet manufacture (Gupta et al., 2022). The endurance of biomass pellets can be influenced by their water content, which can be modified by incorporating different kinds of forest biomass (Song et al., 2023). In particular, the average durability of forest biomass significantly increases to 95% when the moisture level is lowered to a range of 1-5% (Míguez et al., 2021). This reduction in moisture content is advantageous for both the transportation and storage of biomass products (Ramos et al., 2022). In the context of forest biomass pellet production, it is necessary to pre-dry the biomass material before the manufacturing process (Yun et al., 2022; Raihan & Tuspekova, 2022d). A potential method for reducing the moisture content in aspen wood chips is the utilization of a rotary drier, which has demonstrated a moisture removal efficiency of approximately 17% (Bianchini, & Simioni, 2021). When comparing the data, it is observed that the moisture elimination rate for sawdust derived from *Robinia pseudoacacia* is significantly greater, reaching 31% (Dudziec et al., 2023). The observed variations can be attributed to disparities in the proportions of different categories of forest biomass (Puglielli et al., 2021). It is worth mentioning that in cases where the rotary drier fails to efficiently eliminate moisture, the pneumatic dryer presents itself as a viable alternative, with an enhanced drying rate of 22% (Palacios-Bereche et al., 2022). According to environmental analysis, the substitution of coal with biomass pellets for power generation is projected to result in an annual reduction of 205 million metric tons of CO_2 emissions (Ter-Mikaelian et al., 2023). In 2008, the European Union countries collectively prevented the release of approximately 12.6 million tons of CO_2 emissions by utilizing 8.2 million tons of pelleted wood.

When forest biomass pellets are combined with coal, they result in a comparatively lower environmental impact compared to traditional fuels such as sawdust and coal (Sarker et al., 2023). According to Masum et al. (2022), the combined combustion of woody biomass pellets and coal resulted in a notable 50% decrease in CO_2 emissions. Additionally, the ash generated during the combustion process constituted about 1% of the total, which is significantly lower compared to coal combustion, estimated to be 15-20 times less (Borowski, 2022). The utilization of wood pellets in conjunction with coal for co-firing purposes yielded a reduction in CO_2 emissions when compared to alternative renewable energy sources (Picciano et al., 2022; Raihan & Tuspekova, 2022e). There is an additional assertion that the inclusion of eggshells in the process of combustion of woody biomass pellets may result in the absorption of CO_2 due to the presence of calcium carbonate in eggshells, hence leading to a further reduction in greenhouse gas (GHG) emissions (Ivanović et al., 2023). The emissions levels of CO and NOx resulting from the combustion of pellets were found to be highly satisfactory (Saravanan et al., 2023). The implementation of co-firing biomass pellets with coal, namely by burning wood pellets in lower-row burners, has the potential to mitigate CO emissions (Daba et al., 2023). Notwithstanding the encouraging outcomes, power plants that depend on woody biomass pellets encounter a range of challenges. These include elevated energy consumption, a labor-intensive production process, comparatively higher prices compared to other solid biofuels, the requirement for larger storage capacity in comparison to oil, the necessity for ash removal, and the vulnerability of pellets to water exposure (Ibitoye et al., 2021).

Liquid biofuels from forest biomass

Diesel the combustion process in engines powered by diesel is well recognized as a significant factor in the exacerbation of worldwide air pollution (Peng et al., 2020; Raihan et al., 2023a). The emissions of utmost significance resulting from the process of diesel combustion encompass carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOX), carbon monoxide (CO), and particulate matter (PM) emissions (Ni et al., 2020; Guven & Kayalica, 2023). There exists empirical evidence indicating that such emissions play a pivotal role in causing harm to the natural world and human well-being (Raihan & Voumik, 2022a; Raihan et al., 2023b). In response to the issue of emissions from diesel engines and the need to address environmental concerns, there is a significant demand for environmentally friendly alternatives to diesel fuel (Ni et al., 2020; Raihan & Voumik, 2022b; Das et al., 2022; Raihan et al., 2023c). Biodiesel, which refers to the methyl or ethyl esters of long-chain fatty acids, is mostly synthesized through the transesterification reaction utilizing short-chain alcohols such as methanol or ethanol (Santaraite et al., 2020). This reaction takes place in the presence of a catalyst, either a base or an acid. The combustion of biodiesel results in reduced emissions of smoke, particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC) in comparison to diesel (Attia et al., 2022; Raihan & Tuspekova, 2022f). Additionally, biodiesel has a far lower impact on global warming compared to diesel since the carbon included in biodiesel primarily originates from biogenic CO_2 sources (Cabrera-Jiménez et al., 2022; Raihan & Tuspekova, 2022g). The research about the manufacturing of biodiesel has attained a level of maturity, leading to the substitution of conventional diesel fuel with diverse blends of biodiesel in numerous regions across the globe (Benti et al., 2023). It is noteworthy to mention that neat biodiesel, along with its blends of up to 20% with diesel, can be utilized in diesel-powered vehicles without necessitating any alterations to the engine (Gowrishankar & Krishnasamy, 2023). Despite the numerous advantages it offers, biodiesel faces certain limitations in terms of its physicochemical features that hinder its broad deployment (Akinwumi et al., 2022). These limitations include a higher viscosity compared to fossil diesel and inadequate cold flow properties (Devaraj et al., 2022). In addition, the manufacturing of biodiesel using first-generation feedstock, specifically edible vegetable oils, has resulted in elevated production expenses and instigated a rivalry between fuel and food for arable land and water resources (Mahmud et al., 2022). Second-generation biofuels, which are fuels obtained from waste biomass, have been categorized as a potential option to address the issue of competition between food and fuel (Singh et al., 2022). Tree species with a high oil content are considered to be appropriate raw materials for the synthesis of biodiesel (Osman et al., 2022). Pyrolysis is a thermochemical valorization approach that shows promise in the production of biofuels from forest waste (Osman et al., 2023). This process occurs at moderate temperatures, typically ranging from 300 to 1,300° C (Mlonka-Mędrala et al., 2021). Throughout this procedure, the chemical composition of the feedstock undergoes significant alterations (Murtaza et al., 2022). Pyrolysis is well recognized as a versatile process capable of generating a diverse range of solid, liquid, and gaseous outputs, contingent upon the specific circumstances employed throughout the pyrolysis procedure (Sivaranjani et al., 2023). The process of slow pyrolysis yields solid byproducts, namely biochar or charcoal, whereas quick pyrolysis leads to the generation of liquid products, specifically bio-oil (Costa et al., 2022; Raihan & Tuspekova, 2022h). According to Ramos et al. (2022), forest biomass has been identified as a very suitable feedstock for the process of pyrolysis. Various researchers have effectively carried out pyrolysis on forest biomass to generate bio-oil (Chireshe et al., 2020). It is important to acknowledge that the bio-oil generated using the pyrolysis method generally exhibits elevated levels of oxygen and water content. Consequently, it necessitates undergoing an upgrading procedure (Kumar & Strezov, 2021).

Gasification is an additional method that can be employed to enhance the value of forest biomass (Gomes et al., 2023). In a study conducted by González and García (2015), wood biomass was subjected to a gasification process followed by liquefaction (Fischer-Tropsch) to produce bio-oil. According to the findings of Natarajan et al. (2014), the implementation of five Fischer-Tropsch plants has the potential to make significant contributions toward Finland's 2020 objectives. These objectives include utilizing up to 58% of the accessible forest biomass for energy generation, achieving an overall reduction of 4% in emissions, and ensuring that the transportation sector is entirely powered by biofuel. Additionally, an estimation was made on the potential reduction of environmental impacts in the transportation sector of Norway by substituting fossil diesel with liquid biofuel derived from biomass from forests and woody wastes through the Fischer-Tropsch process (Jahangiri et al., 2023). The predicted greenhouse gas (GHG) reductions and decreases in greenhouse impacts (Raihan et al., 2022d) resulting from the production and utilization of Fischer-Tropsch biofuel derived from forest wastes are projected to range from around 20% to 90% over a 100-year timeframe (Cheng et al., 2023). It is important to acknowledge that biofuel production derived from forest biomass has the potential to not only mitigate CO_2 emissions but also present economic prospects, such as the generation of employment opportunities (Benti et al., 2022; Raihan & Said, 2022).

The investigation of bioethanol synthesis from biomass from forests has been underway since the beginning of the 1990s (Benti et al., 2022). Forest biomass, including species that consist of *Populus* L., *Salix babylonica*, and *Saccharum officinarum*, possesses a lignocellulosic composition and is characterized by its plentiful availability. These attributes render it a viable candidate for utilization as a feedstock in the production of second-generation bioethanol (Ko et al., 2020; Raihan et al., 2022e). The International Energy Agency (IEA) has projected that by the year 2030, harnessing around 10% of the world's forest and agricultural biomass has the potential to yield approximately 233 billion liters of bioethanol, which is equivalent to 155 billion liters of gasoline (Morales et al., 2021). Table 3 displays the bioethanol generation potentials of various forest biomass sources.

Table 3. Bioethanol generation potentials of various forest biomass sources.

Biomass species	Potential yield of bioethanol (L/ha)	Sources
Panicum virgatum	555–3,871	Zabed et al. (2016)
Manihot esculenta	4,500–4,901	Zabed et al. (2016)
Salix spp.	769–4,026	Zamora et al. (2014)
Miscanthus spp.	4,600–12,400	Ho et al. (2014)
Populus spp.	1,500–3,400	Ho et al. (2014)
Triticum aestivum	1,001–1700	Lebaka (2013)
Saccharum spp.	5,345–9,950	Lebaka (2013)

Bioethanol is widely recognized as a highly promising alternative to petroleum-derived gasoline, primarily due to its significantly reduced emissions across its entire life cycle (Ingrao et al., 2021; Raihan et al., 2022f). In a study conducted by Becerra-Ruiz et al. (2019), it was shown that substituting gasoline with bioethanol in 5500 W transportable engine generators of an alternating current resulted in significant reductions of 99%, 93%, and 67% in CO, HC, and NOx emissions, respectively. In contrast to first-generation bioethanol derived from crops like corn and sugarcane, second-generation bioethanol, which is produced from lignocellulosic feedstocks, exhibits a notable reduction in greenhouse gas (GHG) emissions over its entire life cycle (Hirani et al., 2018; Raihan et al., 2023d). In addition, it is worth mentioning that the bioethanol yields derived from forest biomass exhibit comparatively greater levels when compared to other forms of biomass (Fan et al., 2020). According to a study conducted by Mabee and Saddler (2010), the bioethanol yields obtained from forest biomass were found to vary from 0.12 and 0.3 m^3/t (dry basis), while the bioethanol yields from agricultural residues ranged from 0.11 to 0.27 m^3/t (dry basis). The processing of lignocellulosic materials into bioethanol primarily involves two methods: biochemical conversion and thermochemical conversion (Siwal et al., 2022; Raihan & Tuspekova, 2022i). The biochemical conversion process commences with a pretreatment step aimed at the separation of lignin and hemicellulose from cellulose (Sharma et al., 2020). Subsequently, cellulose undergoes hydrolysis to produce fermentable sugars (Sun et al., 2022). Ultimately, the process of fermentation results in the conversion of carbohydrates into ethanol (Tse et al., 2021; Raihan et al., 2022g). Pretreatment is a crucial stage in the process, and as such, the specific type and conditions of pretreatment significantly impact the overall technical feasibility of the whole procedure (Morales et al., 2021). According to Sharma et al. (2020), there are several pretreatment methods available, including chemical, physical, physicochemical, and biological approaches.

It is important to acknowledge that forest biomass generally exhibits increased lignin concentrations as a result of its inclusion of bark and immature wood (Siwal et al., 2022; Raihan & Himu, 2023). Consequently, the bioconversion of forest biomass into sugars is hindered to a greater extent compared to other biomass categories, such as agricultural leftovers (Manikandan et al., 2023). Despite the existence of pretreatment methods to address the significant challenge of recalcitrance in achieving effective sugar/biofuel production, these approaches are characterized by increased time requirements and higher costs. One of the techniques employed is the steam explosion treatment, which has been documented to enhance bioethanol production from Hemp fiber by as much as 70% (Zhao et al., 2020). Furthermore, it has been postulated that the utilization of surfactants, due to their distinctive composition and functional characteristics, may enhance the solubility, flowability, accessibility, and degradation of forest biomass, thus augmenting the bioethanol output (Azelee et al., 2023; Raihan, 2023l). According to Zheng et al. (2020), it has been suggested that the utilization of tween, polyethylene glycol (PEG), and sulfonate-based surfactants may potentially enhance the conversion rate of lignocellulose by approximately 10-20%. In contrast to biochemical converting, thermochemical processing, specifically gasification, exhibits wider applicability to many types of forest biomass (Ramos et al., 2022). The process of gasification involves the conversion of lignocellulosic biomass into syngas under high-pressure conditions and without the presence of inert gases (Mohanty et al., 2021). Subsequently, the syngas is subjected to the Fischer-Tropsch process to produce bioethanol (Laesecke et al., 2017). Moreover, the microbe *Clostridium ljungdahlii* can produce bioethanol through the utilization of syngas, facilitated by its inclusion of catalysts (Sajeev et al., 2023). Figure 4 depicts the thermochemical conversion procedure of biomass.

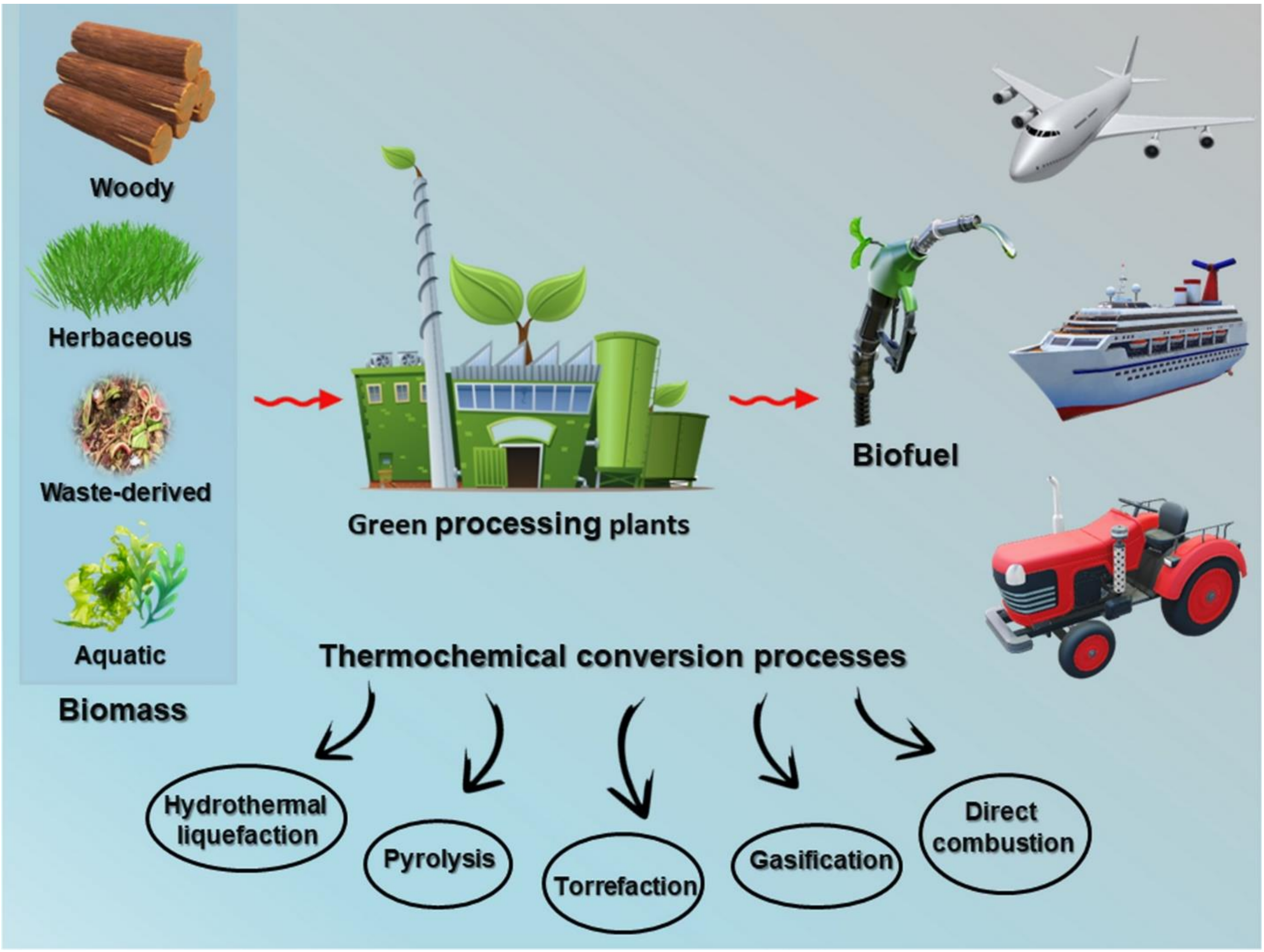

Figure 4. Thermochemical conversion procedure of biomass (Osman et al., 2021).

Forest biomass to gaseous biofuels

The gasification method of forest biomass results in the creation of syngas through a sequence of heat-induced cracking reactions (Zhang et al., 2020; Raihan & Tuspekova, 2022j). The pyrolysis of forest biomass, including various components such as seeds, leaves, trunks of trees, and fruit shells, can be conducted in a fixed-bed gasifier operating at elevated temperatures over 1,200°C (Samiran et al., 2016). This process yields syngas rich in hydrogen, which has garnered significant attention as a highly potential alternative energy source (Raihan et al., 2022h; Vuppaladadiyam et al., 2022). According to Duan et al. (2020), there is a claim that a biomass quantity of 1.3 Gt per year has the potential to generate an annual output of 100 Mt of hydrogen. Figure 5 presents the process of forest biomass to gaseous biofuel conversion.

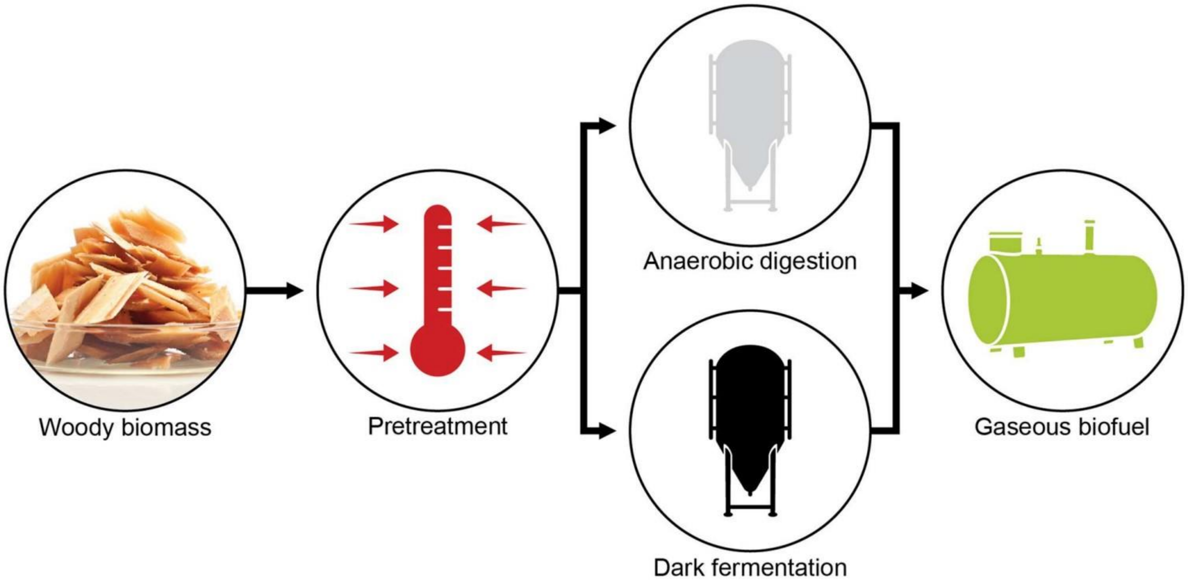

Figure 5. The procedure of forest biomass to gaseous biofuel conversion (Wijeyekoon & Vaidya, 2021).

The rate of the gasification process can be regulated by manipulating the flow rate of the gas (Luo et al., 2022). By employing this particular approach, it is possible to achieve a breakdown rate of up to 60% for forest biomass into hydrogen (Vuppaladadiyam et al., 2022; Gnanasekaran et al., 2023; Verma et al., 2023). The cost associated with the production of hydrogen from forest biomass via gasification is approximately 1.2-2.4 USD per kilogram of H2, which is over 50% lower compared to alternative methods (Lepage et al., 2021). It is important to acknowledge that commercial gasification equipment is commonly associated with power generation equipment, enabling the simultaneous production of energy and gas (Aguado et al., 2023). The latter can be distributed to neighboring houses.

The incorporation of suitable catalysts into the gasification process has the potential to enhance the composition of the produced gas (Galadima et al., 2022; Raihan et al., 2022i). In the experimental study on catalytic gasification, Eucalyptus residue was subjected to gasification using NiO as the catalyst (Ruivo et al., 2021). The results indicated a significant increase of 30% in the overall gas output. The application of catalytic gasification resulted in a reduction in both the biochar and ash contents, leading to an enhanced usage rate of biomass (Shrestha et al., 2022; Raihan et al., 2023e). There exists a contention that catalytic cracking exhibits more economic viability when compared to conventional techniques of biofuel production, namely pyrolysis and fermentation (Chia et al., 2022). Figure 6 presents the Biochemical conversion of biomass to biofuel that includes fermentation and anaerobic digestion.

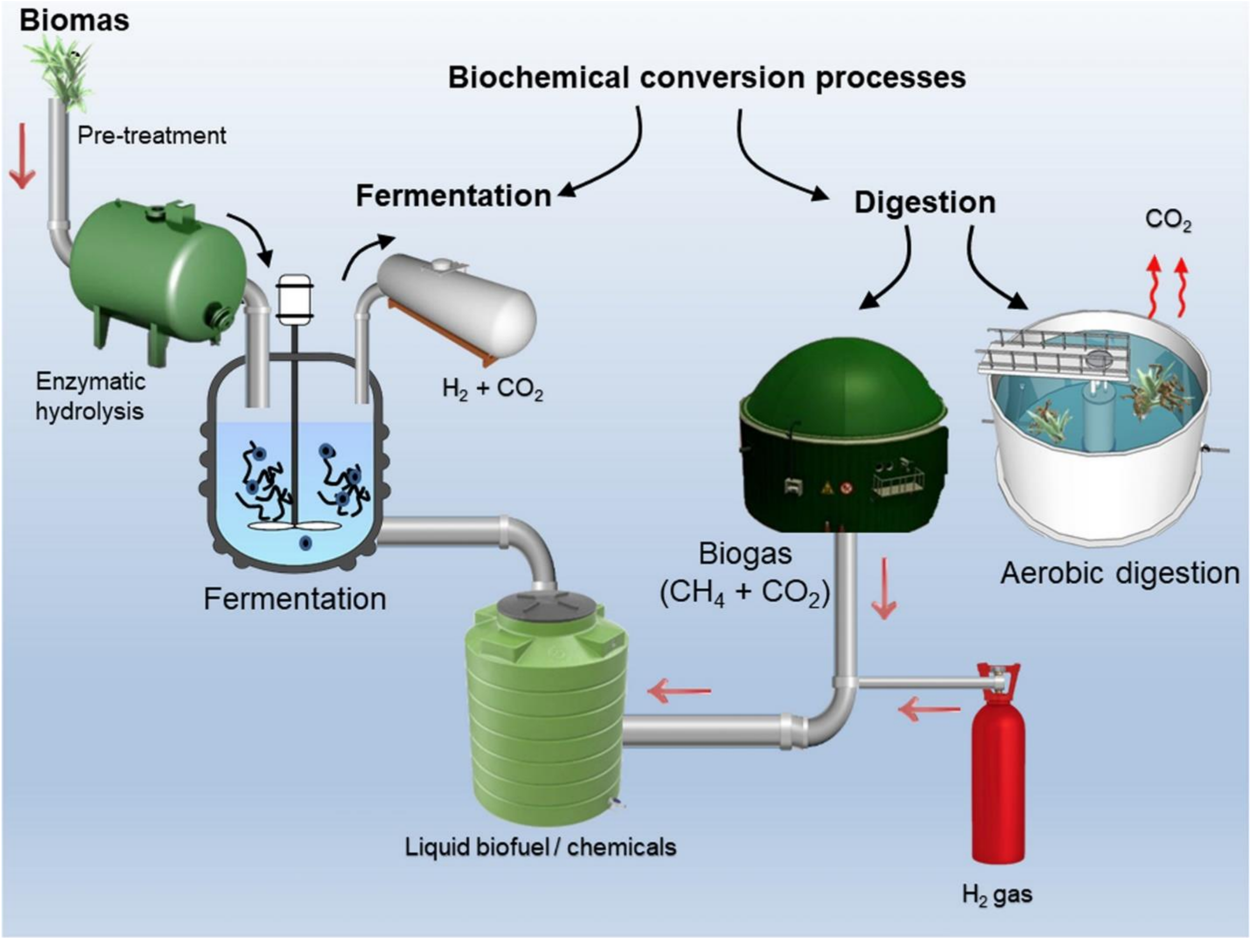

Figure 6. Biochemical conversion of biomass to biofuel includes fermentation and anaerobic digestion (Osman et al., 2021).

Furthermore, forest biomass has the potential to generate biogas via the process of anaerobic digestion, in addition to its capacity to produce syngas rich in hydrogen (Vuppaladadiyam et al., 2022; Raihan & Tuspekova, 2022k; Osman et al., 2023). The process of turning forest biomass into methane (CH_4) has reached a significant level of development and has been successfully employed for practical purposes for an extended period. The generation of biogas is significantly influenced by the structure of the raw materials, primarily consisting of CH_4 and CO_2 (Aghel et al., 2022; Raihan et al., 2022j). It is important to acknowledge that, apart from species, the physical characteristics of forest biomass may also be influenced by geographical location and growing environment disparities (Raihan et al., 2021b). One of the primary obstacles encountered in anaerobic digestion is the limited degradability of lignin in the absence of oxygen (Gao et al., 2022). Lignocellulosic organic resources, such as forest biomass, are characterized by a drawback in terms of the limited accessibility of hemicellulose and cellulose as biodegradable constituents for microbes and their associated enzymes (Periyasamy et al., 2023). However, like other forms of lignocellulosic biomass, forest biomass can also undergo various pretreatment methods, such as chemical (acid, alkali, or oxidant hydrolysis), physical (irradiation, cutting, thermal, and hydraulic shocks), and biological (fungi, actinobacteria, or their enzymes) in order treatments, to enhance its anaerobic biodegradation capabilities (Kumar et al., 2022).

Conclusion

The utilization of forest biomass as a source of energy has been demonstrated, both through direct and indirect means. In a more specific context, the utilization of forest biomass involves its direct combustion as a means to mitigate the CO_2 emissions linked to conventional methods of energy production. Nevertheless, the energy conversion efficiency of forest biomass is very low, resulting in the generation of soot and residues as byproducts. Furthermore, the limited availability of consistent biomass resources and the substantial financial requirements and storage capabilities pose significant challenges to the long-term viability of utilizing forest biomass for direct energy generation. When considering the reduction of emissions and the maintenance of production efficiency, the utilization of co-burning of biomass and coal can be seen as a potentially favorable approach in contrast to the exclusive combustion of coal. Furthermore, it partially addresses concerns about the accessibility of biomass, the spatial requirements for storage, as well as cost challenges associated with transportation and distribution.

Notwithstanding the aforementioned advantageous characteristics, forest biomass is subject to suboptimal energy density and excessive moisture content, both of which may be effectively mitigated through the process of pelleting forest biomass. The combustion rate is accelerated when pelleted forest biomass is directly combusted or co-combusted with coal, owing to its enhanced density and moisture content. However, power plants that depend on pellets from woody biomass encounter various challenges, including elevated energy consumption, a labor-intensive production method, and comparatively higher costs compared to alternative solid biofuels. The present study provides a comprehensive analysis of the biochemical and thermochemical processes used to convert forest biomass into bio-oil, bioethanol, and biogas.

With the increasing recognition of the ecological ramifications associated with the combustion of fossil fuels, the trajectory of the future will inevitably incline toward the utilization of biomass and biofuels. While there is existing knowledge on the conversion of forest biomass to bioenergy, it is important to note that further investigation is required to thoroughly evaluate its long-term sustainability. Future research should employ advanced sustainability assessment methodologies, such as life cycle assessment and exergy analysis, to provide a more comprehensive analysis of these processes.

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REVIEW ARTICLE

An overview of the energy segment of Indonesia: present situation, prospects, and forthcoming advancements in renewable energy technology

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Abstract

The rising usage of fossil fuels increases greenhouse gas (GHG) emissions, leading to global climate change. Thus, addressing global environmental challenges requires a widespread switch from fossil fuels to renewable energy. Renewable energy reduces GHG emissions, extreme weather, and climate change while boosting energy efficiency. Indonesia ranks among Asia-Pacific's top five renewable energy producers. Indonesia, a vast country with abundant natural resources, has seen a rise in renewable energy demand as consumption has increased. Thus, this study examines Indonesia's renewable and sustainable energy technologies' existing position, possibilities, and future improvements. With 420 gigawatts (GW) of theoretical renewable energy capacity, Indonesia has great potential. This capacity includes 208 GW of solar, 75 GW of hydro, 61 GW of wind, 33 GW of biofuel, 24 GW of geothermal, and 19 GW of micro-hydro. The need to increase renewable energy consumption in Indonesia is driven by environmental and economic growth laws. This review study is expected to guide future research on renewable energy technology in Indonesia. This study would guide energy-related policies, particularly renewable energy ones, to meet future demands and goals.

Keywords: Energy consumption; Renewable energy; Emission reduction; Energy efficiency; Sustainability

Introduction

Energy plays a significant role in the developmental processes of both social and environmental aspects, hence providing support to the national economy (Raihan et al., 2022a; Voumik et al., 2022; Ghosh et al., 2023; Xing et al., 2023). In addition, energy has a crucial role in driving multiple areas of society, including technology, information, agriculture, education, health, and transportation (Raihan & Voumik, 2022a; Woo & Whale, 2022; Raihan & Tuspekova, 2023a). The energy demand is experiencing a significant increase over time, in accordance with the growth of both the economy and population (Raihan & Voumik, 2022b; Chien et al., 2023; Raihan & Tuspekova, 2023b). According to the World Bank (2023), there has been a significant increase in global energy consumption since 1971, approximately tripling in order to meet the continuously growing energy needs. The escalating utilization of fossil fuels, including coal, oil, and natural gas, exerts a substantial influence on the amplification of GHG emissions, predominantly carbon dioxide (CO_2), hence contributing to the phenomenon of global warming and climate change (Raihan et al., 2019; Begum et al., 2020; Jaafar et al., 2020; Raihan et al., 2021a; Li et al., 2022; Sultana et al., 2023; Voumik et al., 2023a). In addition, it is important to note that fossil fuel energy is non-renewable, leading to a gradual decline in its availability (Raihan & Tuspekova, 2022a; Raihan et al., 2022b; Raihan et al., 2023a). Hence, the accessibility of sustainable energy plays a crucial role in upholding sustainable development (Raihan & Tuspekova, 2022b; Raihan et al., 2022c; Raihan et al., 2023b). The use of renewable energy sources presents a viable and advantageous substitute for fossil fuels, which encounters significant opposition within the energy markets (Raihan & Tuspekova, 2022c; Raihan et al., 2022d; Donald et al., 2022; Raihan et al., 2023c). It is anticipated that the energy sector will see future expansion, prompting a transition towards renewable energy sources (Raihan & Tuspekova, 2022d; Ullah et al., 2022; Sharif et al., 2023). This transition is expected to contribute to the mitigation of GHG emissions by mitigating the adverse effects of extreme weather events and climate change (Raihan & Tuspekova, 2022e; Raihan et al., 2022e; Raihan, 2023a). Additionally, the adoption of renewable energy sources will ensure the provision of energy that is both dependable and economically viable (Wang et al., 2021; Raihan & Tuspekova, 2022f; Raihan et al., 2022f; Raihan, 2023b).

The utilization of renewable energy sources has the potential to establish a more environmentally sustainable energy framework in comparison to the reliance on fossil fuels (Raihan & Tuspekova, 2022g; Raihan et al., 2022g; Umar et al., 2022; Raihan, 2023c). Numerous countries are actively engaged in efforts to tackle climate and environmental change through the enhancement of energy efficiency and the broadening of accessibility to renewable energy sources (Aleluia et al., 2022; Raihan & Tuspekova, 2022h; Raihan, 2023d). The demand and potential for renewable energy have experienced substantial development primarily as a result of the enormous increase in global energy consumption (Luderer et al., 2022; Raihan & Tuspekova, 2022i; Raihan, 2023e). Renewable energy sources such as wind, geothermal heat, solar power, biofuel, and hydropower have garnered significant attention in several policy papers and empirical research studies due to their crucial role in mitigating energy challenges and environmental degradation (Sharif et al., 2020; Shoukat et al., 2021; Muhammad et al., 2022; Ullah & Sharif, 2022). This initiative also aligns with the pursuit of Sustainable Development Goal 7 (SDG7), which encompasses the objectives of ensuring accessible and clean energy, as well as mitigating carbon dioxide emissions (Raihan & Tuspekova, 2022j; Raihan, 2023f). Furthermore, the aforementioned endeavors influence state policies about the achievement of a sustainable environment via the utilization of renewable energy, promotion of economic activities, and facilitation of trade freedom (Santika et al., 2020; Raihan & Tuspekova, 2022k; Raihan, 2023g). The reduction of emissions through the use of renewable energy sources can be achieved by implementing poverty alleviation efforts, which hold significant importance in developing nations such as Indonesia (Setyowati, 2021).

In the preceding thirty years, Indonesia has largely depended on energy consumption as a means to propel its swift economic growth (Farabi et al., 2019). Nevertheless, at present, the Indonesian economy faces significant challenges in mitigating the extensive reliance on fossil fuels for energy generation and the resulting environmental degradation (Yana et al., 2022). Indonesia is currently facing pressure from the international community to effectively tackle the challenges associated with the increasing levels of GHG emissions (Puspitaloka et al., 2021). According to Raihan et al. (2022h), Indonesia has articulated its commitment to pursuing ambitious objectives and implementing policies aimed at mitigating the reliance on fossil fuel energy by promoting the utilization of alternative renewable energy sources. The ultimate aim of these efforts is to foster sustainable growth within the country (Raihan et al., 2023d). Figures 1 and 2 illustrate the ongoing reliance of Indonesia on fossil fuels, despite its efforts to transition towards the utilization of renewable energy sources. The transition is achieved through a gradual increase in the proportion of renewable energy sources in the overall energy mix. According to Tambunan et al. (2020), the percentage of renewable energy is projected to rise from 11% in 2021 to 23% in 2025 and further to 31% in 2050. According to Karakurt and Aydin (2023), there is a projected decline in the percentage of fossil energy mix, despite an increase in the demand for primary fossil energy supply. According to a study conducted by Gunawan et al. (2022), coal remained the primary source of energy generation in Indonesia in the year 2021.

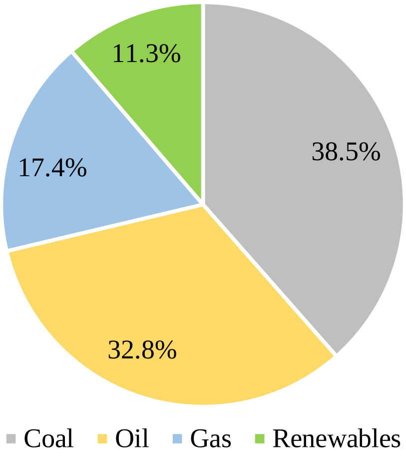

Figure 1. Indonesia's major energy sources (NEC, 2021).

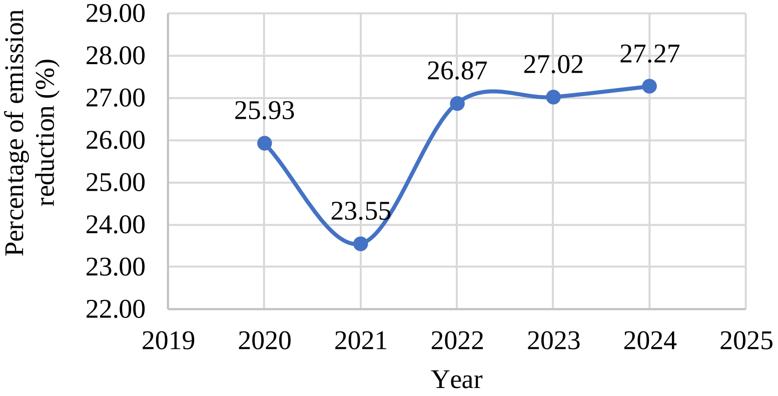

Figure 2. Indonesia's GHG emissions reduction Projection (PRRI, 2021).

According to the PRRI (2021), Indonesia achieved a reduction of 25.93% in its GHG emissions in 2020. However, in 2021, this reduction was reduced to 23.55%. Hence, it is imperative to effectively implement low-carbon development measures in the next years through the augmentation of government initiatives and financial allocations (Tiawon & Miar, 2023). Potential strategies to address environmental concerns include reforestation, the prevention of deforestation, the augmentation of renewable energy capacity, and the enhancement of energy efficiency (Raihan et al., 2018; Raihan et al., 2021b; Ali et al., 2022; Isfat & Raihan, 2022; Raihan & Said, 2022; Raihan, 2023h). Hence, it is imperative to align the restoration of economic and social activities, especially in the aftermath of the COVID-19 pandemic, with endeavors aimed at mitigating GHG emissions (Raihan & Himu, 2023; Raihan, 2023i; Zhang et al., 2023). Multiple nations, including Indonesia, have enhanced their global collaboration efforts to enable the acquisition of clean, renewable, and efficient energy technology (Raihan et al., 2022h). According to the World Bank (2023), Indonesia is positioned within the top five countries in the Asia-Pacific region in terms of its renewable energy capability. The imperative to enhance the demand for renewable energy in Indonesia is stipulated by multiple legislative measures aimed at safeguarding the environment and fostering sustainable economic development (Raihan et al., 2023d).

As per the Indonesian Ministry of Energy and Mineral Resources, the government has become a participant in the Clean Energy Demand Initiative (CEDI). This approach serves as a means of bolstering the global community's efforts to enact climate change mitigation measures and enhance the sustainability of the economy. Hence, the implementation of the president's instructions pertaining to the Comprehensive Environmental Development Initiative (CEDI) is imperative in expediting the requisite measures for attaining the nationally determined contribution (NDC) and net zero emissions (NZE) objectives, set for the years 2030 and 2060 correspondingly. The promotion and strengthening of Indonesia's renewable energy transformation policies will be emphasized. In addition, the organization possesses a clear vision and goal to attain a 23% share of renewable energy in the primary energy composition by the year 2025. This objective is accompanied by a corresponding reduction in emissions ranging from 29% to 41% (Santika et al., 2020).

Indonesia possesses considerable potential for renewable energy, hence necessitating its future optimization (Yana et al., 2022). However, there is limited research highlighting the future potential of renewable energy in Indonesia. There is a research gap between the current status, potential, and future development of renewable energy technologies in the context of Indonesia. Hence, the objective of this study is to critically explore the current state, prospects, and forthcoming advancements in renewable and sustainable energy technologies within the context of Indonesia. The novelty of this study lies in the incorporation of the most recent data pertaining to the accessibility of renewable energy sources in Indonesia. This review aims to depict a visual representation of its prospective advancement in the forthcoming years. This review study fills up a research gap in the existing literature by providing a valuable resource for future research endeavors and enhancing understanding of the capabilities of renewable energy technologies, with a specific focus on the Indonesian setting. This study would provide valuable insights for the implementation of energy-related policies, particularly those focused on renewable sources, with the aim of addressing future needs and goals.

Methodology

The present study used the systematic literature review method to explore the energy segment of Indonesia with a focus on the present situation, prospects, and forthcoming advancements in renewable energy technology. Following the selection of the research topic, this study proceeded to identify and locate pertinent articles, conduct an analysis and synthesis of various literature sources, and compile written materials for the purpose of article review. The synthesis phase involved the gathering of diverse articles that were afterward compiled into conceptual or empirical analyses that were pertinent to the completed research.

Current Status of Indonesia's Energy Sources

The nation of Indonesia possesses a substantial abundance of natural resources that can be utilized for the purpose of energy production, either through direct utilization or by means of a conversion process (Raihan et al., 2023d). The energy mix comprises both non-renewable fossil fuel sources, including oil, gas, and coal, and renewable sources such as hydro, geothermal, mini- and micro-hydro, solar, wind power, nuclear, and various others (Raihan et al., 2022h). Certain sources have the potential to undergo processing in order to meet the requirements of the community, and the management should consult the principles of sustainable development as outlined by Litvinenko et al. (2022). The energy balance in Indonesia has undergone consistent fluctuations throughout the years. The primary energy supply, excluding biomass, experienced a notable rise from 170 million tonnes of oil equivalent

(TOE) in 2015 to 202 million TOE in 2020, exhibiting an average annual growth rate of 3.5%. In the year 2020, the overall energy production amounted to 443 million tons of oil equivalent (TOE), with fossil fuels, namely oil, gas, and coal, accounting for 95% of this production (NEC, 2021).

At present, fossil fuels continue to hold a significant proportion of the overall consumption of final energy. These resources are widely distributed over many regions, encompassing the islands of Sumatra, Java, and Kalimantan. The estimated quantity of oil reserves stands at around 4.17 billion barrels, out of which 2.44 billion barrels have been designated as reserved. In the present context, it is worth noting that the existing natural gas reserves amount to approximately 62.4 trillion cubic feet, out of which 43.6 trillion cubic feet have been confirmed as proven reserves, as reported by the Ministry of Energy and Mineral Resources in 2021. According to estimates, the available reserves of oil and gas are projected to last for a duration of around 9.5 years and 20 years, respectively. This analysis is based on the premise that no novel findings have been made, and the current rate of oil extraction stands at around 0.7 million barrels per day, while gas extraction amounts to 6 billion standard cubic feet per day, as reported by the Ministry of Energy and Mineral Resources in 2021. According to the Ministry of Energy and Mineral Resources (MEMR, 2021), Figure 3 illustrates a fall in oil and gas output attributed to the natural deterioration of reservoir performance and the challenges associated with identifying substantial new reserves. Hence, it is projected that the reserves of oil and gas will exhibit a persistent reduction until the year 2024. According to the projection made by the country, it is anticipated that the quantity of remaining oil reserves in the year 2024 will amount to 1138 million stock tank barrels (MMSTB). This projection indicates a decline of 49% in comparison to the reserves recorded in the year 2020, as illustrated in Figure 4. A similar trend is expected to be observed in the case of natural gas, as it is projected to undergo a decrease of 22% according to the Ministry of Energy and Mineral Resources (MEMR, 2021).

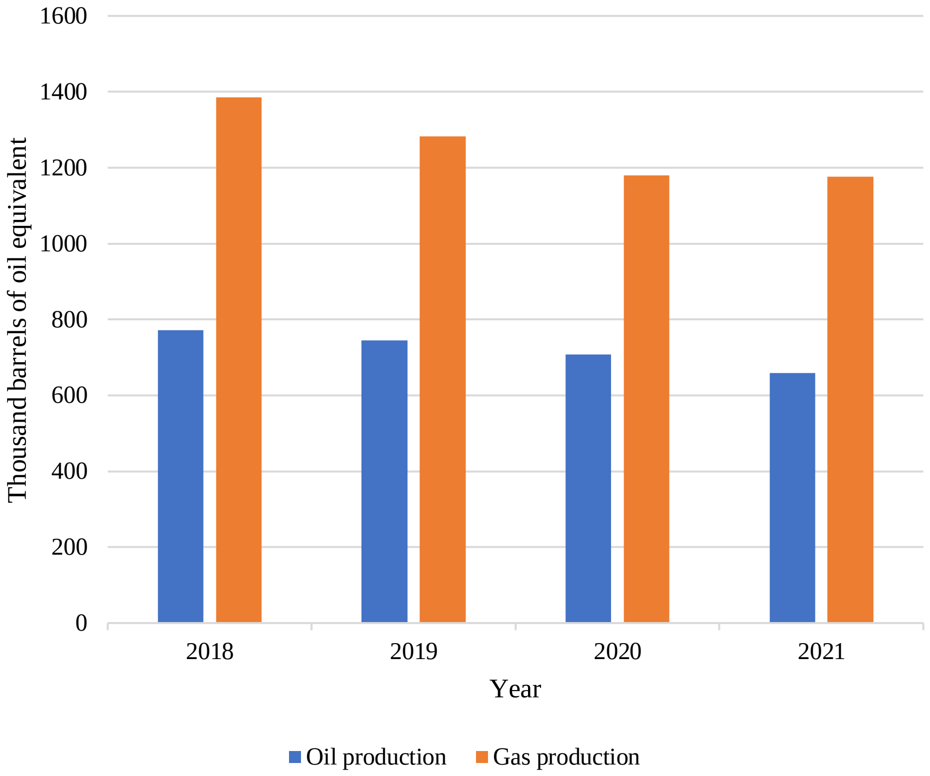

Figure 3. Yearly production of oil and gas in Indonesia (MEMR, 2021).

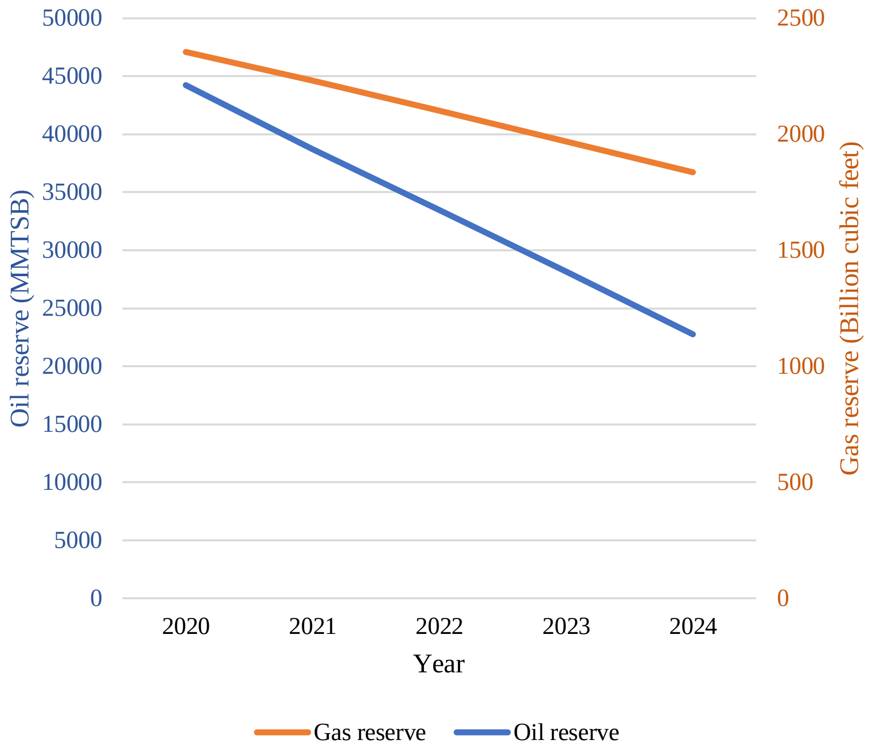

Figure 4. Current and projected reserves of oil and gas in Indonesia (MEMR, 2021).

Coal, like oil and gas, is a non-renewable natural resource that possesses significant strategic worth at both regional and national levels. The Asia Pacific region heavily relies on this particular natural resource to offer cost-effective and accessible sources, particularly during the ongoing pandemic and the Russia-Ukraine conflict (Wicaksana & Ramadhan, 2022). The coal reserves in Indonesia are distributed among 21 provinces, amounting to a total of 39 billion tons. In the year 2021, the average output of coal in Indonesia was recorded at 606 million tons, as reported by the Ministry of Energy and Mineral Resources (MEMR, 2021). There is a 7.2% increase observed in comparison to the previous year, 2020, which recorded a total of 566 million tons, as depicted in Figure 5. Based on current estimates, it is projected that the coal reserves will remain accessible for a period of approximately 65 years, under the assumption that no more deposits are discovered. In addition, it is worth noting that there exists a significant quantity of coal resources, estimated at 144 billion tons. Notably, the majority of these resources, accounting for 62% or 88 billion tons, are concentrated in the region of Kalimantan. Additionally, there are 26 billion tons of coal reserves in this area. Coal deposits are also present in Sumatra, exhibiting a substantial quantity of resources amounting to 55 billion tons, alongside reserves estimated at 13 billion tons (MEMR, 2021).

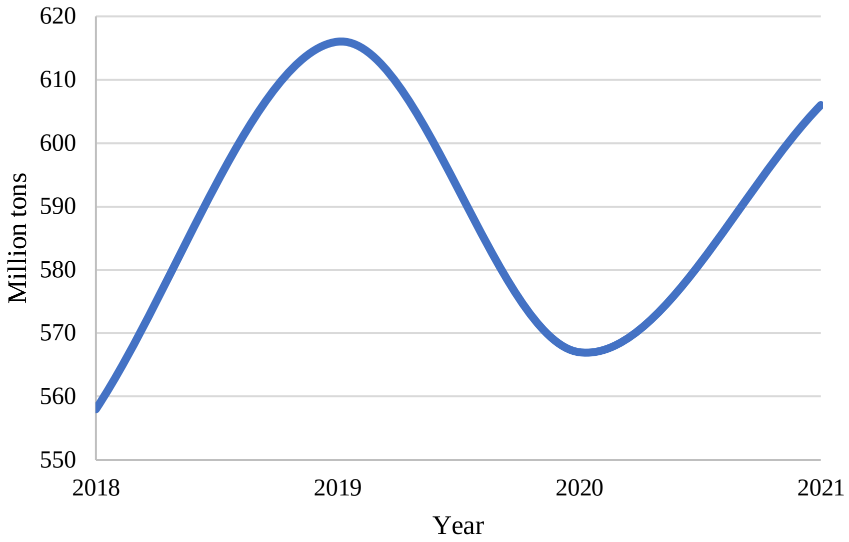

Figure 5. Yearly production of coal in Indonesia (MEMR, 2021).

The utilization of coal can be categorized into two distinct purposes, namely as a primary material and as a source of energy. The utilization of this substance as a primary component encompasses several industrial applications such as the production of coal briquettes, metal processing, coal liquefaction, gasification, and upgrading (Liu et al., 2023). Simultaneously, it finds application in the power production sector, industrial settings, small enterprises, and residential environments as a source of fuel (Chen et al., 2022). Coal has a crucial role in generating state revenue, making it a significant economic resource (Adebayo, 2023). Hence, the management of the aforementioned entity must be conducted in an efficient, transparent, responsible, and equitable manner, so as to provide substantial advantages for the community (Sriwahyuni, 2023). The consideration of environmental changes, both domestically and globally, should be a crucial aspect of government policies aimed at promoting the advancement of coal mining (Triady & Saraswati, 2021).

The demand for renewable energy sources in Indonesia arises from the anticipated decline in the accessibility of non-renewable energy sources (Aswadi et al., 2023). The utilization and viability of renewable energy sources had a significant growth, surging from 5% in 2015 to 11% in 2020. This notable gain may be attributed to the amplified use of biofuels and the integration of renewable energy technologies in the establishment of off-grid power plants, including hydroelectric, geothermal, and solar power facilities (Pandey et al., 2022). Currently, the renewable energy supply in Indonesia amounts to 23 million tons of oil equivalent (TOE), which accounts for around 11% of the total energy supply. This renewable energy mix includes hydro, geothermal, solar, wind, biofuel, and biogas sources. In contrast, the current level of production accounts for a mere 5% of the overall national energy production, as reported by the Ministry of Energy and Mineral Resources in 2021. The production of renewable energy in Indonesia in recent years is depicted in Figure 6. According to the Ministry of Energy and Mineral Resources (MEMR, 2021), there was a rise in the generation capacity of solar power plants from 4.56 Gigawatt hours (GWh) in 2018 to 5.66 GWh in 2021. In the meantime, there has been a notable rise in the consumption of hydropower, with an increase from 10,729 GWh in 2018 to 11,869 GWh in 2021. Comparably, the production of geothermal energy had an upward trend, rising from 4013 GWh in 2018 to 4217 GWh in 2021. The data provided by the Ministry of Energy and Mineral Resources (MEMR, 2021) indicates a growing trend in the adoption of renewable energy sources, leading to a corresponding decline in the utilization of fossil fuels.

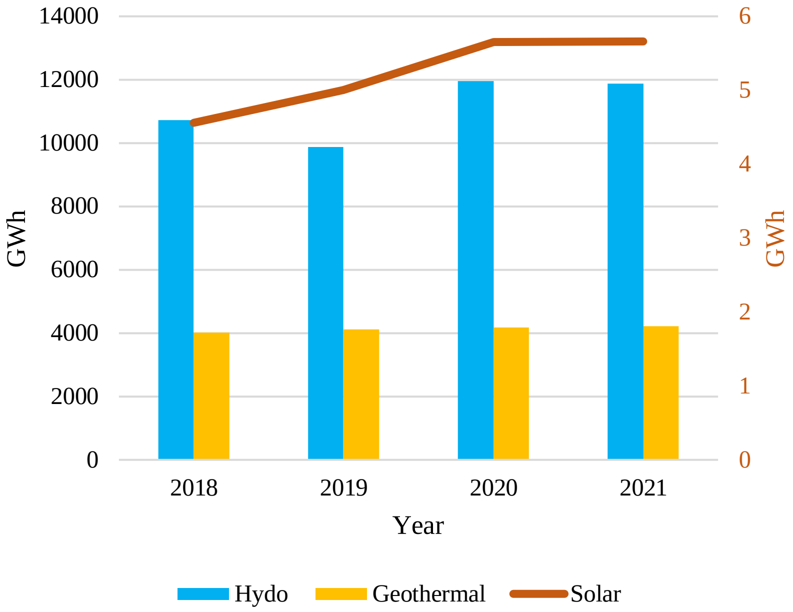

Figure 6. Yearly production of water, geothermal, and solar energy in Indonesia (MEMR, 2021).

Energy Consumption in Indonesia

Energy, being a crucial natural resource, plays a pivotal role in fostering community prosperity (Raihan et al., 2023e; Voumik et al., 2023b; Raihan, 2023j). Consequently, it becomes imperative to implement effective energy management strategies to facilitate sustainable development (Raihan et al., 2022i; Chen et al., 2023; Raihan, 2023k). The Indonesian government has set a goal of achieving a 17% reduction in final energy consumption by the year 2025, along with a 1% decrease in energy intensity. In addition, the Ministry of Energy and Mineral Resources (MEMR, 2021) has set a specific goal of achieving a reduction ranging from 10% to 30% in the industrial, transportation, commercial, and home sectors. In 2021, Indonesia's energy consumption amounted to approximately 939 million barrels of oil equivalent (BOE). The consumption mentioned comprised a biogas oil component, accounting for 46% of the total. This biogas oil component was composed of gasoil, biodiesel, and blended products, with respective proportions of 16%, 7%, and 23% (MEMR, 2021). Additional forms of energy consumption encompass many sources such as oil, electricity, natural gas, coal, liquefied petroleum gas (LPG), biodiesel, biogas, and biomass (MEMR, 2021). The energy consumption of Indonesia in 2021, categorized by energy type, is depicted in Figure 7.

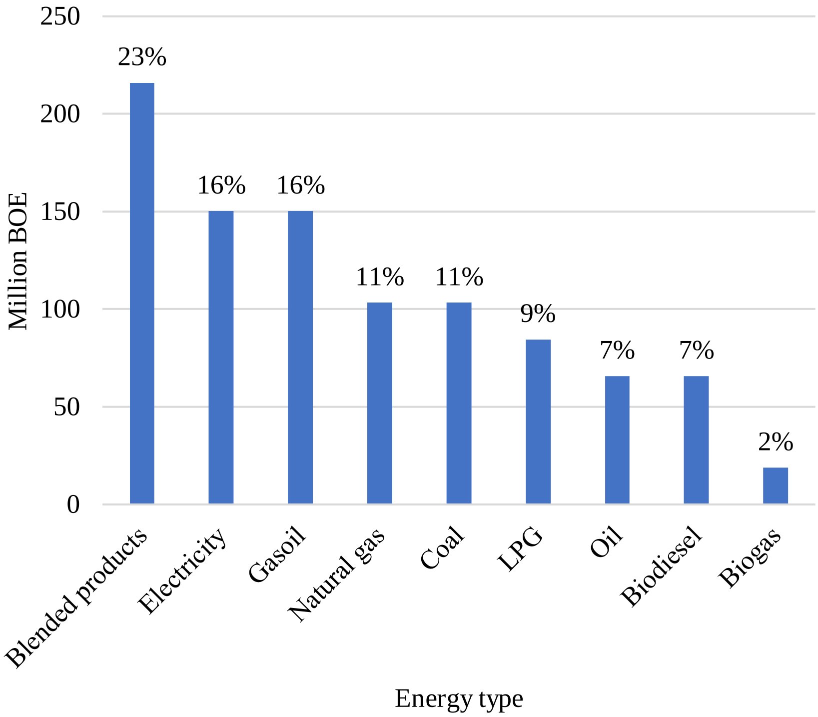

Figure 7. Indonesia's energy consumption in 2021 by energy type (MEMR, 2021).

The energy consumption in Indonesia for the year 2021, categorized by industries, is depicted in Figure 8. According to the Ministry of Energy and Mineral Resources (MEMR, 2021), the transportation sector accounted for the highest proportion of energy consumption, representing nearly 46% of the total energy consumed. The energy consumption rates in industries and families were 31% and 17%, respectively. In addition, it is worth noting that the commercial sector accounts for 5% of total energy consumption, with the remaining energy being allocated to various other sectors (MEMR, 2021). The rise in energy consumption in both the industrial and vehicular sectors can be attributed to the substantial increase in industrial and vehicular operations (Raihan et al., 2023f). The demand in the industrial sector is anticipated to correspond with its growth as outlined in the "Indonesia Vision 2045". In the transportation sector, various factors have had an impact. These include the increasing number of motor vehicles, the implementation of a substitution program aimed at transitioning from conventional to electric cars, the introduction of mandatory biodiesel and bioethanol initiatives, and the transition from private to mass automobiles (NEC, 2019). The projected increase in power consumption is expected to have an impact on the future development of electric vehicles by the year 2035, exhibiting an annual pattern.

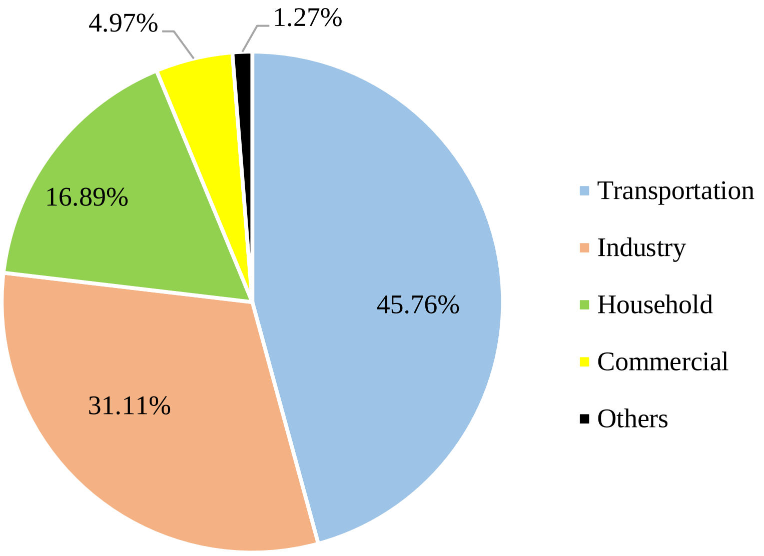

Figure 8. Indonesia's energy consumption in 2021 by sectors (MEMR, 2021).

Fossil fuels are employed as an interim energy resource inside the nation, particularly during the transitional phase before the complete conversion to 100% renewable energy in power generation facilities. Natural gas is employed as a fuel source to supplement intermittent renewable energy facilities, whereas minerals are primarily utilized in the latter stages of production. Nevertheless, the government has initiated a process of diminishing the utilization of coal as an energy source through the implementation of CCS/CCUS (carbon capture, utilization, and storage) technology. Additionally, they are exploring the substitution of LPG with dimethyl ether (DME) and enhancing the value of minerals by means of local downstream activities. According to the Ministry of Energy and Mineral Resources (MEMR, 2022), the emissions from the energy sector in Indonesia for the year 2021 reached a total of 530 million tons of carbon dioxide equivalent (CO_2e). A projection has been made indicating that there will be a rise in peak emissions to around 706 million tons of CO_2e by the year 2039. Nevertheless, it is anticipated that there will be a substantial decrease in emissions post-2040, subsequent to the fulfillment of contracts pertaining to fossil fuel power plants (MEMR, 2022).

The achievement of energy conservation Is presently being pursued through the acceleration of the worldwide energy transition, a process that is bolstered by a collective consensus among all members of the International Energy Agency (IEA) with regard to the promotion of energy efficiency. According to Rabbi et al. (2022), this acceleration has the potential to attain the objective of achieving net-zero emissions on a worldwide scale. The implementation of energy management in Indonesia, particularly in relation to government restrictions on energy conversion, has been designed (Redaputri & Barusman, 2021). The government has also undertaken measures to broaden the scope of the minimum performance standards (MEPS). Furthermore, the aforementioned law includes energy conservation measures, such as the adoption of electric vehicles and induction cookers, which are facilitated through the execution of governmental initiatives. These initiatives encompass the transition from diesel to gas generators, the establishment of rooftop solar power plants, and the conversion of electric motors (MEMR, 2022). According to Yudiartono et al. (2023), the government provides backing for the implementation of induction cookers and the expansion of the gas network, aligning with the objectives outlined in the energy transformation roadmap and the pursuit of carbon neutrality. In addition, it is important to note that the enhancement of energy efficiency in commercial buildings necessitates a comprehensive approach that encompasses both the design phase and the operational aspects of the structure (Raihan, 2023l). This can be achieved by including efficient equipment and systems, as highlighted by Yudiartono et al. (2022).

In order to facilitate the realization of a zero-emission scenario, a minimum of 47% of a generatio''s energy production must be derived from renewable sources by the year 2030. It is projected that throughout the upcoming decade, the capacity of solar photovoltaic (PV) systems will experience a significant increase, reaching a magnitude of 108 GW, or a hundredfold growth. The primary objective of this initiative is to provide valuable assistance in promoting the adoption of electrification in both the industrial and transportation domains. According to Setiawan et al. (2021), the government has implemented budget tagging as a means of tracking the allocation of public funds towards climate change mitigation and adaptation efforts, specifically in the areas of energy and transportation. Nevertheless, the organization has been unable to effectively mitigate emissions, resulting in consequential implications for budgetary allocations. Over the course of the previous five years, the allocation of the state budget has been primarily directed towards financing the energy and transportation sectors, resulting in a total sum of IDR 221.6 trillion, which accounts for approximately 81.73% of the budget. According to Hilmawan et al. (2021), the existing budget allocations and expenditures are insufficient to meet the National Determined Contributions (NDC) objective of IDR 318.18 trillion years from 2020 to 2030.

Potential Future Development of Renewable Energy

Indonesia, comprising 34 provinces, is characterized as an archipelago abundant in diverse energy resources. Hence, it is imperative to develop a comprehensive cartographic representation that delineates the technical capacity of renewable energy sources (Yana et al., 2022). Additionally, this initiative must facilitate the gradual shift towards the adoption of entirely renewable energy sources, with the ultimate goal of attaining a carbon-neutral Indonesia by the year 2050 (PRRI, 2017). The feasibility of implementing renewable energy solutions is contingent upon the prevailing geographical conditions. In response to this, the government has undertaken the establishment and deployment of power plants across several locations (Putranto et al., 2022). The population and economy have experienced significant exponential growth, which currently exerts a notable influence on climatic patterns, ecological dynamics, and biodiversity. According to Yilanci et al. (2023), there is a tendency for indicators of socioeconomic status and other ecological repercussions to exhibit a correlation with energy demand. In the context of Indonesia, the utilization of fossil fuels, including oil, gas, and coal, remains prevalent. The extensive utilization of this resource contributes to the expansion of the economy, albeit frequently accompanied by environmental degradation that poses the risk of potential catastrophes of natural or human origin (Sharma & Malaviya, 2023).

Regarding the Nationally Determined Contributions (NDCs), all nations throughout the globe, including Indonesia, expressed their dedication to upholding a limit on the increase in global temperature within the range of 1.5 ◦C to 2 ◦C during the initial phase. The objective of this initiative is to achieve a reduction in emissions of 29% by individual efforts, and a more substantial reduction of 41% under the assumption of international collaboration. The forthcoming no-action plan, projected to be executed in 2030, will be accomplished by leveraging various sectors, namely forestry, energy (including transportation), waste management, industrial processes, product utilization, and agriculture. The resolve is reinforced by the legislation enacted by the government to ratify the Paris Agreement under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC). In order to accomplish this objective, Indonesia has established a renewable energy objective within the national energy composition, aiming for a minimum of 23% and 31% by the years 2025 and 2050, respectively. Furthermore, the region exhibits considerable potential for several forms of renewable energy, including solar, hydro, wind, geothermal, and bioenergy or biomass (Raihan et al., 2022h).

Table 1 presents an overview of the efficacy of Indonesi"s renewable energy sources in the year 2021. Despite the considerable renewable energy potential of 420 GW in Indonesia (NEC, 2021), its current use remains limited. Hence, the strategic plan for the development of NZE includes the optimization of renewable energy utilization in power generation, as stated by Utami et al. (2022). The limited adoption of renewable energy sources for power generation can be attributed to the comparatively higher cost of establishing and operating such facilities (Raihan et al., 2022h). This poses a significant challenge in terms of competing with fossil plants, particularly coal. In addition, hindrances to the growth of renewable energy include insufficient domestic industrial backing and challenges in securing low-interest funding (Raihan et al., 2023d).

Table 1. The potency of Indonesia's renewable energy in 2021 (NEC, 2021).

Type of renewable energy	Potency (GW)
Solar	208
Hydro	75
Wind	61
Bioenergy	32
Geothermal	24
Micro-hydro	19
Total	420

Solar energy

Solar energy is a fast-emerging type of renewable energy that is seeing significant global development (Raihan, 2023m). As a nation situated in a tropical region with consistent solar exposure year-round, there is a pressing need to maximize energy utilization (Sorooshnia et al., 2023). The solar energy potential in Indonesia is substantial, as indicated by a capacity of 208 MW (Junihartomo et al., 2022) and an average sun irradiance of 4.80 kWh/m2/day (Windarta et al., 2019). The assessment of solar potential is an essential initial stage in the adoption of solar energy in Indonesia. Figure 9 illustrates the annual installed capacity of solar power plants in Indonesia. In 2021, the Ministry of Energy and Mineral Resources (MEMR) reported a total installed capacity of 208 MW for the production of solar energy, which is achieved through the generation of both on-grid and off-grid energy (MEMR, 2021).

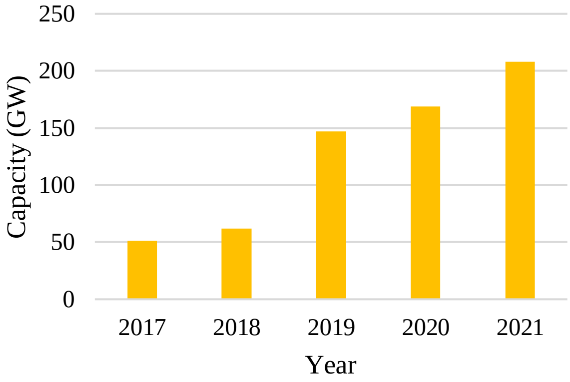

Figure 9. Yearly installed capacity of solar power plant in Indonesia (MEMR, 2021).

The solar power plant exhibits intermittent behavior, characterized by the variability of energy output due to factors such as seasonal circumstances, humidity, temperature, cloud movement, and other weather conditions (Raihan, 2023n). According to Tambunan et al. (2021), the generato"s operational continuity at its installed capacity is compromised. Moreover, the construction process is also associated with significant investment expenses, resulting in an uneconomical selling price of electricity (Tercan et al., 2022). In the year 2019, a regulatory measure was enacted by the government pertaining to the utilization of rooftop solar installations by individual consumers. The primary objective of this law was to facilitate the inclusion of consumers from many sectors, including households, businesses, social government, and industry, in the usage and management of renewable energy. The overarching goal was to enhance energy security and foster self-sufficiency in the energy sector. In addition to the implementation of rooftop solar power plants, it is anticipated that solar energy will also find application in energy-efficient solar lamps (Suparwoko & Qamar, 2022). Moreover, the government has expedited the deployment of energy-efficient solar lighting systems to individuals lacking access to power. The present strategy pertains to the allocation of energy-efficient solar lighting systems in remote, underprivileged, and geographically isolated regions that lack access to conventional power infrastructure (Cahyani et al., 2022; Raihan, 2023o).

The subsequent endeavor entails t"e de'elopment of a solar streetlight, which is an illumination device that harnesses solar energy as its primary source of electrical power. Between the years 2016 and 2020, a total of 65,501 units of solar streetlights were constructed, out of which 18,888 units were successfully installed (NEC, 2021). In 2021, a total of 4829 units were erected during the fourth quarter, specifically targeting road sites that lack connection to the energy network. In the year 2020, the installation of solar plants was categorized into two distinct segments: rooftop installations and installations within cold storage facilities. Furthermore, this technology can be utilized in various architectural structures, serving as both the primary energy source and a supplementary backup system to complement pre-existing power sources (Raihan, 2023p). Cold storage is among the applications of electricity derived from solar power plants. In the year 2021, a total of 100 units were discovered, consisting of 88 units located on rooftops and 12 units stored in public cold storage facilities (NEC, 2021).

In addition to its terrestrial applications, solar power plants can also be deployed in aquatic environments, aligning with the unique geographical characteristics of Indonesia as an archipelagic nation. Silalahi et al. (2021) have identified a significant potential for solar energy in a tropical country. Following this, a floating solar power facility was constructed and deployed in several aquatic environments, including reservoirs, lakes, ponds, and canals (Chirwa et al., 2023). The various elements encompassed under this system consist of solar modules, platforms, pontoons, mooring systems, inverters, power conditions stations, cabling, network interconnection infrastructure, supporting facilities, meteorological centers, remote monitoring, and data gathering systems (Islam et al., 2023). The offshore solar power plant has a greater number of obstacles compared to a conventional land-based solar power plant. These challenges arise from factors such as the limited historical data available, the inherent uncertainty around costs, and the potential environmental impact (Zeng et al., 2023). The design, construction, and operation of this model pose inherent complexities due to its interdependence with electrical, anchoring, and mooring systems (Moodliar & Davidson, 2023).

The utilization of floating solar plants has several notable benefits. Firstly, these installations do not necessitate the use of land, a resource that is typically of high value. Additionally, they contribute to the mitigation of water evaporation and effectively suppress the proliferation of undesirable vegetation, such as water hyacinth (Solomin et al., 2021; Raihan et al., 2022j; Raihan et al., 2023g). In addition, the performance of the PV module is hindered by the implementation of a cooling system, hence enhancing the overall efficiency of power production. At now, it is projected that the construction of the Citara floating plant in Indonesia will be finalized by 2022, followed by the establishment of another plant in the Sutami Reservoir, located in Malang, by 2023. It is projected that the proportion of renewable energy sources in Central Java province will rise to 22% by the year 2025, with a particular emphasis on harnessing solar and geothermal energy resources. The solar potential of this province is estimated to be 4.05 kWh/kWp per day, above the national average of 3.75 kWh/kWp per day. Central Java is home to a total of 42 reservoirs, which possess a significant potential for accommodating floating solar power plants with a combined capacity of 727 MWp. According to a report by the Institute for Essential Services Reform (IESR, 2021), the technical capacity of 11 big reservoirs accounted for 92.3% or 672 MWp of the overall contribution. Additionally, 7.36% (53 MWp) was generated by 24 medium-sized reservoirs, while the remaining 2 MWp was attributed to 7 minor reservoirs.

Hydro energy

Hydroelectric power plants, such as the Jelok Hydro Power Plant, were initially constructed in 1938 during the Dutch era, and are recognized for their dependable energy generation capabilities. The categorization of hydroelectric power generation depending on its scale consists of three classifications: hydro, micro-hydro, and mini-hydro power plants (Hermawati et al., 2023). Figure 10 illustrates the annual installed capacity of hydroelectric power plants in Indonesia. According to the Ministry of Energy and Mineral Resources (MEMR) in 2021, the total potential for hydroelectric power generation was estimated to be 6602 MW. This figure encompasses a hydropower plant with a capacity of 5639 MW, as well as micro-hydro and mini-hydro installations with capacities of 126 MW and 376 MW, respectively.

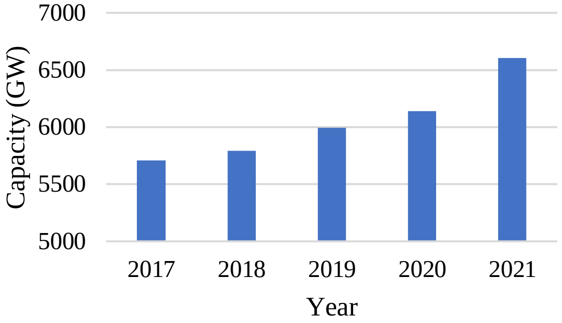

Figure 10. Yearly installed capacity of hydropower plant in Indonesia (MEMR, 2021)

Wind energy

According to PRRI (2017), there is a projected goal for wind power plants to achieve a capacity of 7 GW by the year 2030, with an installed capacity of 2.2 GW. According to Prasita et al. (2022), multiple regions in Indonesia have wind potential characterized by velocities ranging from 4 to 6 m/s. According to PRRI (2017), Indonesia now possesses a wind power facility with an installed capacity of 154.3 MW. However, the country aims to increase its wind power capacity to 255 MW by the year 2025. The nation encompasses two significant botanical entities, specifically Sidrap and Tolo. Sidrap is situated in the Sidenreng Rappang regency and is home to a total of 30 wind turbines, collectively generating a capacity of 75 MW. Tolo is situated in the region of Turatea, which is located in the southern part of Sulawesi. It possesses a total power generation capacity of 72 MW, facilitated by a collection of 20 wind turbines, each having a capacity of 3.6 MW (PRRI, 2017). The potential for wind energy is promising, as there is a prospective opportunity to construct wind power plants in three sub-districts of South Garut, namely

Pameungpeuk, Cibolang, and Cisompet. In 2023, a number of plants are scheduled to be constructed, including the Sukabumi Project and the Tolo II in Jeneponto (PRRI, 2017).

Bioenergy

Aside from bioenergy's application in the power sector, it has the potential to fulfill energy demands in several sectors such as transportation, industry, and households (Rehan et al., 2023). The identification of a wide range of raw materials, including livestock manure, agricultural waste, plantation waste, and urban trash, is readily achievable. The energy derived from various sources such as biomass, biogas, municipal waste, domestic biogas, and bioenergy furnaces has the potential to be utilized as a power source for power plants (Kalak, 2023). Figure 11 illustrates the annual installed capacity of biofuel power plants in Indonesia. According to the Ministry of Energy and Mineral Resources (MEMR, 2021), the total installed capacity of bioenergy power plants in the year 2021 amounted to 2284 MW. The national energy strategy aims to achieve a capacity of 9.6 GW generated from bioenergy power plants, as well as 1.09 GW generated from biomass, biogas, and waste bioenergy sources. The ample potential of bioenergy presents expanded prospects for the younger demographic to actively contribute to endeavors aimed at advancing bioenergy and clean energy across diverse sectors (MEMR, 2020). Within the realm of academia, it is imperative to go further into the exploration of research and innovation development opportunities in order to fully harness the potential of domestic bioenergy. Community service activities coordinated by universities have the potential to make valuable contributions toward the advancement of bioenergy utilization in everyday community settings.

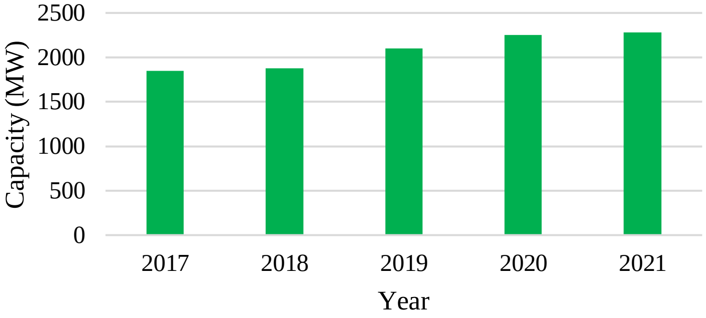

Figure 11. Yearly installed capacity of bioenergy power plant in Indonesia (MEMR, 2021).

Biomass refers to organic matter derived from living organisms, encompassing both flora and fauna, as well as their associated byproducts (Yana et al., 2022). In the Indonesian context, several industrial waste materials, including but not limited to palm oil, tapioca, pulp and paper, sugar cane, rice, and wood, have the potential for extraction. According to the Ministry of Energy and Mineral Resources (MEMR, 2021), the estimated biomass potential for generating energy in 2021 is 32,654 MW. Out of this total, there is an installed capacity of 152 MW for on-grid systems and 1970 MW for off-grid systems. The potential for biomass energy in the future lies in its ability to be effectively harnessed through the co-firing technique, which involves blending biomass with coal within a steam power plant. The co-firing process involves the utilization of garbage and wood as primary raw materials (Szufa et al., 2023). In addition, it is worth noting that the country has a potential capacity of 2603 MW for biogas production. According to the Ministry of Energy and Mineral Resources (MEMR, 2021), the power generation capacity of on-grid and off-grid biogas plants in 2021 was reported to be 22 MW and 113 MW, respectively. Furthermore, biogas possesses the potential to serve as a source of energy not just for power plants but also for residential households through the utilization of cow dung and household trash, a practice commonly referred to as communal biogas development (Nadan & Baroutian, 2023).

Biofuels typically consist of energy and constituents derived from plants and biomass (Gnanasekaran et al., 2023). The body of literature pertaining to the production of biofuels derived from biomass resources through ecologically sustainable approaches has been steadily growing (Khan et al., 2022). A range of liquid and gaseous biofuels can be derived from biomass, including ethanol, biodiesel, methane, methanol, and bio-oil (Kazmi et al., 2023). In order to promote the utilization of renewable energy sources, researchers have undertaken endeavors to blend palm oil with diesel oil as a means of generating biodiesel (Gunawan et al., 2023). In addition, there have been endeavors to blend ethanol derived from the processing of sugarcane with gasoline in order to generate bioethanol. In 2021, the implementation of biofuel use has achieved a volume of 6.66 million kiloliters, which represents a proportion of the initial target of 10.2 million kiloliters designated for domestic consumption. The potential of biofuel as a viable alternative to petroleum has garnered significant attention, leading to the exploration of many sources including terrestrial and marine plants, such as microalgae, for the production of alternative energy (Singh et al., 2023).

In addition, it is worth noting that the trash generated by the community has the potential to serve as an energy resource capable of generating an estimated 2000 MW of power (MEMR, 2020). The waste-to-energy facility situated in Benowo, Surabaya presently possesses a power generation capacity of 12 MW. Its operations commenced on the 6th of May 2021. The outlook appears promising since there are multiple locations encompassing Jakarta, Surabaya, Tangerang, Semarang, Bandung, Surakarta, Denpasar, Makassar, Manado, Bekasi, Palembang, and South Tangerang City. The proposed development plan entails the allocation of 38 MW, 29 MW, 10 MW, and 9 MW of power generation capacity in Jakarta, Bandung, Surakarta, and Bekasi City, respectively. According to the National Energy Council (NEC, 2021), the five remaining cities, namely Makassar, Palembang, Manado, South Tangerang, and Denpasar, possess an equivalent capacity of 20 MW apiece.

Geothermal energy

The development of geothermal energy commenced a century ago, marked by the inaugural drilling of a geothermal well at Kamojang by the Dutch in 1926. This geothermal facility has been in operation since 1983, as documented by Fajarudin et al. (2022). According to the Ministry of Energy and Mineral Resources (MEMR, 2021), Indonesia possesses a geothermal capacity of 23,766 MW. The specific allocation of this capacity is outlined in Table 2. Nevertheless, as depicted in Figure 12, the installed capacity in the year 2021 amounted to 2286 MW, indicating a significant amount of untapped potential in geothermal energy utilization. Hence, the government aims to achieve a rise in geothermal use to 7242 MW, equivalent to 16.8%, by the year 2025 (PRRI, 2017).

Table 2. Geothermal energy potential in 2021 by region (MEMR, 2021).

Region	Potency (MW)
Sumatra	9,517
Java	8,050
Sulawesi	3,071
Nusa Tenggara	1,399
Maluku	1,144
Bali	335
Kalimantan	175
Papua	75
Total	23,766

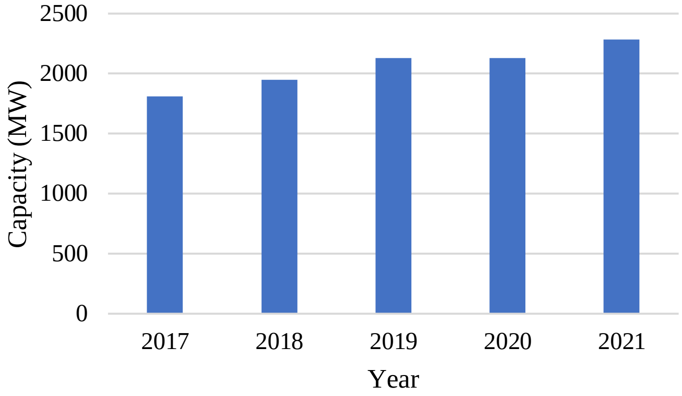

Figure 12. Yearly installed capacity of geothermal power plant in Indonesia (MEMR, 2021).

Nuclear energy

Uranium and thorium, both radioactive components, are among the fundamental raw resources utilized in nuclear manufacturing (Putri et al., 2022). According to the National Energy Council (NEC, 2021), Indonesia possesses a combined quantity of 81,091 tons of uranium resources and 140,411 tons of thorium reserves. Table 3 presents the estimated potential of uranium and thorium resources within the geographical boundaries of Indonesia. According to Wisnubroto et al. (2023), Indonesia possesses the capacity to establish nuclear power facilities in order to meet its domestic energy requirements, with support from the commercial and industrial sectors. Southeast Asia has the potential to become the first region in the area to establish a nuclear power plant, mostly driven by the presence of uranium resources. This development holds the promise of transforming uranium into a significant export commodity (Km, 2022). In relation to its influence, this form of energy has the capacity to mitigate the generated waste without exerting any discernible influence on power expenses. According to Krūmiņš and Kļaviņš (2023), the environmentally friendly outcome is disposed of in the ground to prevent any adverse impacts on the local community.

Table 3. Indonesia's prospective uranium and thorium reserves (NEC, 2021).

Region	Uranium (ton)	Thorium (ton)
Sumatra	31,567	126,821
Kalimantan	45,731	7,028
Sulawesi	3,793	6,562
Total	81,091	140,411

Conclusion

Renewable energy is suitable for powering social and economic infrastructure. The characteristics are sustainability, affordability, reliability, and improved safety. The Indonesian government is promoting renewable energy. Thus, this study suggests using solar, hydro, wind, bioenergy, and geothermal energy sources to harvest significant amounts of energy. Indonesia has also implemented energy policies and intends to increase its renewable energy mix. The country wants to increase renewable energy from 11% in 2021 to 23% in 2025 and 31% by 2050. This research also provides energy landscape information. In 2021, coal energy produced 559 million barrels of oil equivalent (BOE), while renewable energy produced 181 million. Energy supply, production, and consumption are interdependent, creating balance. The current situation may determine sustainable energy implementation steps. Indonesia's primary energy sources, excluding biomass, grew 3.5% year from 2015 to 2020 while preserving energy balance. Energy production in 2020 was 443 million tons of oil equivalent (TOE), with roughly 95% coming from fossil fuels like oil, gas, and coal. The 2021 trend of energy consumption per type is up 1%, or 939 million barrels of oil equivalent. Energy consumption is highest in the transportation sector, at 46%. This sector uses gasoline as its main fuel. According to energy consumption figures, fossil fuel use is still high and rising. Thus, Indonesia's vast renewable energy resources must be maximized.

The NZE power plant development strategy optimizes renewable energy sources for electricity generation. Renewable energy and energy conversion sub-sector performance targets are set for 2022. These aims include a 15.7% primary energy mix and 366 MBOE production. Many renewable power plants help the government reduce steam power plant coal use. The solar energy resource has a theoretical capacity of 207,898 MW with an average irradiation of 4.80 kWh/m2/day. Hydro energy sources have 95 GW of potential, including 75,000 MW of hydro and 19,370 MW of micro-hydro. The present wind energy capacity in Indonesia is 154 MW, with a goal of 255 MW by 2025. Bioenergy is used in biomass, biogas, municipal garbage, households, and power plants. The total bioenergy capacity is 32,653.8 MW. Geothermal power stations can generate 23,965 gigawatts. The switch from fossil fuels to renewable energy could boost the nation's economy. However, private sector investments in renewable energy projects are needed to lower transition costs. This review paper will help guide Indonesia in developing and implementing renewable energy policies.

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Authors Contribution: Asif Raihan contributed to conceptualization, visualization, methodology, reviewing literature, extracting information, synthesize, and manuscript writing.

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RESEARCH ARTICLE

Emerging Frontiers of Public Safety: Synergizing AI and Bioengineering for Crime Prevention

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Abstract

The convergence of artificial intelligence (AI) and biological engineering technology (BET) can potentially revolutionize public safety efforts. However, the responsible use of these technologies requires crucial considerations. This study employed an exploratory sequential mixed-method to examine the governance mechanisms apropos AI and BET in the context of crime prevention in the Philippines. It identifies several key components that contribute to establishing governance mechanisms, including multisectoral agencies, legislative initiatives, and regulatory frameworks. The study also identifies a 3-factor model for the governance convergence of AI and BET in public safety. These factors include empowerment and sufficiency, ethical considerations, and laws and regulations. The findings underscore the notable implications of integrating AI and BET into public safety efforts, such as improving surveillance systems, proactively preventing public health crises, and optimizing emergency response capabilities. However, ethical considerations and regulatory guidelines must be in place to address privacy concerns and mitigate potential risks associated with these technologies. The convergence of AI and BET also presents opportunities for sustainability. Nevertheless, concerns arise regarding its improper utilization. Based on the study's findings, policy recommendations are directed at ethical considerations, governance and regulation, and sustainability. These policy actions aim to address the opportunities and challenges associated with the convergence of AI and BET in public safety, ensuring responsible and beneficial use within the framework of Public Safety 4.0.

Keywords: sustainability; ethical considerations; frameworks; empowerment and sufficiency; emerging trends

Introduction

The realm of public safety in the Philippines has undergone significant transformations, tracing its roots to the historical periods of the Spanish Colonial Era and the Spanish-American War. A notable milestone during this period was the establishment of the Philippine Constabulary, which symbolized the integration of police and military forces aimed at tackling diverse security issues (Varona, 2010; Ladwig, 2014). To date, the landscape of the public safety in the country has now evolved immensely due the advent of technology which recalibrate the dynamics and trends of the security threats around the world.

Industry 4.0, characterized by the fusion of digital technologies and automation, is at the forefront of driving the development of Public Safety 4.0. As industries embrace advanced technologies like the Internet of Things (IoT), artificial intelligence (AI), biological engineering technology (BET), and big data analytics, there is a transformative impact on the field of public safety (Chang & Andreoni, 2020). Public Safety 4.0 leverages these advancements to enhance emergency response systems, optimize resource allocation, and improve situational awareness. Through intelligent sensors, real-time data analysis, and predictive modeling, it enables proactive and efficient management of emergencies, prevention of crimes, and safeguarding the communities (Kartskhiia, 2018). The integration of Industry 4.0 technologies into public safety operations is paving the way for a more interconnected, resilient, and effective approach to ensuring the well-being and security of individuals and society (Ding et al., 2019; Henman, 2020).

In one facet of public safety, the rapid advancements in technology have paved the way for new frontiers in public safety. The convergence of Artificial Intelligence (AI) and Biological Engineering (BET) has emerged as a promising avenue for enhancing crime prevention strategies. The synergistic potential of these two fields opens exciting possibilities for bolstering public safety measures in a holistic and efficient manner (Stahl, 2021). However, as AI and BET continue to mature, ensuring effective governance becomes paramount. Governance mechanisms play a crucial role in regulating and guiding the development, deployment, and utilization of these technologies (Cath, 2018; Medvedec, 2012).

In a nutshell, public safety in the Philippines faces multifaceted challenges arising from local to global security threats, and to include the convergence of emerging technologies, like the case of AI and BET. Hence, striking a balance between leveraging the benefits of these two powerful technologies while addressing the challenges are essential to ensure that public safety initiatives remain effective, responsible, and trusted by communities. Understanding and addressing these challenges are crucial for ensuring effective governance and safeguarding the well-being of society. Thus, it is imperative to understand the level of adoption and adherence to established frameworks, regulations, and guidelines. By evaluating the implementation status, this research aimed to shed light on potential barriers or bottlenecks that hinder the effective integration of AI and BET into public safety practices. Moreover, this study also delved into the ways forward of these frontier technologies to forecast its possibilities in the purview of public safety.

Methodology

This study adopted an exploratory mixed-methods approach, incorporating both qualitative and quantitative methodologies. The quantitative aspect involved analyzing numerical responses from the survey, while the qualitative aspect involved gathering narrative data through literature review, focus group discussions (FGDs), and participant narratives. The combination of these methods provided a comprehensive and robust analysis of the research topic, especially in developing the governance convergence model using Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) through Structural Equation Modeling (SEM). By employing triangulation of approaches, the study obtained a more comprehensive understanding of the subject matter, enhancing the validity of the findings. Additionally, a foresight tool known as "Look Back To Look Forward" was employed to forecast the future of artificial intelligence and biological engineering technology in the context of public safety 4.0.

Primary sources of data for the study were obtained from survey questionnaires and narratives provided by participants. Secondary data were collected from various sources such as textbooks, peer-reviewed scholarly journal articles, published studies, and available reports and policies relevant to artificial intelligence and bioengineering technology in the country. The study covered the national level and various units/departments of the Philippine National Police (PNP) responsible for maximizing the benefits of these technologies in public safety. The participants included the heads of offices and personnel from these units, such as the Information Technology Management Service (PNP-ITMS), the Anti-Cybercrime Group (PNP-ACG), Regional Anti-Cybercrime Units (RACU), and the Explosive Ordnance Disposal and Canine Group (PNP-EOD/K9) across the country.

Qualitative data obtained from participants were transcribed systematically, preserving language mannerisms and code-switching. The BARD app and conventional thematic analysis were used to analyze the qualitative data, allowing for the identification of elements and indicators for a good governance convergence model. Quantitative data from the survey questionnaires were statistically analyzed using frequency distribution and employed EFA and CFA through SEM to explore and validate the latent variables and factors. Descriptive statistics were also used to describe the level of agreement among respondents regarding the governance mechanisms related to AI and bioengineering in the country.

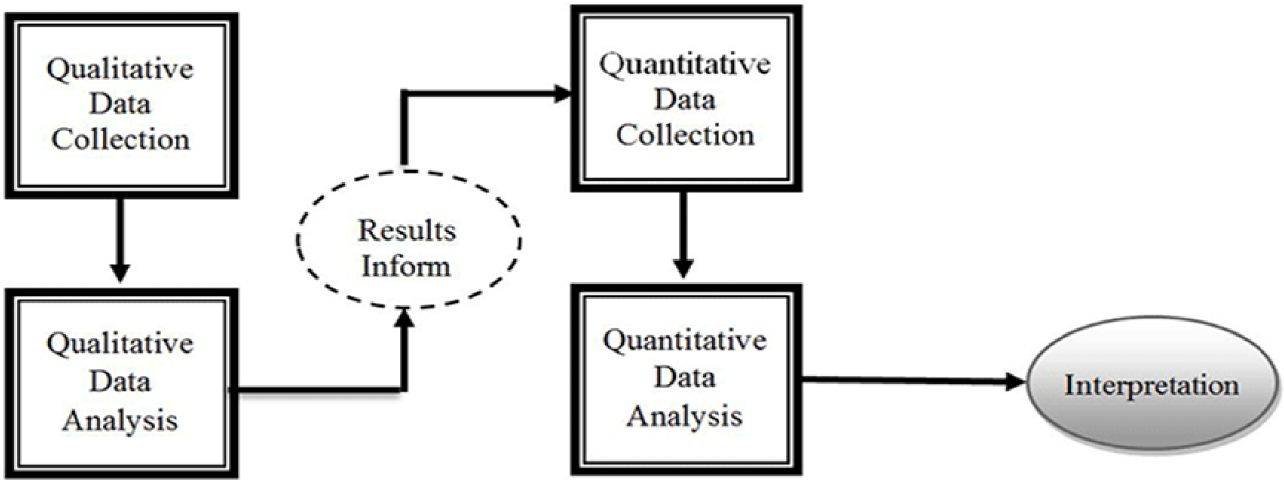


Figure 1. The Research Design of the Study

Results and Discussions

Philippine Status Quo on AI and BET

The governance mechanisms for Artificial Intelligence (AI) and Biological Engineering Technology (BET) in crime prevention in the Philippines involve multiple stakeholders, including government agencies, legislative initiatives, and regulatory frameworks. Key agencies include the National Privacy Commission (NPC), Department of Science and Technology (DOST), Commission on Higher Education (CHED), Philippine National Police (PNP), and Private Sectors (PVs). These agencies play important roles in formulating governance mechanisms, such as implementing data privacy policies, promoting development and utilization of AI and BET, integrating technologies into academic programs, and implementing them in crime prevention and public safety. Legislative initiatives and regulations, such as the Data Privacy Act, and Cybercrime Prevention Act, provide guidelines and penalties for the responsible use of these technologies. These governance mechanisms aim to ensure ethical and responsible use of AI and BET in crime prevention in the Philippines.

Although various frameworks and initiatives have been introduced in the Philippines, comprehensive governance mechanisms for artificial intelligence and biological engineering technology are still lacking (Chua et al., 2023; Simeon, 2022). Nevertheless, the government has recognized both the positive and negative potential impacts of these technologies on various sectors in the country (DailyGuardian, 2022).

Extent of Implementation of Governance Mechanisms Apropos AI and BET

The descriptive statistics in Table 1 provide an overview of the degree of existing governance mechanisms based on a sample of 1,268 observations. The range of responses for the governance mechanisms is represented by a minimum value of 1.00 and a maximum value of 5.00. The mean value of 3.3155 indicates that, on average, the degree of existing governance mechanisms is at a neutral point. The small standard deviation of 0.98004 suggests that most responses are clustered closely around the mean, indicating relatively little variability in the dataset.

Table 1. The Descriptive Statistics of the Degree of the Existing Governance Mechanisms

	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**	**Interpretation**
Governance Mechanism	1267	1.00	5.00	3.3155	.98004	**Neutral**
N	1267					

Legend: 4.21-5.00 "Very High," 3.41-4.20 "High," 2.61-3.40 "Neutral," 1.81-2.60 "Low," 1.00-1.80 "Very Low"

Overall, the descriptive statistics suggest that the existing governance mechanisms for the convergence of AI and BET in the context of public safety are moderately true, leaning towards a neutral position. However, there are variations in the responses, as indicated by the range and standard deviation, implying that some participants may hold different perspectives on the governance mechanisms. It also highlights that the existing governance mechanisms are relatively less known, not only among the public but also within the public safety sector, indicating a need for greater awareness and understanding of legal frameworks and government initiatives related to AI and BET.

Governance Model for AI and BET

Exploratory Factor Analysis

The collected data underwent an Exploratory Factor Analysis (EFA), and the results are presented in the table below. The analysis included the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy and Bartlett's test of Sphericity, which are used to determine the suitability of the data for factor analysis. The KMO measure ranges from 0 to 1, with values closer to 1 indicating better suitability for factor analysis. In this study, the KMO value obtained was 0.966, which is considered excellent. This high value suggests that the sample size used and the correlations among variables are highly appropriate for conducting factor analysis. Additionally, Bartlett's Test of Sphericity was performed, resulting in a chi-square value of 97719.871, a degrees of freedom (df) value of 780, and a p-value of 0.000 ($p<0.05$). These results indicate that the correlation matrix is significantly different from the identity matrix, providing evidence of underlying factors in the data. According to Kaiser (1974), a sampling adequacy value higher than 0.5 is considered suitable for exploratory factor analysis. Since the obtained KMO value surpasses this threshold, the data is deemed appropriate for analysis. If the KMO value had been lower, additional data would have been required, and more respondents would need to be added to achieve the necessary level of sampling adequacy.

Table 2. The KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.966
Bartlett's Test of Sphericity	Approx. Chi-Square	97719.871
	df	780
	Sig.	.000

The dataset was subjected to an exploratory factor analysis (EFA), which revealed three factors with corresponding eigenvalues of 26.977, 6.252, and 1.060. Eigenvalues are indicators of the total variance explained by the identified factors. They offer valuable insights into how effectively the factors capture the underlying patterns of variation in the data, serving as an essential measure for assessing the goodness of fit of the EFA model.

Examining the Total Variance Explained table, we find that the first factor accounts for 67.442% of the total variance, indicating a substantial contribution to the dataset's variability. The second factor explains 15.629% of the variance, while the third factor explains 2.649%. Consequently, the first factor has the most significant impact in explaining the variance, while the third factor has the least impact. When considering all three factors together, they collectively account for 85.720% of the total variance explained, as indicated in the table. This demonstrates that these three factors effectively capture much of the underlying variation in the dataset, providing a meaningful representation of its structure.

Table 3. Total Variance of the Dataset

Total Variance Explained

	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings a
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	26.977	67.442	67.442	26.977	67.442	67.442	25.066
2	6.252	15.629	83.071	6.252	15.629	83.071	14.038
3	1.060	2.649	85.720	1.060	2.649	85.720	18.419

Extraction Method: Principal Component Analysis.

a When components are correlated sums of squared loadings cannot be added to obtain a total variance

Based on the result of the Exploratory Factor Analysis (EFA) through Principal Component Analysis, considering all the explored indicators, the three components/ dimensions extracted are namely: *Empowerment and Sufficiency, Ethical Considerations,* and *Laws and Regulations.*

Dimension 1 encompasses a wide range of aspects related to empowerment and sufficiency in the context of public safety programs that integrate AI and bioengineering technologies. It includes the adoption and implementation of these technologies in public safety initiatives, the promotion and sharing of knowledge through public forums and events, research studies and publications examining their impact and effectiveness, the formulation of policies and regulations by public safety organizations, educational programs provided by institutions, public outreach campaigns emphasizing responsible use, incident reporting and response evaluation, assessment of data accuracy and cost-effectiveness, collection of user feedback, monitoring of public opinion, addressing security risks and ensuring compliance with regulations, investments in research and development, patents and collaborations between organizations and technology companies, scientific publications, practical applications, conferences and workshops, government initiatives, and grants and scholarships specifically dedicated to AI and bioengineering technology in public safety.

Dimension 2 focuses on the ethical considerations associated with the application of artificial intelligence and biological engineering technologies in the field of public safety. This dimension emphasizes the need to develop and implement these technologies in a manner that respects and safeguards individuals' rights to privacy and autonomy. It underscores the importance of transparency, whereby technology companies are expected to provide relevant information to the public regarding the utilization of these technologies. Accountability is also highlighted, with technology companies assuming responsibility for any errors or shortcomings in their AI and bioengineering technologies. Non-discrimination is a fundamental principle, necessitating that these technologies treat all individuals fairly and impartially, without any biases based on factors such as race, gender, age, or ethnicity. The dimension further emphasizes the significance of accuracy and reliability, urging technology companies to strive for precise outcomes in their AI and bioengineering technologies. Additionally, it stresses the need for robust security measures to protect against malicious attacks, ensuring the integrity and confidentiality of these technologies.

Dimension 3 of the analysis highlights the importance of laws and regulations that govern the utilization of artificial intelligence and biological engineering technology in the context of public safety. This dimension focuses on specific guidelines, rigorous standards, and responsible protocols that dictate the proper use of these technologies. It places a strong emphasis on privacy and data protection protocols to ensure the security of personal information. Furthermore, well-defined protocols for certification and accreditation, along with robust oversight and monitoring mechanisms, are established to ensure compliance and accountability. The dimension also encompasses evaluation processes and reporting requirements for incidents involving AI and bioengineering technology, aiming to maintain transparency and accountability throughout their implementation.

Confirmatory Factor Analysis

The factors resulting from the Exploratory Factor Analysis (EFA) were further subjected to Confirmatory Factor Analysis (CFA) using AMOS to test the measurement model. CFA evaluates the alignment between observed variables (indicators derived from survey questions) and a proposed factor structure or pre-defined theory/model. It examines whether the observed variables effectively capture the underlying latent constructs or factors. Throughout the process of conducting CFA, an iterative approach was followed to achieve desirable fit indices by adjusting the model specification. This involved covarying error values and removing items with high residuals.

Covarying variables allowed for the inclusion of correlated error terms between specific observed variables within the model. By accounting for the shared variance not explained by the latent factors, the model's alignment with the observed data was enhanced, leading to improved fit. High residual items represented discrepancies between the observed and predicted values, indicating that the model did not adequately explain the variance in those observed variables. Therefore, these items were removed to enhance the fit to the observed data. In total, 24 out of 40 items were removed during this process.

Various model fit measures were employed to assess the overall goodness of fit of the model. The CMIN/df ratio evaluated the fit between the model and the observed data, with a lower value indicating a better fit. The GFI (Goodness-of-Fit Index) measured the proportion of variance and covariance accounted for by the model, with values ranging from 0 to 1. A GFI value of 0 indicated a complete lack of fit, while a value of 1 indicated a perfect fit. The CFI (Comparative Fit Index) compared the fit of the proposed model with that of a baseline model in which all variables were uncorrelated. A CFI of 1 indicated a perfect fit, and values above 0.90 were generally considered acceptable. The TLI (Tucker-Lewis Index) also assessed model fit, penalizing complexity more than the CFI. A TLI of 1 indicated a perfect fit, and values above 0.90 were generally considered acceptable. The SRMR (Standardized Root Mean Square Residual) measured the average discrepancy between the observed and predicted correlations from the model, with values below 0.08 indicating a good fit. Lastly, the RMSEA (Root Mean Square Error of Approximation) evaluated the discrepancy between the model-implied and observed covariance matrices, adjusted for model complexity and sample size. The obtained values for these fit indices fell within commonly accepted levels of goodness of fit, as suggested by Ullman (2001), Hu and Bentler (1998), and Bentler (1990).

Fit Indices

The 3-factor model exhibited a good fit to the data, as indicated by various fit indices. The CMIN/df ratio was 7.019, slightly higher than the threshold suggested by Schumacker and Lomax (2004). It is important to note that with a sample size of 1,268, the test becomes more sensitive, meaning even minor differences between the model and the data can result in a significant chi-square value and a higher CMIN/DF ratio. However, despite this slight discrepancy, all other fit indices met their respective threshold values, indicating a favorable fit of the model to the observed data in this study. The other fit indices assessed were as follows: the Comparative Fit Index (CFI) was 0.984, the Tucker-Lewis Index (TLI) was 0.977, the Goodness of Fit Index (GFI) was 0.945, the Standardized Root Mean Square Residual (SRMR) was 0.032, and the Root Mean Square Error of Approximation (RMSEA) was 0.069. These indices provide further evidence that the model fits well with the observed data, indicating a satisfactory alignment between the proposed model and the collected information in this study.

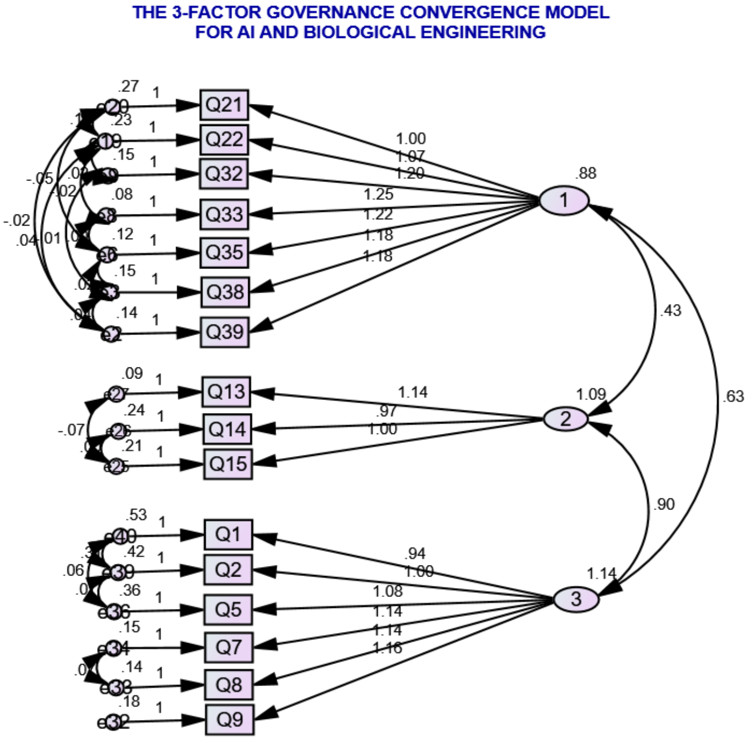
Table 4. The Model Fit Indices of Governance Convergence Model for AI and Biological Engineering

Fit Indices	**Recommended value**	**Source**	**Obtained Value**
P-value	< .05	Bagozzo and Yi (1988)	0.000
CMIN/df	< 5	Less than 2 (Ullman, 2001) to 5 (Schumacker & Lomax 2004)	7.019
Comparative Fit Index (CFI)	> .9	Bentler (1990)	0.984
Tucker-Lewis Index (TLI)	> .9	Bentler (1990)	0.977
Goodness of Fit Index (GFI)	> .9	Hair et al. (2010)	0.945
SRMR	<.08	Hu & Bentler (1998)	0.032
RMSEA	<.08	Hu & Bentler (1998)	0.069

Model Path Diagram

In order to develop an acceptable model, it is necessary that the specifications of fit indices have been met. Since the initial model did not acquire satisfactory values, respecification was done by removing residual items (items with high measurement errors) or those exhibiting correlation deviations to correct discrepancies in the model.

Figure 2. Governance Model of AI and BET in Public Safety.



The model of governance convergence between artificial intelligence (AI) and biological engineering technology in the context of Public Safety 4.0 revealed three essential dimensions for the successful and ethical implementation of these technologies. These dimensions are Empowerment and Sufficiency, Ethical Considerations, and Laws and Regulations.

Dimension 1: *Empowerment and Sufficiency*

One of the dimensions identified in the study is Empowerment and Sufficiency, which emphasizes the importance of raising public awareness. The research emphasizes the need to empower individuals and communities by enhancing their understanding of AI and biological engineering technology in the context of public safety. Key components of this dimension include public awareness campaigns, educational initiatives, and platforms for sharing knowledge.

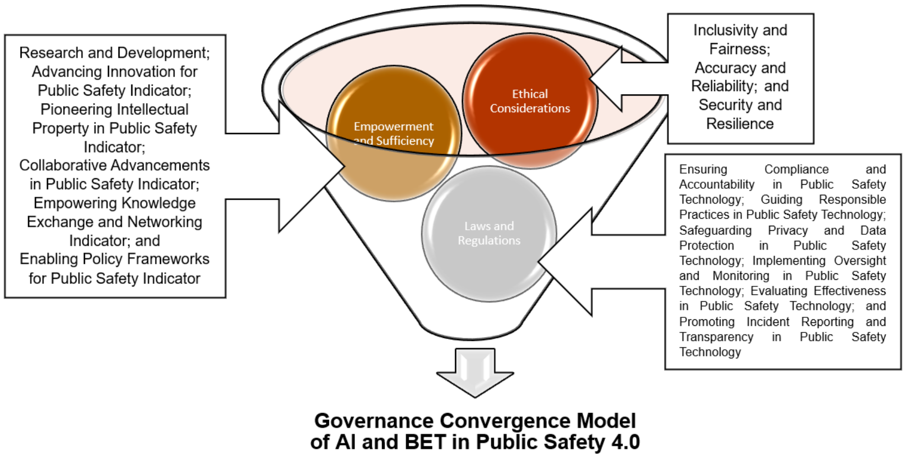
Dimension 2: *Ethical Considerations*

The second dimension that emerged is Ethical Considerations, which recognizes the significance of ensuring inclusivity, fairness, accuracy, reliability, security, and resilience in the use of AI and biological engineering technology in public safety. This dimension highlights the need for these technologies to treat all individuals fairly, provide accurate and reliable results, and protect against malicious attacks.

Dimension 3: *Laws and Regulations*

The third dimension identified is Laws and Regulations, which emphasizes the necessity of comprehensive and effective legal frameworks to govern the use of AI and biological engineering technology in public safety. This dimension encompasses various aspects, including ensuring compliance and accountability, guiding responsible practices, safeguarding privacy and data protection, implementing oversight and monitoring mechanisms, evaluating effectiveness, and promoting incident reporting and transparency.

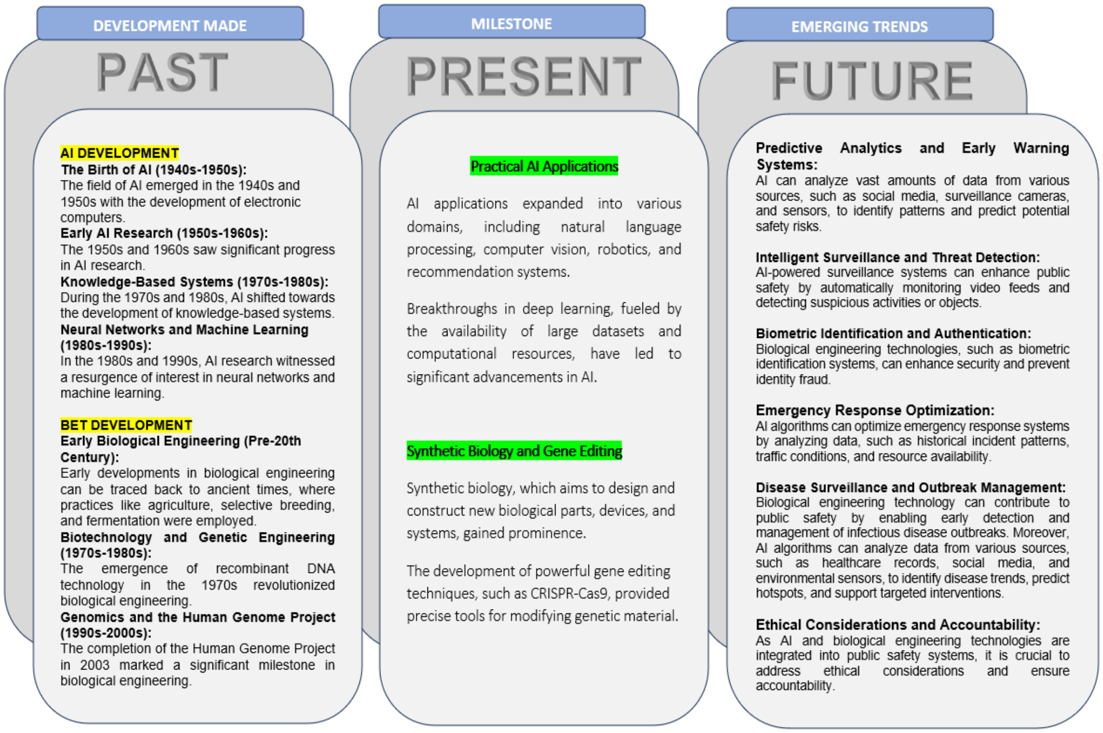
Figure 3. Proposed Governance Model Between Artificial Intelligence (AI) and Biological Engineering Technology in the Context of Public Safety



Ways Forward of AI and BET Apropos Public Safety

Based on the stages of development of AI and BET, it can be gleaned that the emerging trends of AI and BET in public safety are shaping the future of how we ensure security and well-being in society. One prominent trend is integrating AI-powered surveillance systems with biological engineering technologies, enabling more effective threat detection and response to potential biological hazards or bioterrorism threats. Additionally, using predictive analytics and early warning systems, empowered by AI and genomics, is becoming prevalent, allowing proactive measures to prevent public health crises and optimize emergency response efforts (The Alan Turing Institute, 2019). Combining AI algorithms and robotics enhances disaster response capabilities and enables autonomous systems for public safety tasks. However, the ethical considerations surrounding using AI and BET in public safety are gaining attention, especially in synthetic biology and gene editing, prompting the development of responsible frameworks and regulatory guidelines to address privacy concerns and mitigate potential risks. These advancements have opened up new avenues for manipulating and engineering biological systems—offering unprecedented opportunities for targeted modifications at the genetic level and enabling breakthroughs in medicine, biotechnology, and environmental applications (Harvard Gazette, 2020). These emerging trends highlight the immense potential of AI and BET to revolutionize public safety and create a safer and more secure environment for communities when used and regulated properly. Hence, it is important to note that the development and deployment of AI and biological engineering technologies in public safety should be accompanied by appropriate regulations, ethical guidelines, and ongoing evaluation to ensure their responsible and beneficial use for society.

Figure 4. Look Back to Look Forward of AI and BET Vis-à-vis Public Safety



AI DEVELOPMENT

The Birth of AI (1940s-1950s): The field of AI emerged in the 1940s and 1950s with the development of electronic computers.

Early AI Research (1950s-1960s): The 1950s and 1960s saw significant progress in AI research.

Knowledge-Based Systems (1970s-1980s): During the 1970s and 1980s, AI shifted towards the development of knowledge-based systems.

Neural Networks and Machine Learning (1980s-1990s): In the 1980s and 1990s, AI research witnessed a resurgence of interest in neural networks and machine learning.

BET DEVELOPMENT

Early Biological Engineering (Pre-20th Century): Early developments in biological engineering can be traced back to ancient times, where practices like agriculture, selective breeding, and fermentation were employed.

Biotechnology and Genetic Engineering (1970s-1980s): The emergence of recombinant DNA technology in the 1970s revolutionized biological engineering.

Genomics and the Human Genome Project (1990s-2000s): The completion of the Human Genome Project in 2003 marked a significant milestone in biological engineering.

Practical AI Applications

AI applications expanded into various domains, including natural language processing, computer vision, robotics, and recommendation systems.

Breakthroughs in deep learning, fueled by the availability of large datasets and computational resources, have led to significant advancements in AI.

Synthetic Biology and Gene Editing

Synthetic biology, which aims to design and construct new biological parts, devices, and systems, gained prominence.

The development of powerful gene editing techniques, such as CRISPR-Cas9, provided precise tools for modifying genetic material.

Predictive Analytics and Early Warning Systems: AI can analyze vast amounts of data from various sources, such as social media, surveillance cameras, and sensors, to identify patterns and predict potential safety risks.

Intelligent Surveillance and Threat Detection: AI-powered surveillance systems can enhance public safety by automatically monitoring video feeds and detecting suspicious activities or objects.

Biometric Identification and Authentication: Biological engineering technologies, such as biometric identification systems, can enhance security and prevent identity fraud.

Emergency Response Optimization: AI algorithms can optimize emergency response systems by analyzing data, such as historical incident patterns, traffic conditions, and resource availability.

Disease Surveillance and Outbreak Management: Biological engineering technology can contribute to public safety by enabling early detection and management of infectious disease outbreaks. Moreover, AI algorithms can analyze data from various sources, such as healthcare records, social media, and environmental sensors, to identify disease trends, predict hotspots, and support targeted interventions.

Ethical Considerations and Accountability: As AI and biological engineering technologies are integrated into public safety systems, it is crucial to address ethical considerations and ensure accountability.

The Implications of AI and BET in the Pillars of Sustainability

The integration of artificial intelligence (AI) and biological engineering has far-reaching effects on sustainability, covering economic, political, and environmental aspects.

From an economic perspective, this convergence presents both opportunities and challenges. On one hand, it stimulates innovation and the emergence of new industries, leading to economic growth and job creation. AI-powered precision agriculture and genetically modified crops, for example, can enhance food production and address global food security issues. Similarly, AI-driven biomanufacturing can revolutionize pharmaceutical and biofuel production, offering sustainable alternatives and driving economic development. However, concerns arise regarding economic inequalities, limited access to these technologies, ethical considerations surrounding the commercialization of biological resources, and potential concentration of power among dominant players in the field.

In the political sphere, the convergence of AI and biological engineering raises governance, ethical, and privacy concerns. It becomes essential to establish policy frameworks and regulations that address ethical issues related to human genetic manipulation, the privacy of genetic data, and the responsible use of AI technologies. Achieving a balance between scientific progress, innovation, and ethical considerations is crucial to ensure responsible and equitable development. Moreover, geopolitical dynamics may be affected as countries and regions compete for dominance in AI and biological engineering, necessitating international cooperation and governance frameworks.

Environmental sustainability is another critical area impacted by this convergence. AI and biological engineering applications can contribute to mitigating environmental challenges by enabling early detection and response to climate change, natural disasters, and ecosystem disruptions. Techniques such as genetic modification and synthetic biology offer opportunities for developing sustainable solutions, including bio-based materials, clean energy production, and ecological restoration. However, it is vital to assess and regulate these technologies carefully to minimize ecological risks and unintended consequences.

Overall, the convergence of AI and biological engineering holds tremendous potential for advancing sustainability across economic, political, and environmental domains. However, it is essential to consider the ethical, social, and environmental implications to prevent adverse outcomes. Collaboration among governments, scientists, industry, and civil society is crucial to establish robust governance frameworks, ensure equitable access, and guide the responsible development and deployment of these technologies in line with sustainable principles and values.

Conclusion and Recommendation

The findings of this study provide important insights for policy recommendations concerning the artificial intelligence (AI) and biological engineering technology (BET) in the context of public safety during the era of Industry 4.0. The study highlights the opportunities and challenges associated with applying AI and BET in various public safety domains while also acknowledging the ethical, legal, and social risks involved. The recommended policy actions encompass several key areas, including Ethical Considerations, Governance and Regulation, Sustainability and Environmental Impact, Capacity Building and Equity, and Pilot Projects and Continuous Evaluation. Moreover, by implementing these recommendations, policymakers, researchers, and stakeholders can work together to address the challenges and opportunities presented by the convergence of AI and BET in public safety, ensuring responsible and equitable development that aligns with sustainable principles and values.

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Contribution/Originality. This research expands the scope of knowledge by presenting a pioneering body of insights concerning the intersection of Artificial Intelligence (AI) and Biological Engineering technology within the context of public safety. The study employs an exploratory sequential mixed-method approach, analyzed using Sequential Equation Modeling (SEM). This independent and original work is appropriately attributed to the sources from which the ideas have been drawn.

Declaration of Conflicting Interest. The authors affirm that there are no conflicts of interest involved in the conduct and development of this research project.

Availability of Data: The authors affirm that the data underpinning the study's findings are accessible within the article and its Supplementary material. For those seeking access to the raw data that support the study's conclusions, they can make a reasonable request to the corresponding author.

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REVIEW ARTICLE

Revolutionizing Healthcare industry 5.0: Exploring the Potential of Blockchain Technology for Medical Applications

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Abstract

The healthcare industry is experiencing a paradigm shift from an industrial era (Industry 1.0) to a digital era (Industry 4.0), and now towards a more patient-centered, value-driven era (Industry 5.0). The advent of Blockchain Technology (BCT) has provided a significant opportunity to transform the healthcare industry towards Industry 5.0 by enabling secure and decentralized data sharing, improving patient privacy and data security, and streamlining healthcare processes. This paper explores the potential of BCT for medical applications within the context of Industry 5.0. We provide a comprehensive overview of the current state of the healthcare industry and highlight the challenges faced by patients, providers, and researchers in accessing and sharing medical data. We then discuss how BCT can address these challenges by providing secure and decentralized data storage, sharing, and exchange, as well as enhancing patient control over their data. We conclude that BCT has significant potential for revolutionizing the healthcare industry towards Industry 5.0 by improving data security, privacy, and interoperability, reducing costs and improving efficiency, and enabling new models of patient-centered care. However, realizing this potential will require overcoming significant challenges and a collaborative effort from all stakeholders in the healthcare ecosystem. The integration of BCT in the healthcare industry will facilitate the transition towards Industry 5.0 and ensure that patients receive high-quality, value-driven care.

Keywords: BCT; Industry 5.0; Electronic Health Records; Telemedicine; Data security

Introduction

Industry 5.0, also known as the "human-centric" or "collaborative" era, is the latest advancement in industrial manufacturing. It is an innovative approach that emphasizes the integration of human abilities and information with advanced technologies such as artificial intelligence (AI), robotics, and automation to optimize production processes (Adel, 2022). Unlike the previous industrial revolutions, which focused primarily on machines and mass production, Industry 5.0 puts a strong importance on the importance of human involvement and collaboration to achieve greater efficiency, flexibility, and customization. The ultimate goal of Industry 5.0 is to create a more sustainable and inclusive manufacturing ecosystem that benefits both workers and consumers while driving economic growth (Aheleroff et al., 2022). In this context, it is essential to understand the key principles, technologies, and challenges of Industry 5.0 to adapt to this new industrial era and stay competitive in the global market.

Industry 5.0 has the prospective to transform the healthcare industry by combining advanced technologies with human expertise to improve patient outcomes and reduce costs. Here are some applications of Industry 5.0 in the healthcare system.

- Personalized medicine: Industry 5.0 can help healthcare professionals develop personalized treatment plans for patients using data-driven insights and advanced analytics (Alojaiman, 2023; Dev et al., 2022). By analyzing patients' genetic, clinical, and lifestyle data, doctors can tailor treatments to every patients' distinctive needs, resulting in improved outcomes and reduced healthcare costs.
- Robotics and automation: Industry 5.0 can also enhance the efficiency of healthcare delivery by using robotics and automation to perform routine tasks, such as cleaning, disinfecting, and delivering medications (Barata & Kayser, 2023).
- Telemedicine: With the rise of Industry 5.0, telemedicine has become increasingly accessible and convenient (Adel, 2022; De Giovanni, 2023). As a result, patients can receive remote consultations, diagnoses, and treatment plans from healthcare professionals.

BCT for medical applications

By providing a secure and effective way to store, organize, and communicate medical data, BCT has the potential to revolutionize the healthcare business (Fraga-Lamas et al., 2021). Here are some examples of potential BCT medical applications.

- Secure medical records: BCT can be utilized to build a secure and tamper-resistant medical record system (Jafari et al., 2022). Patients have the ability to select who has access to their medical records, and healthcare practitioners can simply and securely communicate patient data across companies.
- Clinical trials: By providing a secure and decentralized approach to manage trial data, BCT can increase the transparency and efficiency of clinical trials (Javaid & Haleem, 2020). This can increase data accuracy, prevent fraud, and speed up drug development.
- Prescription drug tracking: BCT can be utilized to develop a transparent and secure drug tracking system that can aid in the prevention of counterfeit drugs entering the supply chain (Jeyaraman et al., 2022; Fatima et al., 2022). This can increase patient safety while also lowering healthcare expenses.
- Supply chain management (SCM): BCT can be used to trace medical goods and gadgets as they travel from manufacturers to patients, confirming their quality and authenticity (Leng et al., 2022).
- Health insurance: By developing a secure and transparent system for managing insurance claims and payments, BCT can improve the efficiency of health insurance (Lv, 2023). This has the potential to cut fraud and administrative costs while also increasing patient outcomes.

BCT has the potential to increase the efficiency, transparency, and security of medical data management, resulting in better patient outcomes and lower healthcare costs (Maddikunta et al., 2022). However, there are still issues to be solved, including as regulatory and legal considerations, as well as blockchain system interoperability with existing healthcare infrastructure.

Significance of BCT in healthcare industry 5.0 The healthcare industry is moving towards digital transformation with the implementation of innovative technologies, such as AI, IoT, and telemedicine, which aligns with the principles of Health 5.0 (Goswami & Behera, 2021a). BCT can play a noteworthy role in this transformation by providing a secure, decentralized, and transparent coordination for handling medical data. Here are some key benefits of BCT in healthcare Industry 5.0.

- Data privacy and security: BCT can create a secure and tamper-proof system for managing medical data, protecting patients' privacy and preventing data breaches (Mourtzis et al., 2022).
- Interoperability: BCT can enable interoperability among different healthcare systems, facilitating the exchange of medical data and promoting coordinated care (Mukherjee et al., 2023).
- Efficiency and cost reduction: BCT can advance the competence of healthcare delivery by reducing managerial tasks and streamlining data management (Pang et al., 2023). This can reduce healthcare costs while improving patient outcomes.
- Transparency: BCT can create a transparent system for managing medical data, promoting trust among patients, healthcare providers, and insurance companies (Santhi & Muthuswamy, 2023).
- Research and development: BCT can facilitate medical research by providing a secure and transparent system for managing clinical trial data and promoting collaboration among researchers (Sahoo et al., 2023).

The significance of BCT in the healthcare industry lies in its potential to transform the way medical data is managed, promoting privacy, security, and interoperability, while improving efficiency and reducing costs.

Objective of BCT in healthcare industry 5.0

The objective of BCT in the healthcare industry is to provide a secure, efficient, and transparent system for managing medical data, supporting the digital transformation of healthcare towards the principles of Health 5.0. Here are some specific objectives of BCT in healthcare.

- To explore the potential applications of BCT in healthcare Industry 5.0 and examine how it can transform medical data management.
- To analyze the benefits and challenges of using BCT in healthcare and evaluate its impact on patient outcomes and healthcare costs.
- To examine the regulatory and legal considerations associated with the use of BCT in healthcare and assess the feasibility of its adoption in the industry.
- To investigate the role of BCT in promoting interoperability among different healthcare systems and facilitating the exchange of medical data.
- To study the use of BCT in clinical trials and drug development, including its impact on research efficiency, data accuracy, and patient safety.
- To identify the key technological and infrastructure requirements for implementing BCT in healthcare and assess the readiness of the industry for its adoption.
- To propose a framework for the integration of BCT into the healthcare industry, taking into account the unique challenges and opportunities of the sector.

The objectives of the research paper would be to provide a comprehensive understanding of the potential applications of BCT in healthcare Industry 5.0 and assess its impact on the industry's digital transformation.

Literature Review

Following the transformation brought about by Industry 4.0, Industry 5.0 is the next wave of innovation in the manufacturing industry. While Industry 4.0 focused on the combination of progressive technologies such as the Internet of Things (IoT), AI, and robotics, Industry 5.0 emphasizes human-machine collaboration and the incorporation of social and environmental factors into the manufacturing process (Goswami & Behera, 2021b). Lv (2023) examines the notion of business 5.0, its potential benefits, and obstacles for the manufacturing business in their study titled "Digital Twins in Industry 5.0." They emphasize the importance of the human aspect in Industry 5.0, which emphasizes human-machine collaboration. According to the authors, Industry 5.0 can provide new business models and prospects for the manufacturing industry, but it also poses workforce training and management issues. Overall, the article is an excellent introduction to the notion of business 5.0 and its possible consequences for the manufacturing business.

Healthcare 5.0 refers to the growth of healthcare systems that include sophisticated technologies and place a focus on patient-centered treatment. In their article "Metaverse for Climbing the Ladder to 'Industry 5.0' and 'Society 5.0,'?" Tlili et al. (2023) offer an outline of Healthcare 5.0 and its possible benefits. In Healthcare 5.0, the authors emphasize the necessity of patient-centered care, which incorporates patient choices, values, and beliefs into the care process. They also talk about how modern technologies like AI, blockchain, and the IoT will increase efficiency, accuracy, and patient outcomes in Healthcare 5.0. The study underlines the importance of healthcare professionals adapting to a changing healthcare landscape and embracing new technologies in order to provide high-quality care. The report is an excellent introduction to Healthcare 5.0 and its possible consequences for the healthcare business.

BCT for medical applications

Sahoo & Goswami (2023) examine the potential applications of BCT in healthcare. The authors examine the application of blockchain technology in medical record management, clinical trials, drug supply chain management, and health insurance. They also note regulatory problems, scalability, and interoperability as hurdles and limitations of BCT in healthcare. The report provides a complete analysis of BCT's potential in the healthcare business as well as its present implementation status. Sahoo & Goswami (2024) examine the application of BCT to boost trust in healthcare providers. The authors suggest a blockchain-based system enabling patients and healthcare professionals to securely share medical information. They also talk about how BCT can help with clinical trials, patient consent management, and medication SCM. The study discusses the potential of BCT to improve trust and security in the healthcare business. Sharma et al. (2022) perform a comprehensive study of blockchain in healthcare literature to identify possible uses, benefits, and difficulties of this technology. The authors present a paradigm for synthesizing blockchain integration into healthcare systems and indicate significant research objectives for future investigations. The report conducts a thorough assessment of the existing literature on blockchain in healthcare and provides insights into the potential implications of this technology for the healthcare business.

Blockchain application for medical applications

BCT has the potential to transform the way medical records are kept, boosting patient privacy and security while also enabling more efficient data interchange among healthcare providers. Medical records management on the blockchain is a promising application of this technology that has received a lot of attention recently.

Researchers built a prototype blockchain-based electronic health record (EHR) system that solved some of the issues allied with outdated EHR systems, such as data security and privacy concerns, in a report published in the Journal of Medical Systems (Goswami & Behera, 2023a). The technology stored and shared medical records on a private blockchain network, allowing patients to control access to their data and providing healthcare practitioners with accurate and up-to-date information in real-time. Another study published in the International Journal of Medical Informatics investigated the possibility of BCT to improve medical record interoperability across different healthcare organizations. According to the authors, a significant impediment to the efficient exchange of medical records is a lack of interoperability, and BCT could provide a solution by facilitating secure and seamless data transfer across various parties.

A third study, also published in the Journal of Medical Internet Research, looked into the viability of using BCT to handle consent for medical research. The authors contended that blockchain-based consent management might improve transparency, accountability, and patient privacy while lowering the administrative burden associated with traditional consent management systems (Verma et al., 2022). Overall, these studies indicate that BCT has the potential to revolutionize the way medical records are managed, improving patient privacy, data security, and efficiency. While there are still hurdles to overcome, such as the requirement for standardization and interoperability, the potential benefits of blockchain-based medical records administration are substantial and deserve additional research and development. BCT is becoming increasingly acknowledged as a significant tool for improving SCM, allowing for improved transparency, security, and efficiency throughout the supply chain. With promising results, a growing corpus of research is investigating the possible applications of blockchain in SCM.

Researchers investigated the potential of BCT to improve supply chain transparency and trust in a study published in the Journal of Business Research. They discovered that blockchain might help to improve insight into supply chain operations, allow for improved product tracking and tracing, and boost confidence among supply chain participants. Another study (Wang et al., 2023) published in the International Journal of Production Economics looked into the potential of BCT to increase supply chain efficiency. Blockchain, according to the authors, might assist to cut administrative expenses, improve supply chain visibility, and enable more efficient and effective communication among supply chain participants. A third study published in the journal Sustainability investigated the potential of BCT to increase supply chain sustainability. The authors contended that blockchain might offer better openness and accountability, allowing customers to make more informed purchase decisions and incentivizing businesses to adopt more environmentally friendly practices. According to this research, BCT has a considerable potential for improving SCM by increasing transparency, security, and efficiency throughout the supply chain. While there are still issues to work out, such as standardization and compatibility, the potential benefits of blockchain-based SCM are enormous and deserve additional research and development.

Telemedicine, which involves the remote delivery of healthcare services using digital technology, has been identified as a promising avenue for utilizing BCT (Yenugula et al., 2023a). Several researches have been conducted to investigate the possible applications of blockchain in telemedicine, with promising findings. Researchers proposed a blockchain-based system for maintaining electronic health records (EHRs) in telemedicine in a study published in the Journal of Medical Internet Research. They contended that BCT could improve data security and privacy, allow for more efficient and effective EHR sharing among healthcare providers, and improve patient outcomes (Goswami & Behera, 2023b). Another study published in the International Journal of Medical Informatics looked into the possibility of BCT in telemedicine medication management. According to the scientists, blockchain has the potential to improve prescription adherence, eliminate pharmaceutical errors, and improve patient safety and results. A blockchain-based system for remote patient monitoring in telemedicine was proposed in a third article published in the Journal of Healthcare Engineering. The authors stated that blockchain might help to improve patient data security and privacy, promote more efficient and effective patient monitoring and management, and improve patient outcomes (Yenugula et al., 2023b). According to this research, BCT has enormous potential for improving telemedicine by providing increased efficiency, security, and efficacy in the distant delivery of healthcare services. As research and development in this field continues, we should expect to see increasingly inventive and significant applications of BCT in telemedicine.

Novelty and research gap

The paper discusses the potential benefits of BCT in areas such as medical records management, SCM, and telemedicine. While the paper highlights the significant potential of BCT in healthcare, there are several research gaps and areas where further exploration is needed.

Novelty

i. The paper presents a comprehensive overview of the potential applications of BCT in healthcare industry, covering areas such as medical records management, SCM, and telemedicine.
ii. The paper discusses the potential benefits of BCT, including enhanced data security and privacy, more efficient and effective sharing of healthcare data, and improved patient outcomes.
iii. The paper provides examples of existing blockchain-based healthcare systems and applications, highlighting their potential impact on the healthcare industry.

Research gaps

i. The scalability of BCT in large-scale healthcare systems is a significant research gap. While blockchain has been shown to be effective in small-scale applications, its effectiveness in large-scale healthcare systems has not been fully explored.
ii. Interoperability of blockchain-based healthcare systems with existing healthcare systems is another research gap. Healthcare systems often rely on multiple databases and data formats, making interoperability a key challenge. Further research is needed to identify strategies for achieving interoperability between blockchain-based healthcare systems and existing healthcare systems.
iii. Legal and regulatory implications of BCT in healthcare industry are a critical research gap. While BCT has the potential to enhance data security and privacy, it also raises several legal and regulatory challenges related to data ownership and liability. Further research is needed to explore these legal and regulatory implications and identify strategies for addressing them.

Potential applications of BCT in healthcare industry

There are several potential applications of BCT in healthcare industry over the years. The authors tried to highlight some of the practical implications of blockchain within the healthcare industry. Here are few of them.

Medical records management

BCT can be used to create a secure, decentralized system for storing and sharing medical records. This would enhance data security and privacy, and enable more efficient and effective sharing of healthcare data between healthcare providers (Goswami et al., 2022a). Here are some ways in which BCT can help in medical records management.

- Enhanced data security and privacy: BCT can provide a secure and tamper-proof way to store and share medical records. Medical records stored on a blockchain are encrypted and distributed across multiple nodes, making them resistant to hacking and other cyber threats (Yenugula et al., 2024). Additionally, BCT allows patients to control access to their medical records, ensuring greater privacy and security.
- Efficient and effective sharing of healthcare data: BCT can enable more efficient and effective sharing of healthcare data between healthcare providers. With blockchain, healthcare providers can access a patient's medical records in real-time, regardless of where the records are stored. This can improve the speed and accuracy of diagnosis and treatment.
- Reduced administrative burden: BCT can help reduce the administrative burden associated with managing medical records. With blockchain, patients can control their medical records and grant access to healthcare providers, reducing the need for administrative staff to manage and share medical records.
- Improved patient outcomes: By providing a secure and efficient way to manage medical records, BCT can help improve patient outcomes (Goswami et al., 2022b). With faster and more accurate diagnosis and treatment, patients can receive better care and recover more quickly.
- Streamlined regulatory compliance: BCT can help streamline regulatory compliance in healthcare industry. With blockchain, healthcare providers can ensure that their medical records are compliant with privacy and security regulations, reducing the risk of regulatory violations and associated penalties.

BCT has the potential to significantly improve medical records management in healthcare industry, enabling greater data security and privacy, more efficient and effective sharing of healthcare data, and improved patient outcomes.

Telemedicine

BCT can be used to create a secure, decentralized system for telemedicine consultations. This would enable patients to securely share their medical records with healthcare providers, and enable healthcare providers to securely share medical advice and prescriptions with patients. Here are some ways in which BCT can help in telemedicine.

- Secure and private sharing of medical records: BCT can provide a secure and private way for patients to share their medical records with healthcare providers during telemedicine consultations (Sahoo et al., 2023). With blockchain, patients can control access to their medical records, ensuring greater privacy and security.
- More efficient and effective telemedicine consultations: With BCT, healthcare providers can access a patient's medical records in real-time, regardless of where the records are stored. This can improve the speed and accuracy of diagnosis and treatment during telemedicine consultations.
- Increased patient trust: BCT can increase patient trust in telemedicine services by providing a secure and transparent way to manage medical records and telemedicine consultations.
- Improved interoperability: BCT can help improve interoperability between telemedicine platforms, enabling more seamless communication between healthcare providers and patients.

- Reduced administrative burden: With blockchain, patients can control their medical records and grant access to healthcare providers, reducing the need for administrative staff to manage and share medical records during telemedicine consultations.
- Streamlined regulatory compliance: BCT can help streamline regulatory compliance in telemedicine. With blockchain, healthcare providers can ensure that their telemedicine consultations are compliant with privacy and security regulations, reducing the risk of regulatory violations and associated penalties.

BCT has the potential to significantly improve telemedicine, enabling greater data security and privacy, more efficient and effective telemedicine consultations, increased patient trust, and improved regulatory compliance.

Healthcare payments

BCT can be used to create a decentralized payment system for healthcare services. This would reduce the cost and complexity of healthcare payments, and enhance transparency and security in the payment process (Goswami et al., 2022a). Here are some ways in which BCT can help in healthcare payments.

- Reduced transaction costs: BCT can reduce transaction costs associated with healthcare payments by eliminating intermediaries such as banks and payment processors.
- Faster payment processing: BCT can enable faster payment processing by providing a decentralized and automated system for processing payments.
- Improved transparency and accountability: With blockchain, healthcare providers can track the flow of payments and ensure that payments are made to the correct recipients (Sahoo et al., 2023). This can improve transparency and accountability in healthcare payments.
- Enhanced security: BCT can provide enhanced security for healthcare payments by using encryption and distributed ledger technology to protect against fraud and cyberattacks.
- Improved regulatory compliance: BCT can help improve regulatory compliance in healthcare payments by providing a secure and transparent way to manage payment transactions and comply with regulations such as HIPAA.
- Enhanced patient experience: With blockchain, patients can have more control over their healthcare payments, allowing them to make payments directly to healthcare providers and manage their healthcare payments more easily.

BCT has the potential to significantly improve healthcare payments, enabling faster, more secure, and more transparent payment processing, reducing transaction costs, and improving regulatory compliance.

Drug SCM

BCT can be used to track the transit of pharmaceuticals from producers to patients, allowing for improved accountability and lowering the danger of counterfeit or tainted drugs. Here are some ways in which BCT can help in drug SCM.

- Increased transparency: BCT can be used to trace medications as they transit through the supply chain, from producers to wholesalers to pharmacies (Sahoo et al., 2023). This can help to keep counterfeit pharmaceuticals out of the supply chain and guarantee that drugs are carried and stored properly.

- Improved traceability: Every transaction in the drug supply chain is recorded on a tamper-proof ledger using blockchain, making it easier to trace drug movement and pinpoint the source of any problems or faults.
- Enhanced security: BCT can provide enhanced security for drug SCM by using encryption and distributed ledger technology to protect against theft, counterfeiting, and other types of fraud.
- Increased efficiency: With blockchain, drug SCM can become more efficient and streamlined, reducing costs and improving the speed and accuracy of delivery.
- Improved regulatory compliance: BCT can help improve regulatory compliance in the drug supply chain by providing a transparent and auditable record of all transactions.
- Better patient safety: By ensuring that drugs are authentic and have been transported and stored correctly, BCT can help improve patient safety and prevent harm caused by counterfeit or substandard drugs.

BCT has the potential to significantly improve drug SCM, enabling greater transparency, traceability, and security, reducing costs, and improving regulatory compliance and patient safety.

Health insurance

BCT can be used to create a decentralized system for managing health insurance claims and payments, reducing the cost and complexity of the insurance process, and enhancing transparency and security (Maddikunta et al., 2022). Here are some ways in which BCT can help in health insurance:

- Fraud prevention: By creating a clear and irreversible record of all transactions, BCT can help prevent fraud in health insurance by making it harder for fraudsters to change data or commit fraud.
- Claims management: With blockchain, claims management can become more efficient and streamlined, reducing the time and cost associated with claims processing (Dev et al., 2022). This can improve the overall customer experience and increase satisfaction.
- Smart contracts: BCT can enable the use of smart contracts in health insurance, automating many of the processes associated with claims management and reducing the need for intermediaries.
- Improved data security: BCT can provide enhanced security for health insurance data by using encryption and distributed ledger technology to protect against cyberattacks and data breaches.
- Increased transparency: With blockchain, health insurance providers can provide greater transparency to their customers, enabling them to track their claims and understand the costs associated with their healthcare.
- Reduced administrative costs: With blockchain, health insurance providers can reduce administrative costs associated with claims processing and other processes, enabling them to provide more affordable healthcare to their customers.

BCT has the potential to significantly improve health insurance, enabling fraud prevention, claims management, smart contracts, improved data security, increased transparency, and reduced administrative costs.

Patient consent management

BCT can be used to create a secure, decentralized system for managing patient consent for the use of their data in research and other healthcare activities. Here are some ways in which BCT can help in Patient consent management.

- Immutable and secure record-keeping: BCT can provide a secure and tamper-proof system for storing patient consent records (Dev et al., 2022). Once recorded, the data cannot be altered, ensuring that the patient's wishes are accurately represented and cannot be changed without their knowledge and consent.
- Permissioned access: BCT allows for permissioned access to patient consent records. This means that only authorized individuals or entities can access the data, ensuring patient privacy and confidentiality.
- Transparency and accountability: BCT provides transparency in the patient consent process, ensuring that all parties involved in a patient's care have access to the same information. This can improve accountability and reduce the risk of misunderstandings or miscommunication.
- Streamlined consent process: BCT can provide a streamlined and efficient consent process by automating the collection, verification, and management of patient consent. This can reduce administrative burden and ensure that patients' rights are respected.
- Interoperability: BCT can facilitate interoperability between different healthcare systems, allowing for the secure sharing of patient consent records across different organizations and providers. This can improve care coordination and ensure that patients' wishes are respected regardless of where they receive care.

Personalized medicine

BCT can be used to create a decentralized system for storing and sharing genetic and other health data, enabling more personalized and effective treatment plans. Here are some ways in which BCT can help in personalized medicine.

- Secure and standardized data sharing: BCT can facilitate secure and standardized data sharing between different healthcare providers, enabling the exchange of patient data needed for personalized medicine (Leng et al., 2022). This can improve the accuracy and quality of personalized treatments.
- Immutable and transparent data storage: BCT can provide an immutable and transparent storage system for patient health data, ensuring that the data is tamper-proof and can be accessed by authorized parties. This can improve patient privacy and data security.
- Efficient clinical trials: BCT can enable efficient clinical trials by creating a decentralized network for patient recruitment and data sharing. This can reduce the cost and time associated with traditional clinical trials, making it easier for personalized medicine to become more widespread.
- Improved patient outcomes: BCT can help in identifying genetic and other biomarkers that could be used to customize treatments, resulting in improved patient outcomes (Dev et al., 2022). This can lead to more effective and targeted treatments for patients.
- Patient-controlled data sharing: BCT can provide patients with control over their health data, enabling them to share their data with healthcare providers and researchers only when they choose to do so. This can improve patient trust and engagement in their healthcare, leading to better overall health outcomes.

Public health surveillance

BCT can be used to create a decentralized system for tracking the spread of infectious diseases and other public health threats, enabling more effective public health surveillance and response. Here are some ways in which BCT can help in Public health surveillance.

- Secure data sharing: BCT can facilitate secure data sharing between healthcare providers, public health agencies, and other stakeholders involved in public health surveillance (Mukherjee et al., 2023). This can enable timely and accurate data exchange, improving the effectiveness of disease monitoring and outbreak response.
- Real-time monitoring: BCT can enable real-time monitoring of public health data, allowing for early detection and response to disease outbreaks (Sharma et al., 2022). This can improve the accuracy and speed of disease surveillance, resulting in more effective public health interventions.
- Standardized data sharing: BCT can provide a standardized system for data sharing, ensuring that data is consistent and can be easily shared between different stakeholders. This can improve data quality and reduce the risk of errors or misinterpretation.
- Privacy protection: BCT can protect the privacy of individuals involved in public health surveillance by providing secure and anonymous data sharing (Leng et al., 2022). This can encourage individuals to share their health information with public health agencies, leading to better overall disease surveillance and response.
- Traceability: BCT can enable the traceability of public health data, allowing for the tracking of disease outbreaks and the identification of the source of the outbreak. This can improve the effectiveness of outbreak response and prevent future outbreaks.

The potential applications of BCT in healthcare industry are diverse and wide-ranging, and have the potential to transform the healthcare industry in significant ways. However, further research is needed to explore the feasibility and effectiveness of these applications, and to identify strategies for overcoming the challenges and barriers to implementation.

Benefits and Challenges of Using BCT in Healthcare

BCT offers several benefits in healthcare, including the following.

- Improved data security: BCT provides a secure, decentralized ledger that can store data securely and immutably (Goswami et al., 2022a). Healthcare data is highly sensitive, and blockchain's encryption and decentralized storage methods can help prevent data breaches and ensure privacy.
- Interoperability: Healthcare data is often siloed across multiple providers and systems, making it difficult to share data effectively (Barata & Kayser, 2023). BCT can provide a common platform that allows data to be shared and accessed by multiple parties securely and transparently.
- Improved SCM: BCT can help improve the transparency and efficiency of SCM by providing a secure and tamper-proof record of the movement of drugs and medical devices from manufacturers to patients.

However, there are also several challenges of using BCT in healthcare, which may include the following points.

- Scalability: As healthcare data is often large and complex, scalability is a significant challenge for BCT (Sharma et al., 2022). As the number of transactions on the blockchain increases, it can become slower and more expensive to operate.

- Integration with existing systems: Many healthcare organizations have existing electronic health record (EHR) systems and other legacy systems that may not be compatible with BCT. Integration can be complex and costly, requiring significant changes to existing infrastructure.
- Regulatory challenges: BCT is still relatively new, and there are currently no clear regulatory frameworks for its use in healthcare. This lack of regulation can create uncertainty and limit adoption by healthcare organizations.

Overall, while BCT has the potential to revolutionize healthcare, its implementation and adoption will require careful consideration of the benefits and challenges involved.

Regulatory and Legal Considerations Associated with the Use of BCT in Healthcare

The use of BCT in healthcare is subject to a range of regulatory and legal considerations, including.

- Medical device regulations: In some cases, BCT may be used in conjunction with medical devices. In such cases, the use of BCT may be subject to additional regulatory requirements, such as those established by the U.S. Food and Drug Administration (FDA) or similar agencies in other jurisdictions.
- Intellectual property rights: The use of BCT may involve the creation or transfer of intellectual property, such as patents or copyrights (Mukherjee et al., 2023). Healthcare organizations using BCT must ensure that they respect the intellectual property rights of others and protect their own intellectual property.
- Contract law: Transactions on a blockchain are typically governed by smart contracts, which are self-executing agreements with the terms of the contract written into code (Santhi & Muthuswamy, 2023). Healthcare organizations using BCT must ensure that their smart contracts are legally binding and enforceable.
- Jurisdictional issues: BCT is global in nature and can be used by parties in different jurisdictions. Healthcare organizations using BCT must ensure that they comply with the laws and regulations of all relevant jurisdictions.

Overall, the use of BCT in healthcare requires careful consideration of the regulatory and legal considerations involved to ensure compliance and protect patient privacy and safety.

BCT in Clinical Trials and Drug Development

BCT has the potential to transform the clinical trials and drug development process in several ways, including.

- Improved transparency and trust: BCT can create a tamper-proof and transparent record of clinical trial data, ensuring that trial results are reliable and trustworthy (Santhi & Muthuswamy, 2023). This can help build trust between clinical trial participants, researchers, and regulatory authorities.
- Enhanced patient engagement: BCT can enable patients to participate in clinical trials securely and transparently, giving them greater control over their health data and improving their engagement in the clinical trial process.
- Streamlined data management: BCT can facilitate the secure and efficient exchange of clinical trial data between different parties, such as researchers, trial sponsors, and regulatory authorities. This can help streamline the data management process and reduce administrative burdens.

- Improved SCM: BCT can provide a secure and transparent record of the movement of drugs and medical devices throughout the supply chain, improving the efficiency and safety of the drug development process.

However, there are also several challenges to using BCT in clinical trials and drug development, including.

- Data standardization: For BCT to be effective in clinical trials and drug development, there must be a standardized method of capturing and storing data. Achieving data standardization across different stakeholders can be challenging, as each may have their own data formats and requirements.
- Data privacy and security: Clinical trial data is highly sensitive and subject to strict data privacy and security regulations (Barata & Kayser, 2023). BCT must be designed to protect patient privacy and ensure that data is stored securely.
- Integration with existing systems: Many clinical trial and drug development organizations have existing data management systems that may not be compatible with BCT. Integration can be complex and costly, requiring significant changes to existing infrastructure.
- Regulatory compliance: The use of BCT in clinical trials and drug development must comply with regulatory requirements, such as those established by the FDA or similar agencies in other jurisdictions. This may require significant investment in compliance activities.

While BCT has the potential to transform the clinical trials and drug development process, its implementation and adoption will require careful consideration of the benefits and challenges involved.

Key Technological and Infrastructure Requirements for Implementing BCT in Healthcare

Implementing BCT in healthcare requires several technological and infrastructure requirements, including.

- Scalability: Healthcare organizations must ensure that their BCT can handle the volume and complexity of healthcare data, which can be vast and varied.
- Interoperability: BCT must be interoperable with existing healthcare IT systems, such as electronic health records (EHRs), to ensure that data can be easily shared and accessed.
- Data privacy and security: BCT must be designed to protect patient privacy and ensure that data is stored securely, in compliance with data privacy regulations.
- Consensus algorithms: BCT relies on a consensus algorithm to ensure that the data stored on the blockchain is accurate and tamper-proof. Healthcare organizations must choose the appropriate consensus algorithm that fits their specific use case.
- Smart contracts: Healthcare organizations may use smart contracts to automate processes and enforce agreements on the blockchain (Barata & Kayser, 2023). Implementing smart contracts requires expertise in programming and contract law.
- Infrastructure: Implementing BCT requires significant infrastructure, including hardware and software resources, network connectivity, and data storage.
- Governance and standards: Healthcare organizations must establish governance models and standards for the use of BCT to ensure that it is used effectively and transparently.

Implementing BCT in healthcare requires careful planning and consideration of the technological and infrastructure requirements involved (Maddikunta et al., 2022). Healthcare organizations must ensure that their BCT is scalable, interoperable, secure, and compliant with data privacy regulations, and must establish appropriate governance models and standards for its use.

Conclusion

In conclusion, the healthcare business has the latent to assist prominently from the implementation of BCT. The shift towards Healthcare 5.0 emphasizes patient-centric care and the integration of technology to improve healthcare outcomes. BCT can enable secure, transparent, and efficient data sharing and management, providing new opportunities for medical applications. In this research paper, we explored the potential of BCT for medical applications in the healthcare industry, including its use in clinical trials, drug development, medical record-keeping, SCM, and more. We also discussed the key technological and infrastructure requirements for implementing BCT in healthcare, as well as the regulatory and legal deliberations that must be taken into account. While there are challenges connected with the implementation of BCT in healthcare, such as data standardization and interoperability, the potential benefits are significant. As the healthcare industry continues to evolve towards a patient-centric model, BCT can play a essential role in enlightening healthcare outcomes and delivering more personalized and efficient care. This research paper highlights the prominence of exploring the potential of BCT for medical applications in the healthcare industry, as it represents a major shift towards a more patient-centric and technologically advanced approach to healthcare delivery.

Practical implications

The real-world implications of this investigation on the potential of BCT for medical applications in the healthcare industry are significant. Healthcare organizations can leverage the benefits of BCT to improve healthcare outcomes, reduce costs, and enhance patient-centric care. One practical implication is the use of BCT for secure and efficient management of medical records. This can progress the precision and extensiveness of medical records, leading to better diagnosis and treatment outcomes. Another practical implication is the use of BCT in medical trials and drug development. By providing a secure and transparent record of clinical trial data, BCT can enhance the reliability of trial results, leading to faster drug approvals and greater trust between stakeholders. BCT can also be used in SCM, providing a protected and clear record of the movement of drugs and medical devices throughout the supply chain. This can advance the proficiency and safety of the drug enlargement process and diminish the threat of counterfeit drugs entering the marketplace. The practical implications of this research paper highlight the importance of exploring the potential of BCT for medical applications in the healthcare industry. By leveraging the benefits of BCT, healthcare organizations can improve healthcare outcomes, reduce costs, and deliver more personalized and efficient care.

Limitations

Despite the potential benefits of BCT for medical applications in the healthcare industry, there are several limitations that must be considered. One limitation is the current lack of standardization and interoperability in healthcare data. While BCT can improve the security and transparency of healthcare data, it may not be able to integrate with existing healthcare IT systems and data structures. This could limit the potential impact of BCT on healthcare outcomes and reduce its effectiveness in improving healthcare delivery. Another limitation is the complexity of implementing BCT in healthcare. Healthcare organizations must have the technical expertise and infrastructure to implement and maintain BCT, which can be resource-intensive and costly. This could limit the adoption of BCT in healthcare, particularly for smaller healthcare organizations or those with limited resources. Furthermore, regulatory and legal factors, such as data protection and security rules, must be considered when using BCT in healthcare. Noncompliance with these regulations may have legal and financial ramifications for healthcare companies. Finally, there is the problem of adoption and trust. While BCT has the potential to increase the security and transparency of healthcare data, stakeholders' trust in and adoption of the technology may require time. This could limit the potential impact of BCT on healthcare outcomes in the short term. These limitations should be taken into consideration when exploring the potential of BCT for medical applications in the healthcare industry. While BCT has the potential to improve healthcare outcomes, it is important to understand its limitations and work towards addressing them.

Future scope

The future scope for research on the potential of BCT for medical applications in the healthcare industry is significant. While there are challenges and limitations associated with the implementation of BCT in healthcare, there are also numerous opportunities for innovation and advancement in the field. One area of future research is the use of BCT for telemedicine and remote patient monitoring. BCT can enable secure and efficient sharing of medical data between patients and healthcare providers, regardless of geographical location. This can improve access to healthcare and enable more personalized and efficient care delivery. Another area of future research is the use of BCT for precision medicine. By providing a safe and apparent record of medical data, BCT can enable the development of personalized treatments and therapies based on an individual's exclusive medical antiquity and inherited makeup. This can lead to improved treatment outcomes and a more patient-centric approach to healthcare delivery. Furthermore, the use of BCT in healthcare can be extended to healthcare SCM, medical research, and healthcare payments and billing. In all these areas, BCT has the prospective to recover transparency, effectiveness, and security of healthcare data and processes. The future scope for research on the potential of BCT for medical applications in the healthcare industry is broad and significant. Further research and innovation in this area can lead to improved healthcare outcomes, increased efficiency, and a more patient-centric approach to healthcare delivery.

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REVIEW ARTICLE

The Intersection of Facade Engineering and Building Information Modeling: Opportunities and Challenges

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Abstract

Building Information Modeling (BIM) represents a transformative advancement in the architecture, engineering, and construction (AEC) sector, especially in the specialized field of facade engineering. Utilizing a secondary data analysis approach focused on existing case studies, this paper offers a comprehensive examination of the synergistic interaction between BIM and emerging technologies such as generative design, machine learning, performance analysis tools, digital twins, and augmented reality. These technologies are analyzed to understand their impact on the optimization of facade design, detailing, fabrication, as well as long-term maintenance and performance. The study aims to provide a nuanced understanding of the current trends, challenges, and solutions associated with this technological amalgamation. The insights gleaned are invaluable for professionals in the AEC industry, pointing toward an increasingly digitized future where enhanced efficiency, sustainability, and functional efficacy are achievable in building facade engineering.

Keywords: Facade Engineering; Building Information Modeling (BIM); Facade Design; Facade Detailing; Facade Fabrication

Introduction

Facade engineering is a cornerstone of the architecture, engineering, and construction (AEC) industry, profoundly influencing both the aesthetic appeal and functional efficacy of structures (Azcarate et al., 2020). This discipline extends beyond mere aesthetics; its alignment with sustainable practices offers avenues for innovation, as evident in the rise of green facades in smart building designs. Such innovations promise a path towards more sustainable urban development (Aung et al., 2023). Moreover, the intertwining of green facades with renewable energy technologies proffers a robust solution to the environmental quandaries exacerbated by urbanization (Htet et al., 2023).

Amidst these advances, Building Information Modeling (BIM) stands out as a revolutionary force. Termed "disruptive," BIM isn't just another tool; it encapsulates an exhaustive digital representation of buildings, encompassing both their physical structure and functionality (Eastman et al., 2018). This disruption stems from BIM's potential to reshape traditional AEC workflows. By facilitating advanced collaboration, enriched visualization, and superior analytics, BIM is redefining how buildings are ideated, erected, and preserved, underscoring a transformative shift in the AEC landscape (Xiaozhi et al., 2018).

This paper aims to explore the convergence between BIM and facade engineering. It focuses on how this integration refines various aspects of facade design, detailing, and fabrication. A secondary data analysis approach is employed, centering on existing case studies to scrutinize the transformative effects of BIM on facade engineering. The objective is to illuminate the myriad benefits that arise from this integration, including optimized performance, improved stakeholder coordination, and enhanced efficiency and sustainability in building projects (Sacks et al., 2020)

The paper further discusses how BIM's incorporation of advanced tools like parametric design and computational algorithms amplifies the capabilities of facade engineering. These advancements are becoming increasingly crucial in a dynamic AEC environment that demands adaptability, resilience, and innovation (Seong-In, 2021).

Through detailed analysis, the paper seeks to catalyze broader adoption of BIM in facade engineering, thereby promoting the development of buildings that are not only more efficient and sustainable but also aesthetically compelling and functionally robust.

Facade Engineering: An Overview

In order to create modern, energy-efficient, and visually beautiful buildings, architects and engineers started concentrating on the design and construction of building envelopes around the beginning of the 20th century (Knaack et al., 2007). Over the years, facade engineering has evolved into a specialized discipline that combines architectural design, engineering principles, material science, and construction technology to create high-performance building envelopes (Levy, M., & Salvadori, M, 2020).

Key components and considerations in facade design include energy efficiency, sustainability, and aesthetics. Energy efficiency is crucial because the building envelope reduces energy usage for heating, cooling, and lighting (Zhang et al., 2018). Sustainable facade design entails using environmentally friendly materials, employing passive design principles, and incorporating renewable energy systems like as photovoltaic panels or sun shading devices (Faragalla, A.M.A., & Asadi, S., 2022). Aesthetics, on the other hand, contribute to the building's visual identity, urban context, and cultural significance, making it an essential consideration in facade engineering (Belarbi et al., 2023).

Facade engineering is crucial to the overall building design process, as it influences not only the building's appearance but also its performance and functionality. In addition to increasing occupant comfort and indoor air quality, a well-designed facade can also lessen the impact of the building on the environment (Shady, 2016). Furthermore, by promoting energy-efficient, low-carbon, and resilient building design, facade engineering plays an important role in tackling climate change, urbanization, and resource scarcity concerns (Webb, 2022).

Traditional facade engineering processes often face several challenges, including fragmented communication between stakeholders, inadequate performance analysis, and the reliance on manual, time-consuming design and construction methods (Sacks et al., 2018). These challenges can result in suboptimal facade performance, increased construction costs, and delays in project delivery (Hady et al., 2018). Utilizing contemporary technology, like as Building Information Modeling (BIM), can help overcome these challenges by speeding up the design, construction, and maintenance of building envelopes (Karam, K. & Jungho, Y. , 2016).

By streamlining the design, construction, and maintenance of building envelopes, new technologies such as BIM can assist address these difficulties. BIM facilitates enhanced collaboration among architects, engineers, contractors, and fabricators, enabling them to share information more efficiently and coordinate their efforts throughout the project lifecycle (Noor et al., 2019). This collaborative approach can lead to better-performing facades, optimized for energy efficiency, sustainability, and aesthetics.

Additionally, BIM offers advanced performance analysis, which enables experts to evaluate various façade design options and find the best solutions in terms of energy consumption, thermal comfort, and aesthetic appeal (Seong-In, 2021). By utilizing the power of digital tools, designers may make more informed decisions and produce building envelopes that serve the needs of building occupants, owners, and the environment.

In sum, facade engineering is a vital aspect of the building design process that has evolved significantly over the years. It encompasses critical considerations such as energy efficiency, sustainability, and aesthetics, which directly impact the building's performance, functionality, and appearance. While traditional facade engineering processes face several challenges, the adoption of advanced technologies like BIM can help professionals overcome these obstacles and pave the way for more efficient, sustainable, and innovative building design.

Building Information Modeling (BIM): An Overview

BIM (Building Information Modeling) is a digital representation of a building's structural and functional details that enables collaboration, visualization, and analysis throughout the building's lifecycle, from design to construction to maintenance (Eastman et al., 2018). BIM has evolved significantly since its inception in the early 2000s, driven by advances in computer technology, software capabilities, and the growing demand for more efficient and sustainable building practices (Succar, 2019).

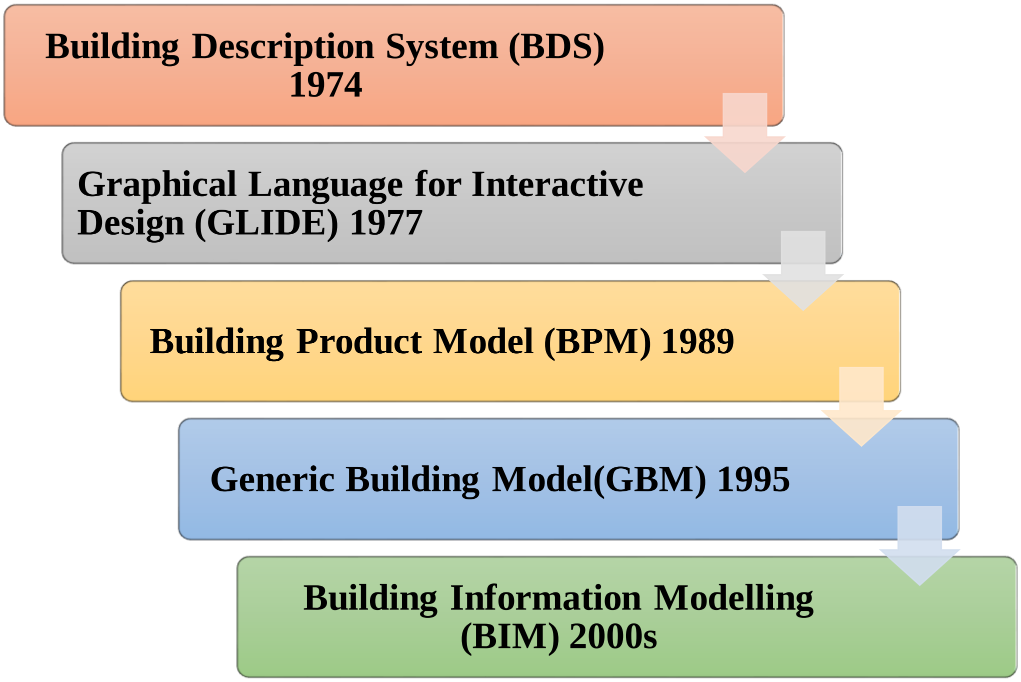
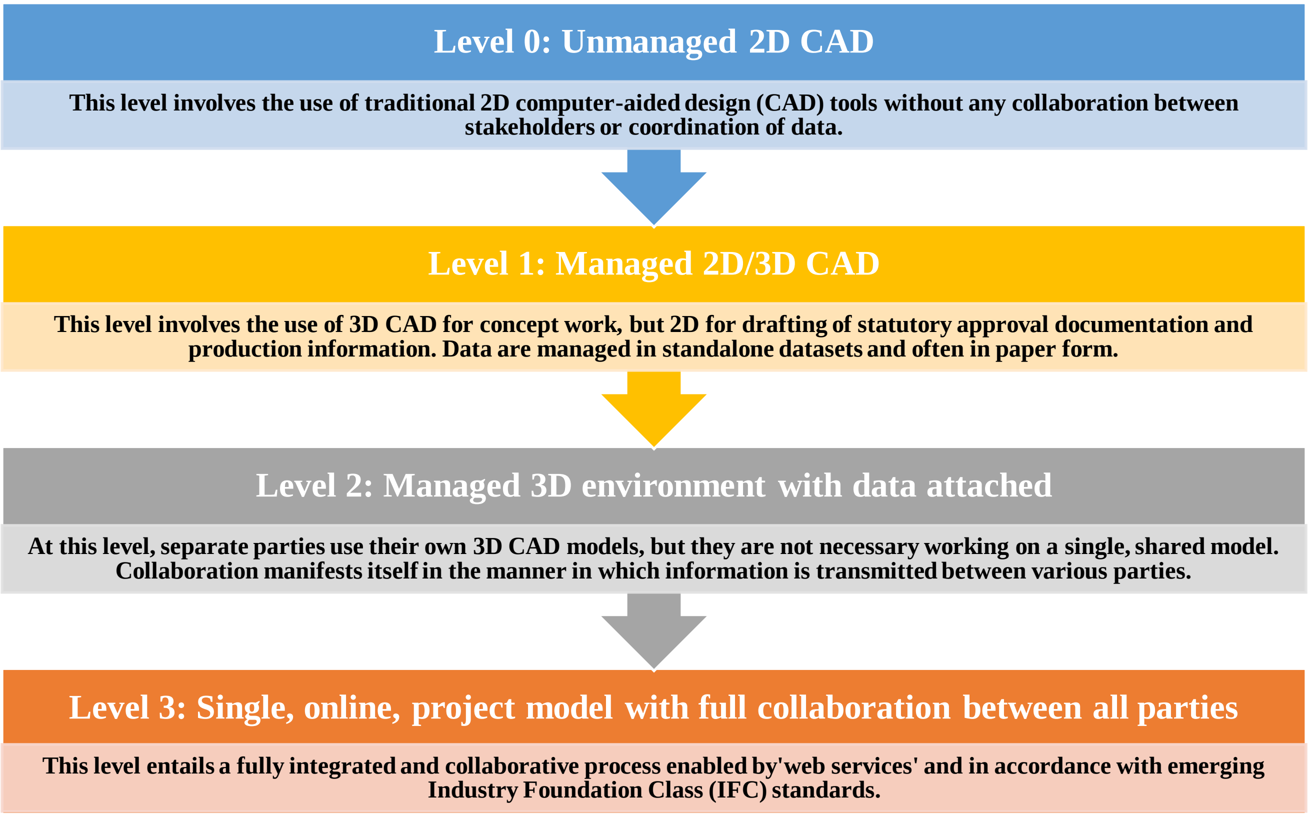


Figure 1: Evolution of BIM

The advantages of BIM in building design and construction are numerous. One of the primary benefits is improved cooperation, as BIM allows architects, engineers, contractors, and other stakeholders to collaborate on a shared digital platform, speeding communication and minimizing the chance of errors and conflicts (Chen et al., 2023). Enhanced visualization is another benefit, as BIM allows for the creation of comprehensive and interactive 3D models, enabling stakeholders to better understand and evaluate different design options (Sampaio et al., 2023). Furthermore, BIM makes it possible to do sophisticated analyses including energy modeling, structural analysis, and cost estimation, supporting professionals in improving building efficiency and reaching more well-informed decisions (Azhar, 2019).

The maturity of BIM adoption and implementation can be categorized into different levels, ranging from Level 0 (unmanaged 2D CAD) to Level 3 (fully integrated and collaborative processes). Level 1 represents the use of managed 2D CAD with some 3D capabilities, while Level 2 involves the use of managed 3D models with information exchange through common file formats (British Standards Institution, 2013). Level 3, often referred to as "Open BIM," encompasses a fully integrated and interoperable approach, with all project data stored in a single, shared model (Elbeltagi, 2021).



Level 0: Unmanaged 2D CAD

This level involves the use of traditional 2D computer-aided design (CAD) tools without any collaboration between stakeholders or coordination of data.

Level 1: Managed 2D/3D CAD

This level involves the use of 3D CAD for concept work, but 2D for drafting of statutory approval documentation and production information. Data are managed in standalone datasets and often in paper form.

Level 2: Managed 3D environment with data attached

At this level, separate parties use their own 3D CAD models, but they are not necessary working on a single, shared model. Collaboration manifests itself in the manner in which information is transmitted between various parties.

Level 3: Single, online, project model with full collaboration between all parties

This level entails a fully integrated and collaborative process enabled by'web services' and in accordance with emerging Industry Foundation Class (IFC) standards.

Figure 2: Levels of BIM Maturity

The implications of these different levels of BIM maturity for the industry include varying degrees of efficiency, collaboration, and technological integration, with higher levels offering greater potential for improving building design and construction processes (Gledson et al., 2020).

BIM adoption and implementation rates in the building industry vary by location and sector. According to a recent poll performed by Dodge Data & Analytics (2021), the global BIM adoption rate among architects, engineers, and contractors has reached roughly 67%, with greater rates recorded in nations such as the United States, the United Kingdom, and Singapore.

Factors contributing to the varying adoption rates include government policies, industry awareness, and the availability of skilled professionals (Jung et al., 2020). Despite increasing BIM acceptance, it is crucial to remember that many businesses are still in the early stages of BIM maturity, emphasizing the need for additional investment in training, technology, and research to fully fulfill BIM's potential (Eadie et al., 2018).

The Intersection of Facade Engineering and BIM

Facade Design

BIM is critical in the conceptualization and design of building facades, providing a platform for visualizing, assessing, and optimizing façade system performance (Lee et al., 2020). By incorporating 3D modeling and data management capabilities, BIM enables architects and engineers to explore various facade configurations and materials, assess their impact on building performance, and make informed design decisions (Sung-Chi et al., 2019).

The role of BIM in optimizing facade performance is significant, as it facilitates the analysis of factors such as energy efficiency, solar control, and acoustic insulation. BIM-based energy modeling tools enable professionals to assess the thermal performance of various facade systems, thereby reducing energy consumption and improving occupant comfort (Lin et al., 2019). Similarly, BIM can be used to evaluate the efficacy of sun management measures such as shading devices and glazing qualities in terms of decreasing glare and overheating (Wang et al., 2018).

To visualize the steps involved in facade design using BIM, refer to Figure 3 below. The flowchart outlines the typical process from initial conceptualization to final design decision, illustrating how BIM tools support each step.

Figure 3:The process of facade design using BIM

In addition, the integration of parametric design and computational tools in BIM-enabled facade design opens new possibilities for innovative and high-performance facade systems. Designers can use parametric design to specify connections between design characteristics, allowing them to explore a large range of design choices and automatically generate facade variations based on performance criteria (Hendro, T. P., & Luhur, S. P., 2019). This approach supports the development of optimized and responsive facade designs that can adapt to specific site conditions and performance requirements.

Facade Detailing

BIM can significantly streamline the facade detailing process, including the development of fabrication drawings and schedules. By providing a collaborative platform for architects, engineers, and contractors, BIM enables efficient communication and coordination during the detailing phase, reducing errors and inconsistencies that can lead to costly delays and rework (Jung et al., 2020). Furthermore, BIM allows for the automatic generation of detailed 2D drawings and schedules from the 3D model, ensuring accuracy and consistency throughout the project documentation (Sacks et al., 2018).

By connecting facade elements with other building systems including structural and MEP systems, BIM plays a significant role in enabling interdisciplinary collaboration and information exchange. This coordination helps prevent conflicts and design errors, improving the overall efficiency of the building design and construction process (Lin et al., 2019). For example, BIM can be used to ensure that facade elements, such as curtain walls and cladding systems, are accurately aligned with structural components and do not interfere with the installation of MEP systems (Khanzode et al., 2018).

The benefits of using BIM for clash detection and resolution in facade detailing are significant. By creating a comprehensive 3D model of the building, BIM enables stakeholders to identify and resolve potential conflicts between facade elements and other building systems before they become costly problems on site (Ahmed, A., & Kassem, M., 2020). This proactive approach to clash detection and resolution contributes to improved project outcomes, including reduced costs, shorter schedules, and better overall building performance (Chien et al., 2019).

Facade Fabrication

BIM can be effectively utilized for digital fabrication of facade components, including the use of CNC machines and 3D printing technologies. By directly exporting geometry and data from the BIM model to fabrication equipment, designers and manufacturers can achieve greater precision, efficiency, and customization in the production of facade components (Gallaher., 2021). This digital fabrication process reduces material waste, increases production speed, and enables the fabrication of complex and intricate facade designs that would be difficult or impossible to achieve through traditional methods (Rahmani et al., 2018).

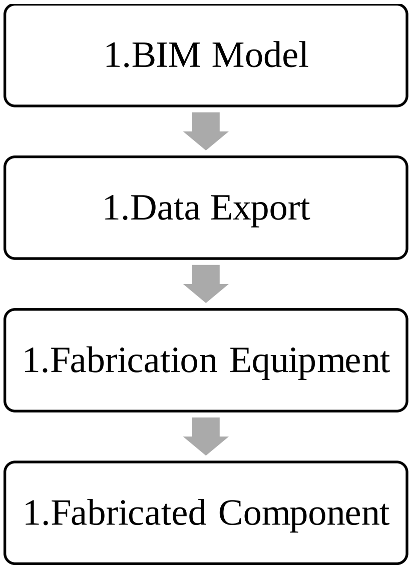


Figure 4: The process of digital fabrication of facade components using BIM

The potential for BIM to improve collaboration between facade engineers, fabricators, and installers is substantial. By providing a shared digital platform for communication and data exchange, BIM facilitates the seamless integration of design, fabrication, and installation processes, reducing the likelihood of errors and miscommunications that can lead to costly delays and rework (Zhen et al., 2015). This enhanced collaboration ultimately contributes to better facade performance, higher-quality construction, and more efficient project delivery (Li et al., 2018).

The benefits of using BIM for quality control and tracking during the fabrication process are also significant. BIM can be utilized to create digital twins of facade components, allowing for real-time monitoring and documentation of the fabrication process (Yu-Cheng et al ., 2019). This digital tracking enables manufacturers to identify and address any deviations from the design specifications, ensuring that the fabricated components meet the required quality standards (Volk et al., 2021). Additionally, BIM can facilitate the integration of fabrication data with other project information, such as schedules and procurement, enabling more efficient project management and better decision-making (Jiang et al., 2018).

The intersection of facade engineering and BIM gives various prospects for improving building facade design, detailing, and fabrication. BIM can help to build high-performance, sustainable, and aesthetically pleasing facade systems by improving collaboration, visualization, and analysis. In addition, combining BIM with new manufacturing technology and quality control methods can result in more efficient and innovative construction techniques. As BIM use grows in the building sector, its potential to alter facade engineering will become more apparent.

Case Studies: Empirical Insights into the Integration of BIM and Facade Engineering

To corroborate the theoretical underpinnings of the BIM and facade engineering integration, the following section presents a series of case studies. These empirical analyses serve to illuminate the practical implications, challenges, and efficiencies achieved through the application of BIM in facade engineering. Each case study was derived from a meticulous review of secondary data sources, encompassing published research articles, whitepapers, and industry reports. These investigations aim to offer a multidimensional view, capturing both the technical and managerial aspects of leveraging BIM for facade optimization. Furthermore, the case studies work in tandem with the preceding discussions to provide actionable insights for stakeholders in the architectural, engineering, and construction (AEC) sector. By examining real-world applications and outcomes, this section seeks to enrich the theoretical discourse with empirical evidence, thereby offering a more holistic understanding of the subject matter.

Case Study 1: Application of BIM in the New Primary School of Melzo (Giuseppe et al., 2020)

This case study exemplifies the effective use of Building Information Modeling (BIM) in constructing a new primary school in Melzo. Collaboratively executed by the Municipality and Politecnico di Milano, this project emphasizes the benefits of BIM in tendering, construction management, and architectural planning, particularly in the realm of facade engineering.

The New Primary School in Melzo serves as a comprehensive model illustrating the multifaceted advantages of employing BIM methodologies from conceptual design to construction and operations. The project involved extensive stakeholder collaboration and integrated various facets of engineering and management.

Architectural Overview

The school building is organized into three primary functional units:

- A central core built with reinforced concrete, housing administrative spaces like offices, a library, and an auditorium.
- Three wooden structural components comprising classrooms and laboratories.
- A double-height section in reinforced concrete that includes amenities like a canteen, gym, and technical rooms.

Information Workflow and BIM Utilization

During Tender Phases: BIM was instrumental in the Most Economically Advantageous Tender (MEAT) approach, enhancing transparency and improving data organization for effective bid evaluations.

Parameters for Bid Evaluation: The evaluation considered four key areas:

- Quantitative Parameters (e.g., energy consumption, performance, waste management)
- Qualitative Parameters Related to Quantitative Classes (e.g., technical requirements for finishing, maintenance)
- Qualitative Requirements of Subjective Matters (e.g., aesthetic and functional characteristics)
- Additional Requirements (e.g., certifications, legal compliances)

Facade Engineering

The application of BIM in the design of the facade enabled optimal use of open space and improved the building's relationship with its exterior environment. The design incorporated expansive glass surfaces as opposed to traditional windows, enhancing the perception of natural surroundings.

BIM Implementation Details

During Construction Phases: BIM played a pivotal role in quantitative and geometric control, aligning material specifications with tender offers, and thereby reducing rework.

For Advanced Project Activities: A custom script in Dynamo was linked to the BIM model for the evaluation of a specialized curved façade. A multi-criteria Design Optioneering approach informed the decision-making process.

Limitations

- **Lack of Mandate for BIM in the Tender Phase**: This necessitated maintaining a parallel traditional documentation process.
- **Absence of a Contractual Information Exchange Platform**: This led to traditional methods for material approval and acceptance.

Conclusions and Future Outlook

The Melzo school project establishes a robust blueprint for integrating BIM into various stages of construction projects, from planning to execution. While the study underscores the significant gains in quality, transparency, and efficiency, it also brings to light the limitations that need to be addressed for fuller BIM integration.

Case Study 2: Facade Engineering through BIM in Signal House, Washington DC (Tejjy Inc. , 2021)

This case study concentrates on the role of Building Information Modeling (BIM) in the facade engineering of Signal House, a mixed-use construction in Washington DC. It highlights the advantages of BIM in managing complex exterior materials and facilitating stakeholder coordination.

Signal House offers an insightful case for understanding the importance of BIM in facade engineering, especially given its unique blend of terracotta, metal, and glass exteriors that enrich the architectural landscape.

Architectural Overview

The building features:

- 11 stories with an emphasis on mixed-use space.
- An architectural facade designed with terracotta, metal, and glass, in harmony with the surrounding historical architecture.

Facade Engineering and BIM Utilization

During BIM Implementation Phases: BIM proved invaluable in modeling and visualizing the unique terracotta, metal, and glass exteriors. It assisted engineers and designers in determining the viability of these materials together, particularly concerning structural integrity and aesthetic cohesion.

Parameters for BIM Evaluation in Facade Engineering

- Material Compatibility
- Structural Integrity of the Facade
- Aesthetic Integration with Surroundings
- Energy Efficiency

BIM Implementation Details

Software: RAM Concept from Finite Element Modeling Software was crucial for detailed facade modeling.
Scope of Work: Beyond structural and interior aspects, special emphasis was given to BIM modeling for facade engineering, involving calculations on material tolerances, stress points, and aesthetics.

Limitations

- Lack of pre-existing standards for integrating such diverse facade materials within BIM software.
- Complexity in stakeholder communication when discussing highly specialized facade engineering topics.

Conclusions and Future Outlook

The Signal House case study underscores the potential for employing BIM in facade engineering. It points out that while BIM can facilitate the integration of complex and diverse materials in building exteriors, more standard protocols for such applications need to be established for more extensive usage.

Case Study 3: Facade Engineering and Parametric Design in the Alto Tower Project (BIM Community, 2018)

This case study delves into the significant role Building Information Modeling (BIM) and parametric design play in the construction and facade engineering of the Alto Tower, a high-rise building with a complex double-skin facade. The study explores how these technologies ensure precision, manage complexity, and enhance collaboration among project stakeholders.

The Alto Tower is not just unique for its 38 levels or 51,000 m² area but also for its distinctive flared-cone shape. One of the standout features is the double-skin facade, accomplished through a complex process of parametric design. BIM serves as a cornerstone in managing this complexity.

Architectural Overview

The tower's flared-cone shape allows it to expand threefold from its base to its top floor.

A double-skin facade shifts 12 cm outwards from floor to floor, creating an angle of 1.5° towards the outside.

Facade Engineering and Parametric Design

Parametric Design Workflow: Designed by IF Architects, the Alto tower uses a parametric design process enabled by the Rhino/Grasshopper software. This allows for the intricate details of the facade, which features hundreds of windows, each with unique dimensions.

BIM Implementation: Permasteelisa, in partnership with Autodesk, adopted the initial design to produce BIM models that carried the project from design to manufacturing stages seamlessly.

Critical Facade Elements Managed Through BIM

- The 12 cm outward shift of each floor
- Angulation of the facade beams for smoke extraction

Collaboration and Stakeholder Involvement

- Construction Privée teams integrated and codified equipment parameters from the beginning, aiming for automated connections among equipment, datasheets, and plans.
- All architectural lots work on the digital model, facilitating technical and architectural syntheses.

Data Utilization for Future Operations

The BIM models of the facade are rich in data, offering potential interface points with GTB and CMMS tools for future building management.

Limitations

- The complex facade design necessitated advanced parametric tools, which may not be universally accessible.
- Data management and codification require careful planning and adherence to standards for future exploitation.

Conclusions and Future Outlook

The Alto Tower case demonstrates the capabilities of BIM and parametric design in managing highly complex architectural and engineering feats, especially in facade engineering. It also signifies a step forward in data utilization for the operation and maintenance of high-rise buildings.

Emerging Trends in BIM for Facade Engineering

Generative Design and Machine Learning

The fusion of generative design algorithms with machine learning techniques is catalyzing a paradigm shift in the facade design process. While generative design offers a myriad of design possibilities constrained by specific performance criteria, machine learning adds a layer of predictive analytics that can help in refining these designs (Joshi et al., 2021). New research is also exploring the role of deep learning algorithms for predictive maintenance, leveraging real-time data to anticipate issues and offer remedial solutions before any major system failure (Das et al., 2022).

Integration of BIM with Performance Analysis Tools

Another significant trend is the seamless integration of BIM with performance analysis tools. These integrative platforms offer a symbiotic environment, where changes to the facade design can be instantaneously evaluated for their impact on energy efficiency, comfort levels, and other key performance indicators (Jorge et al., 2022). This effectively moves the process from reactive performance evaluation to a more dynamic, proactive design approach. It is worth mentioning that cloud-based BIM platforms are making these analyses more accessible and collaborative, thereby influencing decision-making processes in real-time (Smith et al., 2022).

Digital Twins and Augmented Reality

The concept of Digital Twins and the adoption of Augmented Reality (AR) technologies represent a significant leap toward real-time asset management and interactive maintenance strategies. Digital Twins offer a data-rich, real-time model of the building facade, providing insights into wear and tear, and thermal performance that are critical for preemptive maintenance (Alizadeh et al., 2022). When augmented by AR technologies, this allows for real-time, location-based data visualization. Facility managers and engineers can overlay structural and performance data onto the physical asset, making both routine checks and complex repairs far more efficient (Clark et al., 2022).

These emerging trends signal a future where the lines between design, construction, and maintenance are increasingly blurred, driving toward more sustainable, efficient, and user-centric building facades.

Challenges and Strategies in Facade Engineering with BIM

Challenge: Data Management and Interoperability

As demonstrated in the three case studies, effective data management is central to the seamless functioning of BIM in facade engineering projects. The issue is further complicated when interoperability between various BIM platforms and design applications comes into the picture.

Case-Study Insights: In the Melzo school project, one of the limitations was the absence of a Contractual Information Exchange Platform, leading to traditional methods for material approval and acceptance. This impediment is a direct reflection of the data management and interoperability challenges prevalent in the industry.
Strategies for Resolution: Open data exchange standards like Industry Foundation Classes (IFC) can serve as a solution for these interoperability issues, enabling seamless information sharing between diverse BIM platforms and applications (Jiang et al., 2018). Fostering the adoption of these standards can significantly streamline BIM-enabled facade engineering workflows.

Challenge: Integration of Analysis Tools

Despite the robust capabilities of BIM software in aiding design and visualization, the integration of specialized facade analysis tools remains an operational bottleneck.
Case-Study Insights: In the Signal House project, a lack of pre-existing standards for integrating different facade materials within BIM software was noted. The Alto Tower project, with its complex double-skin facade, required advanced parametric tools for design, which are not universally integrated into BIM software.
Strategies for Resolution: To fully utilize BIM's potential in facade engineering, developing integrated analysis tools and plug-ins is crucial (Li et al., 2018). These will facilitate real-time performance analytics, allowing for dynamic adjustments to the design, thereby improving the overall efficiency and building performance.

Challenge: Skilled Workforce and Training

The successful implementation of BIM in facade engineering calls for a workforce that is well-versed in both domains.

Case-Study Insights: The Alto Tower's case showed a good example of stakeholder involvement and collaboration but didn't delve into the challenge of skill set availability. Nevertheless, given the complexities involved, it's easy to deduce that a specialized skill set was a necessity.
Strategies for Resolution: Training programs targeting both facade engineering and BIM technology must be developed (Sacks et al., 2018). Academic institutions can collaborate with the industry to ensure curriculum alignment with practical needs, better preparing future professionals for the integrated disciplines.

Conclusion

The convergence of facade engineering and Building Information Modeling (BIM) carries a spectrum of both opportunities and obstacles for stakeholders in the architecture, engineering, and construction (AEC) sector. The study elucidated the manner in which BIM can enrich the various stages of facade design, from conceptualization and detailing to fabrication and performance analytics. Notable advantages that ensue from this integration encompass heightened collaboration, streamlined visualization, and more sophisticated analytical functionalities. These synergies pave the way for facade systems that are not only more efficient but also sustainable.

Nevertheless, there exists a set of challenges that inhibit the full capitalization on these advantages. Among them are hurdles related to data governance, software interoperability, and the lack of specialized skills to employ BIM in facade engineering practices. Open data exchange protocols like IFC, coupled with the advent of bespoke analytical tools and software plugins, are posited as potential solutions. Skill acquisition and enhancement could further be facilitated by academic-industrial partnerships and specialized training curricula.

The findings of this investigation serve to educate stakeholders in the AEC domain about the latent potential of BIM in facade engineering. They also offer insights into the complexities involved and propose strategies for the efficacious incorporation of BIM, aiming to catalyze its wider acceptance across the industry. In doing so, the aspiration is to encourage more robust, efficient, and sustainable design strategies for building facades.

Future Research

The sphere of future research can be broad and should aim to scrutinize the integration of emergent technologies like generative design, machine learning, and digital twins into BIM-enabled workflows for facade engineering. The AEC industry stands to gain significantly from the articulation of guidelines, best practices, and demonstrative case studies regarding the application of BIM in facade engineering. Additionally, it is essential to explore the compatibility and synergistic effects of integrating BIM with nascent construction paradigms such as robotic manufacturing and automation. These avenues for future exploration could serve to further enrich the discourse on optimizing facade engineering workflows through technological advancements.

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During the preparation of this work the author(s) used Chat GPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Conflict of interest

The author declares no conflict of interest. All views and opinions expressed in this article are solely those of the author, and no external party had any influence over the research, results, or interpretations presented in this paper.

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Data availability

The findings of this research are exclusively based on secondary sources which are publicly accessible and cited within the manuscript. No primary raw data was collected or utilized for this study.

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