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Review

Industrial CHP with Steam Systems: A Review of Recent Case Studies, Trends and Relevance to Malaysian Industry

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Abstract: Malaysia's energy intensity (GWh/GDP) shows an increasing trend since the 1990s, leading to the government's efforts to promote energy efficiency via policies such as the National Energy Efficiency Action Plan (NEEAP), which includes the Energy Performance Contracting (EPC) initiative. This paper reviews recent publications in industrial Combined Heat and Power (CHP) with a focus on international case studies relevant to Malaysian industries that use industrial steam and highlights trends within the research area. It also provides the basis for more case studies to be performed in the Malaysian industry to improve energy efficiency while also supporting further academic research in the area. Additionally, the paper documents the importance of data collection and analysis as well as demand forecasting, not only for a better understanding of industrial energy systems but also to increase profitability since system loads may vary throughout a typical year. A multi-criteria and comprehensive approach is recommended in future case studies to ensure energy efficiency, economic returns and environmental impact are considered to ensure long-term sustainability. A summary of barriers to CHP implementation in the industry is also included to provide a broad understanding of industrial CHP.

Keywords: energy efficiency; CHP; cogeneration; industrial retrofit; case study; industrial steam

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1. Introduction

There is widespread academic and industrial interest in the energy efficiency field, as evidenced by the variety and quantity of publications in this domain on an international level. There is a strong basis for this interest—the International Energy Agency (IEA) [1] considers energy efficiency as the "first fuel" among energy transitions since it was estimated in 2018 that the efficiency approach by itself can potentially trigger the peaking of GHG emissions by 2020. It also further found that a total of 3.5 GT of CO_2 emissions were abated globally between 2015 and 2018 as a result of efficiency measures. This figure was equivalent to the total energy emissions from Japan over the referenced timeframe (IEA, 2018) [1]. Energy efficiency provides three key benefits—limiting climate change, improving economic returns and maintaining energy supply security.

Globally, the industrial sector consumed approximately 54% of total delivered energy in 2016, making it the single biggest consumer of delivered energy worldwide (US EIA, 2016) [2]. In the Malaysian context, the country's energy intensity (GWh/GDP) shows an increasing trend since the 1990s (MEC, 2018) [3], leading to the government's efforts to promote energy efficiency via policies such as the National Energy Efficiency Action Plan (NEEAP), which includes the Energy Performance Contracting (EPC) initiative (MESTECC, 2015) [4]. The Malaysian industrial sector consumed 28% of the total final energy in the country in 2018, making it the second-largest final energy consumer after transportation

(MEC, 2019) [5]. In addition to being a major energy-consuming sector, there are also vast opportunities to improve energy demand and total emissions from industrial activities, as concluded by BoroumandJazi et al. (2013) [6]. Additionally, Malaysia (and other developing Southeast Asian countries) is lagging behind the G8 countries in industrial energy efficiency—defined as units of energy consumed per unit of industrial output (Rahman et al., 2016) [7]. It is, therefore, pertinent to focus energy efficiency efforts on the industrial sector in Malaysia. A common denominator among the energy-intensive industries is the usage of steam systems, either for process heating, electricity generation or both. Steam turbine technology has been in use for power generation since 1884, making it today a mature technology offering high flexibility (both in configuration and output capacity)—these advantages are the reason steam systems are widely in use even today for power generation and industrial purposes (US EPA, 2017) [8].

2. Assessment of Related Literature

The literature review section intends to balance breadth and depth in summarizing recent publications on energy efficiency and CHP applications, with particular emphasis on energy-intensive industries that are relevant to Malaysia's economy.

The aim of this paper is to summarize recent research into industrial CHP with a focus on case studies involving industrial steam that are relevant to the Malaysian context. It also intends to identify recent trends in industrial CHP to highlight interesting opportunities in applications and research. A cross-industry viewpoint was selected to identify energy efficiency best practices and findings from various industries.

This paper is organized into three sections. Firstly, the concept of CHP and its typical applications in industry are introduced together with relevant background information. Secondly, a sampling of case studies is presented, highlighting key findings as well as recent trends in fuel sources, network usage of excess heat and tools for evaluation and optimization of scenarios. Thirdly, the barriers against CHP implementation are presented to provide a balanced viewpoint on the subject. The perceived research gaps are also highlighted here for consideration in future academic research.

2.1. Combined Heat and Power (CHP) and Combined Cooling, Heat and Power (CCHP)

Combined Heat and Power (CHP) or cogeneration involves the simultaneous production of electricity and thermal (or mechanical) energy, thus increasing the amount of useful energy per unit of fuel. The key argument for CHP is the improved overall energy efficiency of about 60% to 80% in the case of power plants, compared to the average of 33% for thermal plants (Athawale et al., 2016) [9]. Additionally, there is vast untapped potential for CHP—a report by ICF (2013) [10] estimated about 56 GW of untapped CHP potential in the US industrial sector alone. The excess energy from industrial processes (either electricity or heat) could be used internally by the source plant or distributed to other external facilities (Svensson et al., 2019) [11] for financial benefit.

According to US EPA (2017) [8], the two main approaches for CHP in the industry include:

(a) Converting surplus thermal energy from an industrial process (e.g., a steam boiler and distribution) into electricity (or mechanical energy) using back-pressure steam turbines (BSTs), extraction steam turbines (ESTs) or condensing steam turbines (CSTs). BSTs are used when steam is also required for the industrial process—only a part of the energy in the steam is extracted for electricity. CSTs are used when process steam is not required, and the steam is dedicated to electricity production. Finally, ESTs are a variant of BSTs, which extract a higher amount of energy for electricity production.

(b) Converting waste heat from a thermal power generation process (e.g., gas turbine exhaust heat) into electricity using a steam turbine or into useful thermal energy via steam distribution for heating. This concept is commonly known as Combined Cycle Gas Turbine (CCGT) (US EPA, 2017) [8].

In both the scenarios for CHP described previously, the fuel input into the system is maintained, but the useful energy is improved by extracting useful thermal energy simultaneously with the useful electrical energy, or vice versa. This nature of CHP, therefore, requires the introduction of the power-to-heat ratio, which can be used as a performance indicator to compare and characterize CHP systems (Birru et al., 2018) [12]. Frangopoulos (2012) [13] cited several typical power-to-heat ratios, e.g., 0.95 for combined cycle gas turbines with heat recovery, 0.75 for internal combustion engines, 0.55 for gas turbines with heat recovery and 0.45 for back-pressure steam turbines.

Combined Cooling, Heat and Power (CCHP) or trigeneration is the progression from CHP—simultaneously extracting electricity, heat and cooling from the same source of fuel, by further exploiting the residual waste heat using thermally driven heat pumps or desiccant technology. Since more useful work is exploited per unit of fuel, CCHP achieves more overall energy efficiency compared to CHP (Al Moussawi et al., 2016) [14]. Similar to CHP systems, CCHP can be implemented via a large variety of technologies, ranging from the commonly used and mature internal combustion engines (ICE) and gas turbines to the relatively recent solid oxide fuel cell (SOFC), as explained by Segurado et al. (2019) [15]. While there are certain merits to CCHP technology, the additional cooling function and associated equipment will inevitably entail higher capital investment, a larger footprint in industrial sites and increased complexity for system design and optimization—for example, Machalek et al. (2020) [16] highlighted the increasing failure risk and complexity with the addition of equipment into existing systems.

2.2. Fuel Sources

The most common fuel for CHP applications is natural gas, owing to its cost-efficiency and position as the "cleanest" source of fossil fuels (Kavvadias et al., 2010) [17]. However, there is growing interest and research into the use of biomass fuels for CHP systems. This is especially true in industries where biomass fuel is available on-site as a process by-product or waste. Shabbir et al. (2016) [18] cited the example of rice husk as a biomass fuel that supports sustainability while also being cost-efficient for rural electrification as part of their study on CHP application in paper mills. Other examples include sugarcane bagasse for sugar mills (Mane, 2016) [19]; (Birru et al., 2018) [12], cassava waste from cassava starch plants (Yin et al., 2019) [20], or sugarcane straw (Watanabe et al., 2020) [21]. Biomass fuels also provide the added benefit of reducing net carbon emissions (Atkins et al., 2017) [22]. However, it should be noted that the moisture content in biomass fuels has a strong influence on process efficiency, as highlighted by Machalek et al. (2020) [16]. Biomass is also considered a potential fuel source for CCHP applications, where Segurado et al. (2019) [15] explored the feasibility of biomass gasification; however, the authors reported reduced economic performance compared to natural gas and recommended further optimization to improve techno-commercial competitivity.

Despite the advantages of natural gas and biomass in standalone applications, research by Shabbir et al. (2016) [18] highlighted that systems with dual-fuel capability (i.e., combining fossil fuel and biomass) might be a better solution compared to biomass-only systems due to improved fuel flexibility, availability and reliability. This finding is consistent with the work from Booneimsri et al. (2018) [23] on the critical benefits of multiple fuel sources towards improving CHP capacity factors and the eventual impact on economic returns.

2.3. Case Studies—Target Industries and Evaluation Criteria

Energy-intensive industries are naturally the primary targets for CHP applications. A prime example is the petrochemical industry, where Chen et al. (2013) [24] concluded that BSTs and CSTs are competitive options to reduce plant OPEX. Tantisattayakul et al. (2016) [25] performed a broader assessment of 35 energy efficiency techniques with data from seven different petrochemical plants in Thailand, concluding that CHP provides the highest capacity to reduce energy consumption and greenhouse gas emissions. Pirmohamadi et al. (2019) [26] considered various configurations involving BSTs, CSTs and GTs with an exergetic approach and found BSTs and GTs to provide the most optimal exergetic performance.

CHP in palm oil mills (POMs) is another relevant topic to Malaysia, given its position as the second-largest producer of crude palm oil (CPO) in the world (Booneimsri et al., 2018) [23]. The authors studied a POM in Thailand and proposed an improved CHP concept to recover more waste heat and operate with multiple fuel sources—pressed palm fiber (PPF) when CPO is produced and empty fruit bunches (EFB) when CPO is not produced, boosting annual operation hours and economics. They also cited that ESTs are compatible with a bigger range of steam demand scenarios.

The sugar industry is more common in developing countries and offers a significant opportunity for energy efficiency (Birru et al., 2018) [12]. Mane (2016) [19] reported 5 GW of installed export capacity to the grid from Indian sugar plants with CHP. Birru et al., 2016 [27] estimated that retrofitting Brazilian sugar mills with energy efficiency concepts (including CHP) can unlock 9.6 TWh of electricity generation to the grid—almost 2% of the country's electrical generation. However, the same authors also cautioned that there was little information in the literature on how much of the technical energy gain potential in sugar mills was actually realized post-modification, recommending more efforts in documenting actual energy performance. Brazil and India (the two largest sugarcane producers) are being referenced by other developing countries with sugar industries, such as Jamaica (Contreras-Lisperguer et al., 2018) [28].

Shabbir et al. (2016) [18] argued that CHP is well suited for the paper industry due to the requirement for continuous heat and power to operate an energy-intensive industrial process, concluding that gas turbine CHP provides the highest energy utilization factor with the lowest Annualized Life Cycle Cost (ALCC). Svensson et al. (2019) [11] also identified the pulp and paper industry as a significant consumer of energy and remarked on its suitability for CHP and potential to provide electricity to other sectors.

Irungu et al. (2017) [29] highlighted the energy intensity in the cement industry and studied the application of CHP in a cement plant. Their work evaluated the electricity generation potential from waste gases and found that annual electricity costs could be reduced by 33% while also providing energy resilience since the plant's location in Kenya reportedly suffered from poor grid reliability. This adds yet another dimension to the benefits of CHP—the ability to partially or wholly mitigate electricity supply risks in critical process equipment.

Papers related to power generation applications were also consulted since CHP was originally implemented in large thermal power installations and therefore considered a valuable source of insight on this subject. Gvozdenac et al. (2017) [30] proposed a modification to the evaluation of a CHP plant's total efficiency by using the power loss coefficient, the referred value of high-efficiency cogeneration and a broader daily measurement of key parameters in a plant for improved transparency. Sayyaadi et al. (2019) [31] proposed an ANFIS (adaptive neuro-fuzzy inference system) model to retrofit a thermal power plant and enable real-time system optimization with the end goal of maximizing the plant's operating profits. The advancement of real-time system optimization indicates the capability to continuously adapt to changing operating conditions—this may provide a significant advantage to industries operating in increasingly competitive environments.

Vellini et al. (2020) [32] found that the food industry's high consumption of both electricity and heat makes it a suitable candidate for CHP and, through a case study, identified the GT-based CHP configuration to be the best suited for technical, economic and environmental parameters. They also found that the BST and CST configurations in the case study could not match the total electrical demand of the process, resulting in the requirement to rely on the grid supply for top-up electricity—this can be explained using the power-to-heat ratio previously introduced in this paper.

There are numerous other records of industrial CHP case studies, with examples summarized in Table 1.

Table 1. Example case studies by industry.

No.	Industry	Authors	Key Findings
1	Cement	Irungu et al. (2017) [29]	This work by Irungu et al. (2017) recognized that the hot waste gases that were vented into the atmosphere from the clinkering process had a net potential to generate 2.9 MWh, which was sufficient to fulfill 33% of the plant's power demand.
2	Composites	Machalek et al. (2020) [16]	The research established that the CHP system itself was the main source of savings. Furthermore, the given electrical and demand rates and natural gas costs make the system configurations 2–4 times more economically favorable. Overall, the dynamic model provided for a thorough technical viability analysis has led to a more reliable economic and environmental conclusion.
3	Food	Vellini et al. (2020) [32]	This research compares different cogeneration technologies as alternative technical solutions for certain food industry facilities, especially the Italian confectionery industry. Overall, the paper presents a preparatory for a generalization: of means and criteria for the assessment of cogeneration plants and, hence, can be extended to other industry sectors.
4	Palm oil	Booneimsri et al. (2018) [23]	In this paper, the cogeneration efficiency enhancement and integrated waste energy utilization of the POMs were demonstrated by recovering significant lost energy, vented sterilization steam, engine waste heat, and EFB biomass fuel harnessed by the proposed cogeneration model. A thermodynamic analysis conducted shows that the surplus power could generate 2.834 and 4.223 MW along with reducing carbon dioxide emissions by 0.66 MMTCO.
5	Paper	Shabbir et al. (2016) [18]	Shabbir et al. (2016) research work explored the cogeneration options for a typical paper mill using rice husk as the biomass with the natural gas energy source. They found that the mill has a good potential for energy saving using a cogeneration system. This has been shown in both technical and economic perspectives based on the energy utilization factor and annualized life cycle cost. Based on the economic analysis, it is also concluded the gas turbine cogeneration system is the most economically viable option for the paper mill and has a CO_2 emission reduction of 68% compared to the existing system.
		Svensson et al. (2019) [11]	This research work by Svensson et al. (2019) proposed a novel tool for the characterization and visualization of excess heat availability from industrial sites, named XHT signature. This is utilized to determine the potential of heat availability at constant temperature levels between supply and target.
6	Petrochemical	Chen et al. (2013) [24]; Tantisattayakul et al. (2016) [25]; Zhang et al. (2017) [33]; Pirmohamadi et al. (2019) [26]	Chen et al. (2013) studied the steam power plant of a petroleum refinery and proposed a comprehensive mathematical model for the analysis and design of the steam power plant. The proposed model can fulfill the existing steam power plant in a refinery, which includes the operational optimization, retrofit of existing units, and import steam integration. A significant reduction has been achieved in operating cost by 13.8% in the case study, where an existing condensing turbine is modified into an extractive turbine, and one new steam turbine is adopted for generating electricity. Tantisattayakul et al. (2016) studied the performance of the energy conservation measures implemented in the Thai petrochemical industry by assessing them from energy, environmental and economic perspectives. The total GHG emission reduction for all sample plants was 502,989 tCO_2eq/yr, equal to approximately 5.70% of the total GHG emissions from petrochemical plants in Thailand. Pirmohamadi et al. (2019) concluded that a set of back-pressure steam turbines and gas turbine systems were to be introduced as the optimal exergetic configuration of the overall heat and power cogeneration system in the total site.

Table 1. *Cont.*

No.	Industry	Authors	Key Findings
7	Power generation	Gvozdenac et al. (2017) [30]; Chen et al. (2019) [34]; Sayyaadi et al. (2019) [31]; Tang et al. (2020) [35]; Zhang et al. (2020) [36]	Gvozdenac et al. (2017) proposed a modified procedure for the verification of the cogeneration plant's efficiency wherein, for calculating the power loss coefficient, they introduced the referred value of high-efficiency cogeneration (hRE), which contains all specificities of the concrete plant, and performed the daily calculation of relevant parameters. Sayyaadi et al. (2019) [31] developed the artificial neuro-fuzzy inference system, ANFIS, and used it for exerting economic optimization of an energy system at the design stage. It was found that the ANFIS could provide a quite fast and accurate optimization algorithm compared to conventional optimization methods that would make a suitable tool for real-time optimization.
8	Sugar	Kamate et al. (2009) [37]; Mane (2016) [19]; Birru et al. (2018) [12]	Kamate et al. (2009) found in their work that bagasse gasification technology is not fully developed and has a long future. They also concluded that the biomass-integrated gasifier-gas turbine system and biomass-integrated system combined with steam-injected gas turbine are more attractive as they generate twice that generated by the extraction of the condensing steam turbine route. The purpose of Birru et al.'s (2018) work was to compare the technological options proposed for the Carlos Baliño sugar mill. For this, different factors are considered as comparison parameters. Some actually brought in massive CO_2 emissions savings, almost 21,538 tonnes/year.
9	Textile	Ozturk et al. (2020) [38]	Ozturk et al. (2020) focused on reducing energy consumption and emissions by applying energy efficiency methods in an integrated woolen fabrics facility and found that after employment of the techniques, 15–32% and 14–36% savings in both electricity and thermal energy were achieved, respectively. The emissions were also cut by 38–76%.

The studies can be organized into three main groups (Table 2)—thermodynamic, techno-economic analysis and comprehensive evaluations, which consider technical, economic and environmental/social factors (also known as the triple bottom line). These indicate a trend towards a more sustainable and longer-term evaluation of energy efficiency solutions.

Table 2. Examples of the 3 main case study groups.

No.	Approach	Authors	Key Findings
1	Thermodynamic analysis	BoroumandJazi et al. (2013) [6]; Palacios-Bereche et al. (2009) [39]; Pirmohamadi et al. (2019) [26]; Bhagwat et al. (2016) [40]; Nandaliarasyad et al. (2020) [41]; Zhang et al. (2020) [36]	Boroumand Jazi et al. (2013) concluded, based on the reviewed literature, that there were significant differences between the energy and exergy efficiency of different industries. The differences between the first and second law efficiencies is attributed to the steam generation and the dependency of industry on electricity. While comparing both the energy efficiency analysis and the exergetic efficiency of a system, it can be seen that the exergy analysis provides a realistic picture. Nandaliarasyad et al. (2020) concluded that the Organic Rankine Cycle (ORC) can be used to utilize wasted steam from the back pressure turbines and also found that the ORC, which uses exhaust steam with 2435 kJ/kg enthalpy, generates power up to 2.25 MW. Zhang et al. (2020) concluded that most of the energy loss in a fossil-fuel thermal power plant came from the steam turbine and suggested that the efficiency of a thermal power plant can be improved by either some energy conservation within the system or expansion of differences between initial steam parameters and final steam parameters.

Table 2. *Cont.*

No.	Approach	Authors	Key Findings
2	Techno-economic analysis	Raghu Ram and Banerjee (2003) [42]; Birru et al. (2016) [27]; Hasanbeigi et al. (2016) [43]; Irungu et al. (2017) [29]; Birru et al. (2018) [12]; Yin et al. (2019) [20]; Kamarudin et al. (2019) [44]	Hasanbeigi et al. (2016) represented an initial effort to provide a transparent methodology for quantifying the energy efficiency potential of steam systems based on sufficient data to document the magnitude and cost-effectiveness of the resulting energy savings for China. Almost nine energy-efficiency technologies were studied, and an energy efficiency cost curve was developed for industrial coal-fired steam systems, where the purpose was to determine the potentials and costs of improving the energy efficiency of the industrial steam systems, taking into account the costs and energy savings of different energy efficiency measures. Yin et al. (2019) [20] concluded that the proposed CHP is better as it produces 725.6 MJ of electric energy and a total of 1311.0 MJ of heat for starch production, in addition to a total reduction in CO_2 emissions of 2017.1–2508.3 t/a for a 200 t/d cassava starch plan. The total investment costs CNY 27.24 million for a CH boiler system and will be paid back in 3.18 years. Kamarudin et al.'s (2019) study also showed that the cold utility cost was increased for the ORC case in comparison to the base case and concluded that it was due to condenser heat release, which required cooling down.
3	Comprehensive evaluation	Atkins et al. (2017) [22]; Contreras-Lisperguer et al. (2018) [28]; Machalek et al. (2020) [16]; Vellini et al. (2020) [32]	These are already discussed in the paper.

A single criteria approach can mislead the case study—for example, the cheapest solution with the lowest upfront CAPEX may not provide a reasonable improvement in total efficiency, thus defeating the purpose of the retrofit. Conversely, the solution offering the highest energy efficiency via advanced equipment may also be CAPEX-intensive and impose an extended payback period. The multi-criteria approach solves this problem by preventing "blind spots" and forcing a comprehensive view. Additionally, the three main groups will also have sub-criteria that may not be of equal importance—this can be addressed by introducing weightage to the different components, resulting in a multi-criteria weighted approach.

In the case of Raghu Ram and Banerjee (2003) [42], a graph between the temperature of the evaporator vessel and the cumulative amount of exergy lost is drawn for both cases and shown in Figure 1 so as to prove the analysis and to establish that the cumulative amount of exergy lost in the evaporators decreases from 33.5 to 17.6 MW if the quadruple effect is modified to a quintuple effect.

The case study approaches previously described consider technical (energy), financial, environmental, industrial or composite criteria to quantify performance. These categories and parameters are summarized in Table 3.

Svensson et al. (2019) [11] argued that case studies will continue to be necessary to construct generic models since industrial plants differ due to technology, age, process layout and extent of heat recovery (even within the same industry). However, this heterogeneity also implies limited repeatability of results. Additionally, ambient conditions can influence results—a striking example is the consideration of the techno-economic performance of a CHP plant in Siberia, where the ambient temperature is −40 °C. González-Díaz et al. (2017) [45] explained that a reduction in ambient temperature improves the overall efficiency of a combined cycle plant due to increased air density and consequently higher mass flow into a gas turbine (GT).

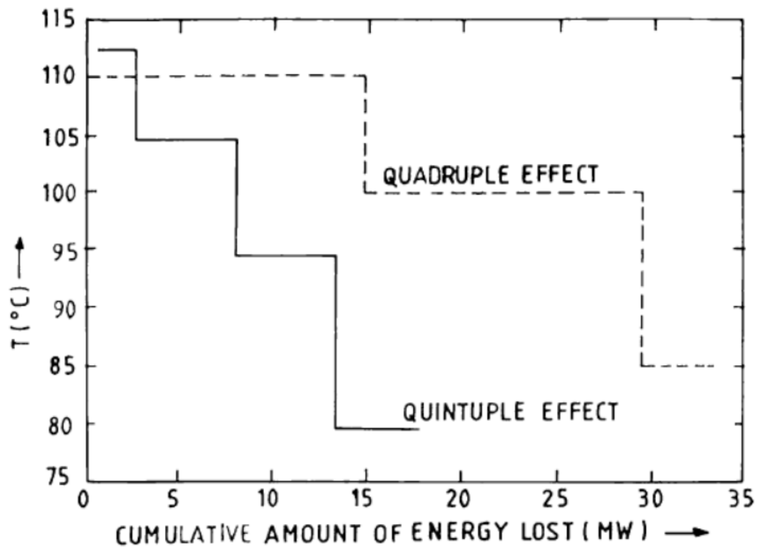

Figure 1. Comparison of the amount of exergy lost. Reprinted with permission from [26]. Copyright 2022 Elsevier.

Table 3. Performance categories and parameters.

No.	Category	Performance Parameters
1	Technical (Energy)	Total electrical output Total system efficiency Thermal efficiency Exergetic efficiency Power to heat ratio Annual energy savings Energy saving index Energy utilization factor Second law efficiency Primary energy savings, (PES)
2	Financial	Levelized cost of electricity, (LCOE) Capital expenditure, (CAPEX) Operating expenditure, (OPEX) Annualized life cycle cost, (ALCC) Net present value, (NPV) Incremental NPV Annual profit Payback period Internal rate of return, (IRR) Benefit to cost ratio, (BCR) Cost of conserved energy, (CCE) Cost of CO_2 abatement Fuel costs
3	Environmental	Annual CO_2 emissions
4	Industrial or Capacity	Capacity factor Annual product output Grid utilization factor
5	Composite	Total key performance indicator, (TKPI) Life cycle sustainability assessment, (LCSA)

These points indicate a research gap in addressing the limited comparability among the results of different case studies—a balance between targeted problem-solving and comparability of results is required. A potential solution to this dilemma is the creation of an additional reference for future case studies by assuming standard conditions as prescribed by the International Organization for Standardization (ISO). This approach could improve the comparability of results regardless of geographic location.

2.4. Network Usage of Waste Heat

Waste heat represents a significant energy resource that remains to be fully exploited—Forman et al. (2016) [46] found that 72% of primary energy consumption worldwide is lost post-conversion and that waste heat is generally the major form of energy loss. A common approach in CHP application involves internal consumption of the extracted electrical or thermal energy, e.g., to offset or entirely replace grid consumption (Irungu et al., 2017) [29] or to extract waste heat for process heating (Ozturk et al., 2020) [38]. However, it is also possible to have surplus electricity or heat due to operational variability. While surplus electricity can be exported to the grid using the appropriate metering equipment, external use of surplus heat is less common in industrial settings, as noted by Moser et al. (2020) [47], who studied the technical potential of industrial waste heat in Austria. The authors identified several barriers, such as the high cost of heat pipes and uncertainty on the existence of the parties involved, especially in industrial settings. Svensson et al. (2019) [11] studied the characterization of excess industrial heat in Sweden and noted the challenge related to the availability of reliable and accurate information in the industrial sector. Additionally, Forman et al. (2016) [46] found a large variability in global waste heat temperatures and noted that this results in variability in the resulting Carnot efficiency potential since lower waste heat temperatures imply lower efficiency from a heat engine. They also highlighted other challenges, such as a mismatch between heat demand and supply due to timing, location and magnitude. Despite these obstacles, network usage of industrial waste heat provides an opportunity to improve industrial energy efficiency and should be considered in CHP systems.

2.5. Importance of Industry Data and Demand Forecasting

Research challenges are still evident despite substantial studies completed on energy efficiency and CHP topics. For example, Forman et al. (2016) [46] remarked on the rarity of detailed data on energy conversion and losses from fuels to end use, notably on burner units. Birru et al. (2018) [12] highlighted the limited availability of actual post-modification energy performance data in the sugar industry. Svensson et al. (2019) [11] explained that the variety of approaches and differing assumptions are reasons for large variances in estimated potential. This raises a valid question on the accuracy of technical potential estimates and the link to actual operational data.

Athawale et al. (2016) [9] investigated the subpar capacity factors observed in CHP plants in the state of New York in the U.S. and highlighted the importance of pre-engineering with accurate forecasting of electricity and heating demand for the plant over a full year for economic viability. They further noted industry guidelines for CHP plants' economic feasibility, citing numbers ranging between 4000 and 5000 operating hours per year. These findings are consistent with the paper by Shabbir et al. (2016) [18], where the annual operating hours were found to strongly influence the profitability of the CHP case study, with their example of 7320 h permitting surplus electricity export and citing the typical annual threshold of 4500 h. Booneimsri et al., 2018 [23] found similar results in their case study on palm oil mills (POMs), reporting that their proposed retrofit to the POM cogeneration model could improve annual electricity output to the grid, owing in part to the significant improvement to the plant's annual operating hours—from 4351 to 7500 h annually. Watanabe et al. (2020) [21] also noted the strong influence of the annual operating period on the feasibility of retrofitting scenarios—stating the example of a sugarcane plant retrofit with negative NPV if the plant only operated during the harvest season. A critical link is therefore evident between the demand data used for engineering design, the actual capacity factor achieved during operations and resulting economic performance. It should be noted that the scarcity of industrial case study data is not only present for CHP applications but also applicable for CCHP implementation, where Segurado et al. (2019) [15]

highlighted the prevalence of case studies based on theoretical approaches rather than experimental or field data.

2.6. Optimization Methods and Tools

The typical CHP retrofit case study involves multiple design scenarios involving:

(a) Equipment sizing and quantity,
(b) Equipment technology (e.g., BST, CST, EST, GT),
(c) Operating strategy (e.g., generate all electricity in-house or partially import from the grid).

The complexity of optimization is directly proportional to the number of design cases and constraints, which justifies the need to leverage the latest technological and numerical methods. There are numerous papers on the application of recent numerical modeling methods and computing capabilities to develop optimization simulation tools or frameworks to improve industrial plant efficiency.

Zhao et al. (2019) [48] highlighted that equipment inefficiencies and varying process conditions are significant hurdles when implementing conventional mathematical programming techniques and therefore selected the data-driven robust optimization (DDRO) approach to optimize steam systems in ethylene plants. They reported that this model could provide a more robust solution compared to a deterministic model. Sayyaadi et al. (2019) [31] proposed a promising application of the adaptive neuro-fuzzy inference system (ANFIS) tool for real-time optimization of a steam power plant on the basis of speed, accuracy and simplicity. The various optimization methods and authors are summarized in Table 4.

Table 4. Optimization methods used in energy efficiency case studies.

No.	Approach	Authors	Key Findings
1	Artificial neural network—adaptive neuro-fuzzy inference system (ANFIS)	Sayyaadi et al. (2019) [31]	Already discussed elsewhere in the paper.
2	Data-driven robust optimization (DDRO)	Zhao et al. (2019) [48]	Already discussed elsewhere in the paper.
3	Decision frameworks	Zhang et al. (2016) [49]; Andiappan et al. (2017) [50]	Andiappan et al. (2017) presented a systematic framework for Design Operability and Retrofit Analysis (DORA). DORA is a framework that explicitly analyzes process units functioning at different operability levels and the corresponding impacts on system flexibility. They mention that in DORA, the inoperability of process units was expressed using inoperability input–output modeling (IIM). Via IIM, a simple mixed integer linear programming (MILP) model is developed to analyze the flexibility of an energy system design when a processing unit experiences inoperability. In the discussed case study, the DORA framework was used to determine if the BTS would require debottlenecking and retrofitting in order to increase its energy production to 4 MW.
4	Mixed-integer nonlinear programming (MINLP)	Chen et al. (2013) [24] Zhang et al. (2017) [33]	Zhang et al. (2017) mentioned that RNGRSs include complex material stream networks and refining processes that closely interact with materials and energy. They also mention that the models presented integrate material stream networks, thermodynamics, refining processes and utility subsystems. They conclude by saying the example given demonstrates a profit increase of 9.4% and the optimal material stream network favors the production of the highest-pressure stream, thereby avoiding the removal of CO_2 from raw natural gas.
5	Multi-criteria decision-making (MCDM)	Ozturk et al. (2020) [38]	Already discussed elsewhere in the paper.

Some researchers also chose to use commercially available software to evaluate scenarios. The software is summarized in Table 5. It is important to note that the software is not considered equivalent and are suited for specific niche applications. For example, SimaPro is focused on lifecycle analysis for studies on sustainability and environmental reporting (SimaPro, 2020) [51].

Table 5. Modeling and optimization software used in previous research and case studies.

No.	Software	Authors	
	ANTIGONE	Zhang et al. (2017) [33]	Already discussed elsewhere in the paper.
	Aspen Plus	Watanabe et al. (2020) [21]	Already discussed elsewhere in the paper.
	EBSILON	Chen et al. (2019) [34]	Chen et al. (2019) performed a comprehensive study of an energy-saving mechanism and sensitivity of the HBP heating system in a typical 300 MW CHP unit. Thermodynamic and economic performances presented the following results: i. The power generation with the standard coal consumption rate of the CHP unit declines by 23.52 g/(kW·h), showing a thermal efficiency improvement of 5.97%. The HBP design and the exergy efficiency of the heating process is raised from 55.07% to 72.6%. ii. If the turbine back-pressure is below the theoretical lowest saturation pressure needed, the increase in the back-pressure raises the unit energy efficiency. iii. Unit thermal efficiency will drop due to the back-pressure increase when the back-pressure exceeds the lowest requested saturation pressure. iv. The conventional unit operates better at adjusting the generation load when the heating load is relatively low.
	EES	Birru et al. (2018) [12]	Birru et al. (2018) analyzed the operation parameters of both traditional and modern sugar mills. The comparison of the performance was based on the power-to-heat ratio and the cogeneration efficiency and helped in identifying the characteristic differences. The study also included a techno-economic and economic sensitivity analyses for various traditional mill retrofit schemes. They also pointed out that such analyses and their results can serve as a basis for analysis of larger numbers of mills and can be used as a reference for performance comparison.
	GateCycle	Vellini et al. (2020) [32]	Already discussed elsewhere in the paper.
	Lingo	Andiappan et al. (2017) [50]	Already discussed elsewhere in the paper.
	Mathcad	Antonova et al. (2017) [52]	Antonova et al. (2017) expressed that the efficient performance of the steam section does not affect the combined cycle gas turbine with a back-pressure steam turbine (CCGT-BP) heat efficiency as the bottoming cycle usually runs without cycle losses. Other than that, it has been observed that being a simple circuit of the plant due to the single-loop bottoming cycle and lack of steam reheating increases the CCGTBP reliability. It is seen that with increased pressure, even though the total capital investment remains virtually unchanged: at a pressure increase in the above range, it actually reduces by 0.73–0.75%. Hence, it is concluded by the authors that the technical and economic efficiency of CCGT-BP largely depends on the temperature chart of the heating system The entire modeling was made in "MathCad" software and tested in the special "Thermoflex" complex.
	MATLAB	Foxon et al. (2018) [53]; Machalek et al. (2020) [16]	Foxon et al. (2018) used a model of a generic raw sugar factory built in MATLAB Simulations proposed by Starzak and Davis (2017) [54] for varying values of the parameter for the extent of prime mover electrification, which showed many ways in which increasing the amount of electrification can be utilized to improve overall factory energy efficiency and fuel consumption.
	Microsoft Excel	Kamarudin et al. (2019) [44]	Already discussed elsewhere in the paper.

Table 5. *Cont.*

No.	Software	Authors	
	Petrosim	Atkins et al. (2017) [22]	Atkins et al. looked into various cases using PetroSim modeling software and found that there is a sensible economic rationale to utilize CHP in NZ. Any use of CHP involving fossil fuels will actually increase emissions. They claimed that, in the future, fossil fuel CHP would not displace thermal/fossil fuel generation but only displace low-emissions renewable generation. For other countries with higher grid emissions factors, the fuel type and marginal efficiency of generation need to be known to determine the emissions reduction potential of CHP.
	SimaPro	Contreras-Lisperguer et al. (2018) [28]	Already discussed elsewhere in the paper.
	Thermoflex	Palacios-Bereche et al. (2009) [39]; Antonova et al. (2017) [52]	Palacios-Bereche et al. (2009) performed an assessment for the cogeneration system of three different sugar cane plants. Even though the data of each cogeneration system were from the sugarcane plants, the assessment was accomplished from a simulation using THERMOFLEX software. Performance parameters show important differences in these systems due to the diverse technologies used in these plants. They mentioned that in comparison with the exergoeconomic analysis, the exergetic analysis presented values acceptable with respect to the literature.

2.7. Barriers to CHP Implementation

There are multiple beneficial aspects of CHP implementation in industry, mainly along the technical, economic and environmental metrics, as previously highlighted. However, it is somewhat paradoxical that there is also evidence that CHP adoption targets have not been achieved (Gvozdenac et al. 2017) [30]. Svensson et al. (2019) [11] remarked that there are numerous papers highlighting the significant untapped potential in excess industrial heat, including in developed countries such as Sweden. This situation suggests that there are barriers preventing CHP adoption.

Gvozdenac et al. (2017) [30] found that ambiguous policies and incongruence among various regulatory directives on CHP contributed to the situation in the European context. Additionally, Irungu et al. (2017) [29] stated that high upfront capital costs are among the factors preventing CHP adoption in the cement industry in Kenya. Birru et al. (2018) [12] also identified the cost factor of modern equipment as a barrier and further noted that CHP application in the sugar industry is hindered since numerous traditional sugarcane mills were initially constructed to be self-sufficient and therefore do not have connections to the national grid. The authors added that the seasonal nature of sugarcane production prevents it from being a constant and reliable source for the electricity grid while also impacting the development economics and payback model. The factors highlighted here are important and should be considered as part of any CHP proposal for both the greenfield and retrofit scenarios.

This review of the literature provided a broad and comprehensive understanding of energy efficiency research areas in recent years. Further research in CHP will contribute towards limiting climate change, maintaining energy security and improving industrial economic performance—this contribution will be valid not just across international borders but also across industrial segments.

3. Research Gaps

Three research gaps were identified during this review—firstly, the demand for industrial case study information, which can be used to develop and validate generic and broader models. The issue of limited data availability is apparent even in industrialized countries. Secondly, the limited comparability of case study data implies the need for the inclusion of a standardized case study scenario in future studies (for example, by assuming standardized ambient conditions for the particular industrial plant) in addition to the core case study. Thirdly, the limited information currently available on energy efficiency case studies in the Malaysian industry.

4. Conclusions

This paper recommends and justifies the basis for further case studies to be performed on CHP applications in Malaysian industries to address the research gaps related to broader data availability on CHP in industrial applications, the comparability of results from these studies and provide additional case studies data with a Malaysian context.

The literature review considered international and regional publications, which were then filtered to select topics oriented toward energy-intensive industries present in Malaysia—these included the petrochemical/refining, palm oil, sugar, cement, food, paper and textile industries. Research trends of interest in industrial CHP include the application of biomass fuels, a network approach to using excess industrial heat and advanced numerical methods to optimize CHP configurations.

Further case studies will not only benefit the industrial plants involved by reducing energy intensity and costs but also encourage cooperation between industry players and academia by providing valuable references for future benchmarking and research work. From a broader perspective, the CHP application will enhance technical performance and economic competitiveness in the Malaysian industry and improve energy security in Malaysia by reducing fossil fuel consumption while reducing the environmental footprint due to greenhouse gases.

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References

1. International Energy Agency (IEA). *IEA Energy Efficiency*; International Energy Agency: Paris, France, 2018.
2. *Industrial Sector Energy Consumption*; US Energy Information Administration (US EIA): Washington DC, USA, 2016; Chapter 7.
3. Malaysian Energy Commission (MEC). *Malaysia Energy Information Hub*; MEC: Putrajaya, Malaysia, 2018. Available online: https://meih.st.gov.my/statistics (accessed on 20 February 2020).
4. Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC) Malaysia: Putrajaya, Malaysia, 2015. Available online: https://www.mestecc.gov.my/web/wp-content/uploads/2019/04/13.-National-Energy-Efficiency-Action-Plan-english-only.pdf (accessed on 10 February 2020).
5. Malaysian Energy Commission (MEC). *Malaysia Energy Information Hub—Energy Commission*; MEC: Putrajaya, Malaysia, 2019. Available online: https://meih.st.gov.my/documents/10620/c7e69704-6f80-40ae-a764-ad0acf4a844d (accessed on 15 March 2020).
6. BoroumandJazi, G.; Rismanchi, B.; Saidur, R. A review on exergy analysis of industrial sector. *Renew. Sustain. Energy Rev.* **2013**, *27*, 198–203. [CrossRef]
7. Rahman, S.; Noman, A.H.; Shahari, F.; Aslam, M.; Gee, C.S.; Isa, C.R.; Pervin, S. Efficient energy consumption in industrial sectors and its effect on environment: A comparative analysis between G8 and Southeast Asian emerging economies. *Energy* **2016**, *97*, 82–89. [CrossRef]
8. *Catalog of CHP Technologies*; United States Environmental Protection Agency (US EPA): Washington, DC, USA, 2017.
9. Athawale, R.; Felder, F.A.; Goldman, L.A. Do Combined Heat and Power plants perform? Case study of publicly funded projects in New York. *Energy Policy* **2016**, *97*, 618–627. [CrossRef]
10. *The Opportunity for CHP in the United States*; ICF International: Fairfax, VA, USA; American Gas Association (AGA): Washington, DC, USA, 2013.
11. Svensson, E.; Morandin, M.; Harvey, S. Characterization and visualization of industrial excess heat for different levels of on-site process heat recovery. *Int. J. Energy Res.* **2019**, *43*, 7988–8003. [CrossRef]

12. Birru, E.; Erlich, C.; Martin, A. Energy performance comparisons and enhancements in the sugar cane industry. *Biomass Convers. Biorefinery* **2018**, *9*, 267–282. [CrossRef]
13. Frangopoulos, C.A. A method to determine the power to heat ratio, the cogenerated electricity and the primary energy savings of cogeneration systems after the European Directive. *Energy* **2012**, *45*, 52–61. [CrossRef]
14. Al Moussawi, H.; Fardoun, F.; Louahlia-Gualous, H. Review of tri-generation technologies: Design evaluation, optimization, decision-making, and selection approach. *Energy Convers. Manag.* **2016**, *120*, 157–196. [CrossRef]
15. Segurado, R.; Pereira, S.; Correia, D.; Costa, M. Techno-economic analysis of a trigeneration system based on biomass gasification. *Renew. Sustain. Energy Rev.* **2019**, *103*, 501–514. [CrossRef]
16. Machalek, D.; Henning, M.; Mohammadi, K.; Powell, K.M. Economic and environmental impacts of a non-traditional combined heat and power system for a discrete manufacturing facility. *J. Clean. Prod.* **2020**, *265*, 121816. [CrossRef]
17. Kavvadias, K.C.; Tosios, A.P.; Maroulis, Z.B. Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis. *Energy Convers. Manag.* **2010**, *51*, 833–845. [CrossRef]
18. Shabbir, I.; Mirzaeian, M. Feasibility analysis of different cogeneration systems for a paper mill to improve its energy efficiency. *Int. J. Hydrogen Energy* **2016**, *41*, 16535–16548. [CrossRef]
19. Mane, S.D. Cogeneration in Indian Sugar Industry: A Review. *Int. J. Sci. Eng. Appl. Sci. (IJSEAS)* **2016**, *2*, 30–40.
20. Yin, Y.; Ma, Z.; Nong, G.; Wang, S. Strategies of energy management in a cassava starch plant for increasing energy and economic efficiency. *J. Clean. Prod.* **2019**, *234*, 1296–1305. [CrossRef]
21. Watanabe, M.D.; Morais, E.R.; Cardoso, T.F.; Chagas, M.F.; Junqueira, T.L.; Carvalho, D.J.; Bonomi, A. Process simulation of renewable electricity from sugarcane straw: Techno-economic assessment of retrofit scenarios in Brazil. *J. Clean. Prod.* **2020**, *254*, 120081. [CrossRef]
22. Atkins, M.J.; Walmsley, T.G.; Philipp, M.; Walmsley, M.R.; Neale, J.R. Carbon emissions efficiency and economics of combined heat and power in new zealand, Chemical Engineering Transactions. *AIDIC Ital. Assoc. Chem. Eng.* **2017**, *61*, 733–738. [CrossRef]
23. Booneimsri, P.; Kubaha, K.; Chullabodhi, C. Increasing power generation with enhanced cogeneration using waste energy in palm oil mills. *Energy Sci. Eng.* **2018**, *6*, 154–173. [CrossRef]
24. Chen, C.-L.; Lin, C.-Y.; Lee, J.-Y. Retrofit of steam power plants in a petroleum refinery. *Appl. Therm. Eng.* **2013**, *61*, 7–16. [CrossRef]
25. Tantisattayakul, T.; Soontharothai, J.; Limphitakphong, N.; Pharino, C.; Chavalparit, O.; Kanchanapiya, P. Assessment of energy efficiency measures in the petrochemical industry in Thailand. *J. Clean. Prod.* **2016**, *137*, 931–941. [CrossRef]
26. Pirmohamadi, A.; Ghazi, M.; Nikian, M. Optimal design of cogeneration systems in total site using exergy approach. *Energy* **2019**, *166*, 1291–1302. [CrossRef]
27. Birru, E.; Erlich, C.; Herrera, I.; Martin, A.; Feychting, S.; Vitez, M.; Abdulhadi, E.B.; Larsson, A.; Onoszko, E.; Hallersbo, M.; et al. A Comparison of Various Technological Options for Improving Energy and Water Use Efficiency in a Traditional Sugar Mill. *Sustainability* **2016**, *8*, 1227. [CrossRef]
28. Contreras-Lisperguer, R.; Batuecas, E.; Mayo, C.; Díaz, R.; Pérez, F.J.; Springer, C. Sustainability assessment of electricity cogeneration from sugarcane bagasse in Jamaica. *J. Clean. Prod.* **2018**, *200*, 390–401. [CrossRef]
29. Irungu, S.N.; Muchiri, P.; Byiringiro, J.B. The generation of power from a cement kiln waste gases: A case study of a plant in Kenya. *Energy Sci. Eng.* **2017**, *5*, 90–99. [CrossRef]
30. Gvozdenac, D.; Urošević, B.G.; Menke, C.; Urošević, D.; Bangviwat, A. High efficiency cogeneration: CHP and non-CHP energy. *Energy* **2017**, *135*, 269–278. [CrossRef]
31. Sayyaadi, H.; Baghsheikhi, M. Retrofit of a steam power plant using the adaptive neuro-fuzzy inference system in response to the load variation. *Energy* **2019**, *175*, 1164–1173. [CrossRef]
32. Vellini, M.; Gambini, M.; Stilo, T. High-efficiency cogeneration systems for the food industry. *J. Clean. Prod.* **2020**, *260*, 121133. [CrossRef]
33. Zhang, B.J.; Xu, T.; He, C.; Chen, Q.L.; Luo, X.L. Material stream network modeling, retrofit and optimization for raw natural gas refining systems. *J. Clean. Prod.* **2017**, *142*, 3419–3436. [CrossRef]
34. Chen, H.; Xiao, Y.; Xu, G.; Xu, J.; Yao, X.; Yang, Y. Energy-saving mechanism and parametric analysis of the high back-pressure heating process in a 300 MW coal-fired combined heat and power unit. *Appl. Therm. Eng.* **2019**, *149*, 829–840. [CrossRef]
35. Tang, S.; Tang, G.; He, X.; Zheng, L.; Yu, C.; Xu, H. Research and Application of New Condensing Extraction Backpressure heating Technology of 330 MW Unit. In Proceedings of the 2nd International Symposium on Architecture Research Frontiers and Ecological Environment (ARFEE 2019), Guilin, China, 20–22 December 2019; Zhou, P., He, Y., Weerasinghe, R., Eds.; E3S Web of Conferences. EDP Sciences: Les Ulis, France, 2020; Volume 143, p. 2047. [CrossRef]
36. Zhang, T. Methods of Improving the Efficiency of Thermal Power Plants. *J. Phys. Conf. Ser.* **2020**, *1449*, 12001. [CrossRef]
37. Kamate, S.C.; Gangavati, P.B. Cogeneration in Sugar Industries: Technology Options and Performance Parameters—A Review. *Cogener. Distrib. Gener. J.* **2009**, *24*, 6–33. [CrossRef]
38. Ozturk, E.; Cinperi, N.C.; Kitis, M. Improving energy efficiency using the most appropriate techniques in an integrated woolen textile facility. *J. Clean. Prod.* **2020**, *254*, 120145. [CrossRef]
39. Palacios-Bereche, R.; Pereira, P.A.; Nebra, S.A.; Oliveira, C.; Rabi, J. Energetic evaluation of cogeneration systems in sugar cane plants in Brazil case studies. *Proc. ECOS* **2009**, *2009*, 449–458.
40. Bhagwat, S.S.; Pohekar, S.D. Thermal Analysis of Sugar Industry Boiler. *Int. J. Res. Sci. Eng. Technol.* **2017**, *4*, 1–3. [CrossRef]

41. Nandaliarasyad, N.; Maulana, D.T.; Darmanto, P.S. Study of Development Scenarios for Bottoming Unit Binary Cycle to Utilize Exhaust Steam from Back Pressure Turbine Geothermal Power Plant. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *417*, 12017. [CrossRef]
42. Raghu Ram, J.; Banerjee, R. Energy and cogeneration targeting for a sugar factory. *Appl. Therm. Eng.* **2003**, *23*, 1567–1575. [CrossRef]
43. Hasanbeigi, A.; Harrell, G.; Schreck, B.; Monga, P. Moving beyond equipment and to systems optimization: Techno-economic analysis of energy efficiency potentials in industrial steam systems in China. *J. Clean. Prod.* **2016**, *120*, 53–63. [CrossRef]
44. Kamarudin, N.; Yen, L.P.; Jusoh, N.W.C.; Ho, W.S.; Lim, J.S. Organic rankine cycle and steam turbine for intermediate temperature waste heat recovery in total site integration. *Malays. J. Fundam. Appl. Sci.* **2019**, *15*, 125–130. [CrossRef]
45. González-Díaz, A.; Alcaráz-Calderón, A.M.; González-Díaz, M.O.; Méndez-Aranda, A.; Lucquiaud, M.; González-Santaló, J.M. Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO_2 capture. *Energy* **2017**, *134*, 221–233. [CrossRef]
46. Forman, C.; Muritala, I.K.; Pardemann, R.; Meyer, B. Estimating the global waste heat potential. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1568–1579. [CrossRef]
47. Moser, S.; Lassacher, S. External use of industrial waste heat - An analysis of existing implementations in Austria. *J. Clean. Prod.* **2020**, *264*, 121531. [CrossRef]
48. Zhao, L.; Zhong, W.; Du, W. Data-Driven Robust Optimization for Steam Systems in Ethylene Plants under Uncertainty. *Processes* **2019**, *7*, 744. [CrossRef]
49. Zhang, W.; Gu, F.; Dai, F.; Gu, X.; Yue, F.; Bao, B. Decision framework for feasibility analysis of introducing the steam turbine unit to recover industrial waste heat based on economic and environmental assessments. *J. Clean. Prod.* **2016**, *137*, 1491–1502. [CrossRef]
50. Andiappan, V.; Ng, D.K.S.; Tan, R.R. Design Operability and Retrofit Analysis (DORA) framework for energy systems. *Energy* **2017**, *134*, 1038–1052. [CrossRef]
51. *SimaPro Database Manual*; SimaPro: Amersfoort, The Netherlands, 2020.
52. Antonova, A.; Vorobiev, A.; Uvarov, A. Technical and Economic Analysis of the Combined-Cycle Plant with Back-Pressure Steam Turbine. In Proceedings of the MATEC Web of Conferences—The Fifth International Youth Forum, Tomsk, Russia, 9–13 October 2017; Kozyreva, A.A., Zhdanova, A.O., Kuznetsov, G.V., Eds.; EDP Sciences: Les Ulis, France, 2017; Volume 141, p. 1024. [CrossRef]
53. Foxon, K.M.; Starzak, M. Upgrading the utility plant module for the generic sugar mill model. *Int. Sugar J.* **2018**, *91*, 294–309.
54. Starzak, M.; Davis, S.B. MATLAB® modelling of a sugar mill: Model development and validation. *Int. Sugar J.* **2017**, *119*, 442–452.