

Cogeneration plant with a low-temperature piston engine

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ABSTRACT

This paper studies the energy concert and economic feasibility of a moderate cogeneration system based on a low-temperature piston engine (LDP), with a particular focus on its potential use in decentralized rural areas. A thermodynamic model implemented in MATLAB is used to estimate system behavior, including electricity production, heat recovery, overall efficiency, and key economic indicators. The results suggest that the system is capable of generating approximately 195,000 kWh of electricity per year, while an additional 292,500 kWh of thermal energy may be recovered and used for practical applications. In this way, the total useful energy output is estimated to reach about 487,500 kWh annually. However, these values depend on the assumed operating conditions and the extent to which the recovered heat can be effectively utilized. From an economic standpoint, the combined use of electrical and thermal energy appears to play a significant role in reducing the overall cost of energy. Under the conditions considered in this study, the effective energy cost is estimated at around 0.072 €/kWh, with a payback period of approximately 3.8 years. It should be said that the given data may diverge reliant to issues such as petroleum fee, system procedure, and request outlines. Overall, the findings indicate that LDP-based CHP systems could represent a practical and potentially cost-effective solution for improving energy supply in rural and decentralized settings, particularly where both electrical and thermal demands are present.

Keywords: Combined heat and power, Low-temperature piston engine, Techno-economic analysis, Decentralized energy systems, Rural energy supply, Heat recovery, MATLAB modeling

1. Introduction

The provision of consistent energy in rustic zones remains to be a multifaceted subject, mainly due to incomplete organization and the raised prices related to spreading unified control networks. Seldom, current network organizations are either out-of-date or lacking, leading to loss of energy and unbalanced supply. Similarly, increasing the network to distant places is frequently problematic to validate economically, particularly when residents' concentration is small and request is detached [1].

Renewable energy foundations such as solar and wind are often measured as substitutes in these backgrounds. Though they give strong ecological profits, their requirement to weather conditions presents a grade of inconsistency that can touch stock dependability. As a consequence, there is a rising attention to resolutions that can offer not only sustainability but then likewise steadiness and constancy of energy stock [2]. This requirement has become even more marked in current years, as efforts to lessen relic petroleum dependency and edge environmental influences have strengthened. In this larger changeover, bioenergy has grown consideration as an applied possibility, chiefly in country locations where resident funds may be accessible [3].

Additionally, to contribute to energy stock, it can similarly sustain resident economic action and modification. Similarly, dispersed energy organizations (such as microgrids and limited joint heat and power (CHP) elements) are progressively observed as practical tactics for taming energy access and pliability. By dropping dependence on central organization, these structures can aid reinforce energy unconventionality while making prospects for local progress [5]. Amid regionalized resolutions, cogeneration (or united heat and power) is often emphasized as one of the more effective tactics. The rudimentary notion is comparatively frank: as an alternative of making electricity and heat distinctly, both are produced concurrently from a solitary energy foundation. In rehearsal,

this permits for a more actual usage of petroleum and decreases general energy losses, as likewise renowned in preceding revisions [6]. Relatively than discharging surplus heat into the atmosphere, CHP structures recuperate and recycle it, which leads to advanced general efficacy related to conservative systems. This idea is thoroughly connected with the central limits of thermodynamic progressions. Throughout electricity generation, not all produced energy can be transformed into valuable exertion, as pronounced by the 2nd law of thermodynamics [7].

A percentage of the energy is unavoidably vanished as high temperature. Yet, in CHP structures, this “missing” heat is taken and utilized in other requirements, such as space solar heating, domestic warm water, or industrial courses [8], [9]. A representative CHP system involves a main agent linked to a generator, lengthways with warmth exchangers that allow the recapture and usage of current energy [10]. The high-quality of main agent rest on system dimensions and request. Extensive systems often depend on condensation turbines or shared cycle arrangements, whereas minor setting up tend to practice core combustion engines or gas turbines [11], [12]. More currently, other machineries (counting microturbines, Organic Rankine Cycle (ORC) systems, and petroleum cells) have likewise been discovered, chiefly for dispersed applications [13], [14].

The key benefit of CHP systems in their aptitude to use petroleum more resourcefully. Meanwhile both electricity and heat are fashioned from a solitary input, general efficacy can upsurge meaningfully related to distinct generation systems, in some cases by about 35-40% [15]. This improved usefulness not lonely lowers petroleum consumption but can also lead to lesser statements and reduced ecological effect [16]. Additional incomes include trivial feast losses, improved steadiness, and better suppleness, mostly in regions with frail or undependable net links [17].

Policy frameworks and regulatory oversight likewise influence the financial feasibility of CHP systems. In many areas, incentives and energy strategies drive the adoption of high-efficiency cogeneration equipment [18]. For instance, under the European Directive 2004/8/EC, CHP systems are assessed based on primary energy reserves associated with specific manufacturing processes. Limited and micro-CHP systems are usually considered effective if they achieve positive energy returns, while larger systems are subject to more stringent standards [19], [20]. Such trials, together with fiscal inducements, can make CHP systems more popular, chiefly in rural settings [21].

Amid the diverse CHP machinery, low-temperature piston apparatuses (LDPs) have recently gained increasing attention as a potential solution for limited submissions [22]. In contrast to conservative systems, LDP machinery operates at comparatively low temperatures, making it appropriate for use with substandard heat sources that are frequently available in rural settings [23]. Their functional value lies in converting low-temperature thermal energy into mechanical work, which is then used to generate electricity. Previous studies suggest that LDP arrangements can operate under varying load conditions and be combined with renewable heat foundations [24], [25]. This plasticity is chiefly pertinent in reorganized environments, where energy demand may vary, and operating conditions are less predictable. In CHP forms, LDP systems similarly certificate heat to be used at varied temperature points, making them suitable for requirements such as domestic heating, interior warm water, and farm measures like greenhouse space heating. Likewise, to their applied structures, LDP systems have many practical profits.

These comprise comparatively modest strategy, lower functioning weights, and condensed keep necessities associated to more multifaceted machineries [26]. Their aptitude to uphold steady concert under variable circumstances further cares their appropriateness for distant or off-grid requests [27]. Furthermore, the option of consuming substitute fuels and sub-standard heat foundations upsurgences suppleness and can aid decrease requirement on conservative fossil fuels [28]. In this mode, LDP-based systems may donate to the wider changeover to low-carbon energy resolutions and abridged greenhouse gas releases [29]. Finally, a number of techno-economic studies have reported encouraging results for LDP-based CHP systems, particularly in rural applications, where both energy demand and resource availability create favorable conditions for their implementation [30], [31].

2. Method

2.1. System configuration

The proposed cogeneration system is based on a low-temperature piston engine (LDP) operating as the prime mover in a decentralized combined heat and power (CHP) configuration. The overall configuration of the CHP system is illustrated in Figure 1.



Figure 1. A schematic layout of the LDP-based combined heat and power (CHP) system

The system is designed to simultaneously generate electrical energy and recover useful thermal energy for heating applications, making it suitable for rural and off-grid environments [16, 17]. The main components of the system include the low-temperature piston engine, an electrical generator, heat recovery heat exchangers, and auxiliary subsystems such as cooling and control units. Provide sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described. Figure 1 illustrates the schematic layout of the low-temperature piston engine (LDP)-based combined heat and power (CHP) system considered in this study.

The system involves 4 key subsystems: the LDP apparatus, the electric generator, the warmth retrieval unit, and the electrical and thermal energy circulation units. The LDP apparatus functions as the major agent of the arrangement, where the chemical energy of the petroleum is transformed into automatic energy over a thermodynamic sequence improved for low-temperature procedure.

The automatic control shaped by the apparatus is straight diffused to the electric generator, which adapts it into electrical energy provided to local customers. Throughout the apparatus action, a noteworthy quantity of thermal energy is made in the form of consumed gases and engine coolant heat. As an alternative of being dissolute into the atmosphere, this surplus heat is seized by the heat retrieval part. As an alternative of being dissolute, this excess heat can be recovered and used over devoted heat exchangers, which is a main feature of limited rustic CHP systems [7].

The gained thermal energy is then shifted to a secondary fluid tour, creating valuable temperature in the form of warm water or low-temperature thermal energy appropriate for space heating and other country submissions. As exposed in Figure 1, the concurrent manufacture of electrical and thermal energy permits the CHP system to exploit fuel use and meaningfully upsurge general effectiveness.

The system arrangement proves that the LDP-based CHP resolution is chiefly suitable for dispersed energy manufacture, particularly in country surroundings where there is a parallel request for both electricity and thermal energy. Thermal energy free throughout apparatus process is gained at diverse temperature heights and complete to resident heat customers, such as housing structures, agrarian services, or cattle frame. Electrical energy produced by the system is chiefly proposed for on-site feeding, dropping broadcast losses and cumulative stock consistency [19]. The energy equilibrium and heat retrieval procedure are accessible in Figure 2.



Figure 2. Energy of the CHP system screening electrical production, improved heat, and losses

This shows the energy movement supply within the LDP-based joint heat and power (CHP) system. The diagram demonstrates how the chemical energy provided by the petroleum is transformed into valuable electrical and thermal productions, as well as the percentage of energy that is unavoidably lost throughout the alteration course [32].

As demonstrated in Figure 2, the contribution fuel energy is provided to the low-temperature piston apparatus, a fragment of it is transformed into automatic exertion and then changed into electrical energy over the generator. The electricity shaped embodies an important share of the entire energy involvement and is transported straight to resident handlers, supporting reorganized power generation. Similarly, a substantial percentage of the involved energy is recovered in the form of valuable heat.

Such thermal energy is mostly pull out from the used gases and the engine refrigeration system, afterward which it is shifted to a heat retrieval part. The recovered heat can be useful for numerous low-temperature usages, such as space heating, internal warm water making, and agrarian doings, all of which are distinctive energy difficulties in rustic zones [33]. The presentation of the system is assessed by means of a thermodynamic model advanced in MATLAB. The study is supported under steady-state settings, smearing frame and energy equilibrium equivalences to each system constituent, subsequent to typical thermodynamic modelling performs [7].

Electrical production is considered grounded on the automatic power produced by the piston engine and transported to the generator, taking into justification both automatic and electrical proficiencies. Figure 3 demonstrates the energy version and retrieval procedures inside the LDP-based CHP system. The higher unit represents the engine part, while the lesser graphic demonstrations the circulation of energy currents, counting electricity cohort, improved thermal energy, and system losses. This shared representation aids to visualize both the physical shape of the organization and its thermodynamic behavior [34]. The energy current shown in Figure 3 defines how the involvement fuel energy is spread amongst electricity generation, valuable thermal energy, and unavoidable losses.

This relationship can be expressed over an over-all energy equilibrium calculation, where the petroleum involvement is alienated into electrical production, recovered heat, and lost energy mechanical indulgence and heat losses to the atmosphere.

$$E_{fuel} = E_{elec} + E_{th} + E_{loss}. \quad (1)$$

The sum of healthier current vigor is determined by assessing the heat replaced through the refrigeration system and related heat exchangers. This tactic is constant with practices described in preceding revisions on CHP systems for rustic requests [22].

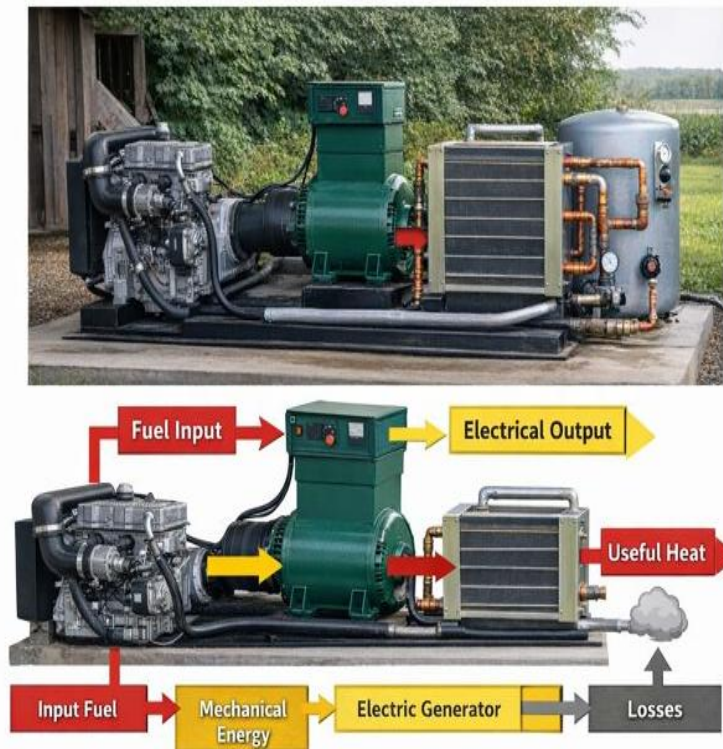


Figure 3. Energy current circulation in the LDP-based CHP system, joining the apparatus item with a schematic depiction of energy translation and heat regaining courses

The general efficacy of the system is distinct as the relation amid entire valuable energy production (electricity and heat) and the entire petroleum energy input [35]. To make simpler the examination while upholding sensible exactness, numerous expectations are accepted, counting stable functioning situations, continuous fuel assets, and slight heat wounded outdoor the retrieval system. Such molds are usually used in initial presentation assessments of CHP systems [36]. Current study also highpoints that high functioning hours and actual use of improved heat are important issues manipulating the economic presentation of dispersed CHP systems in rustic zones [37].

2.1.1. Electrical energy request

In rustic zones, electricity request is mostly related to ordinary domestic doings, counting lighting, elementary applications, water driving, and small agrarian apparatus [38], [39]. Over-all, daily electricity ingesting per domestic inclines to fall within 3 to 6 kWh, while this can differ dependent on active values, the number of applications in usage, and cyclic settings [40]. For the resolutions of this paper, a characteristic group of country handlers is measured, uniting housing request with small agrarian loads.

The request shape is presumed to persist comparatively steady over the development of the day, with an obvious upsurge throughout evening times, when most domestic doings naturally happen. Resident electricity generation over cogeneration can decrease dependence on central network organization, as well as on diesel generators, which are still extensively utilized in distant zones [41].

While diesel-based organizations propose an applied short-term key, they are often related to high petroleum prices and ecological worries [42]. In this background, dispersed generation may offer a more maintainable substitution. New scholarships likewise propose that the usage of demand-side organization policies and prognostic load arrangement can advance general system presentation [43], [44].

Though, the degree of these enhancements hinge on how successfully such tactics are applied in rehearsal [45]. Additionally, when reusable sources such as sun and wind are combined, their inconsistency requests to be measured prudently, as it may impact system constancy and steadfastness [46].

2.1.2. Thermal energy request

Thermal energy request characterizes an important part of entire energy use in rustic parts, mainly in areas with moderate or cooler temperatures. Under such circumstances, warmth is mostly compulsory for central heating, domestic warm water, and preserving appropriate inside settings in cattle conveniences [17].

Cattle constructions, for instance, frequently necessitate comparatively steady temperature environments to provide animal well-being and yield. For this aim, an incessant and consistent heat source turn out to be a significant issue in general system routine [24]. In this paper, the thermal energy got from the LDP-based system is measured appropriate for such requests, as it naturally works within a temperature variety of around 40-70 °C [47], [48].

Preceding study specifies that CHP systems functioning within this temperature variety can advance general energy productivity and decrease key energy ingesting. Steel, real presentation may hinge on how reliably the improved heat is utilized through the year [25]. When CHP systems are joint with reusable energy bases, such as sun or wind, extra consideration is compulsory to accomplish inconsistency and guarantee a steady energy stock [50].

2.1.3. Warm water request for housing and agricultural customs

Warm water request is additional significant constituent of energy usage in country households and agrarian doings. It is characteristically compulsory for everyday domestic requirements, as well as hygiene and housework, as well as for livestock-related procedures. On usual, warm water use in country households is assessed to variety between 30 and 50 liters per individual per day, typically at temperatures of about 45-55 °C [39].

These standards, can differ reliant to home size, practice behaviors, and seasonal aspects. In the proposed system, hot water demand can be met by utilizing thermal energy recovered from the engine cooling system and exhaust gases through heat exchangers. This approach reduces the need for additional fuel specifically for water heating, which in turn contributes to improving overall system efficiency. Such integration of heat recovery for water heating purposes has been widely discussed in the literature on small-scale CHP systems, where it is generally considered a practical way to increase energy utilization [17]. Nevertheless, the actual benefit depends on the consistency of hot water demand and the operating conditions of the system [51].

2.1.4. Representative rural energy demand scenario

Based on the above considerations, a representative rural energy demand scenario is defined for the performance evaluation of the LDP-based CHP system. Similar demand-based approaches have been adopted in previous studies focusing on decentralized CHP systems for rural and off-grid applications [40], [52] (Table 1).

Table 1. Representative rural energy demand profile

Energy demand type	Application	Typical demand
Electrical	Residential lighting and appliances	Low-moderate
Electrical	Agricultural equipment	Low
Thermal	Space heating (houses)	Moderate
Thermal	Livestock housing	Moderate-high
Thermal	Domestic hot water	Moderate

This representative demand profile allows for a realistic assessment of the system's ability to simultaneously meet electrical and thermal needs in rural environments. The defined energy demand parameters are used as inputs in the MATLAB-based model to evaluate system performance, energy efficiency, and economic viability under decentralized operating conditions [53].

2.2. MATLAB model application

The thermodynamic relations relating to the LDP-based CHP system are applied in MATLAB by means of a segmental modelling method, which permits flexible restriction modification and sensitivity analysis. Each system constituent is characterized as a distinct computational component, making it conceivable to assess diverse working setups and other arrangements [36], [54].

The general design technique is demonstrated in Figure 4, which summarizes the assembly of the numerical model utilized in this paper.

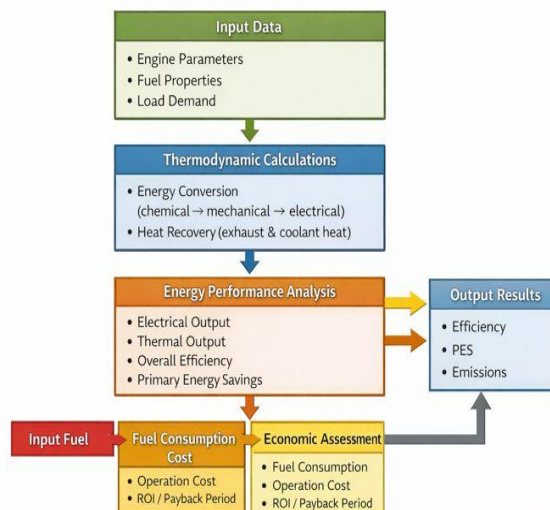


Figure 4. Computational flow diagram of the MATLAB-based model utilized for assessing the LDP-CHP system, counting energy change procedures, heat retrieval, and financial presentation valuation

The flow chart displays the order of controls, opening from the description of effort limits such as engine features, fuel assets, and energy request shapes. These contributions are managed within the thermodynamic segment, where the change of petroleum energy into mechanical and electrical production is assessed, lengthways with the assessment of recoverable heat from exhaust gases and the refrigeration system.

The data found are then moved to the energy presentation unit, where main pointers such as electrical production, improved thermal energy, general competence, and main energy investments (PES) are intended. Then, these pointers are used within the fiscal module to evaluate fuel ingesting, functioning prices, and investment-related limits. In the concluding phase, the production module accumulates the main data, counting efficacy standards, PES, and release discount potential, which are further debated in the Results segment.

The relations amongst modules, signified by missiles in Figure 4, exemplify the rational arrangement and interconnectedness of the computational stages. This organized method allows a complete assessment of both

practical and financial features, making the model appropriate for dispersed rustic energy requests. The model contributions comprise fuel energy contribution, engine functioning temperature, mechanical and generator competences, as well as heat exchanger success. The chief presentation pointers are resulted by means of average productivity meanings. Electrical efficacy is articulated as the relation amid produced electricity and fuel contribution, while thermal efficacy signifies the share of recovered heat comparative to the similar contribution. The general system efficacy is considered as the amount of these two donations. Totaling, main energy investments (PES) are assessed by likening the fuel ingesting of the CHP system with that compulsory for distinct making of electricity and heat [55].

All these relations are applied within the MATLAB model, which has contribution statistics such as apparatus limits, fuel features, and consignment outlines to make energy and financial productions. Also, MATLAB is utilized to make parametric studies, permitting study of how fluctuations in operating circumstances impact electricity making, heat retrieval, and general efficacy, chiefly under mutable rustic request circumstances [17].

2.2.1. Bases of waste heat in the LDP-CHP system

In the examined LDP-based cogeneration system, waste heat is mostly made from three causes: exhaust gases, the apparatus refrigeration system, and trivial supplementary losses. Amongst these, the exhaust stream and refrigeration course characterize the most important and nearly recoverable heat foundations, whereas supplementary losses are characteristically not recoverable due to their low temperature or system limits [25].

The exhaust gases sendoff the apparatus comprises a considerable volume of thermal energy at reasonable temperature points, which can be efficiently improved by means of heat exchangers [56].

Similarly, the heat free over the refrigeration system can be seized and moved to a subordinate heat supply loop. These retrieval methods are extensively useful in small- and medium-scale CHP systems and have been exposed to meaningfully improve general system presentation.

2.2.2. Heat retrieval and supply

The recovered heat is removed to a subordinate fluid over heat exchangers fitted in both the used and freezing tours. This energy is then transported to termination handlers as warm water or low-temperature heat, dependent on the claim. Distinctive stock temperatures vary from 40 to 70 °C, which are appropriate for space heating, local warm water, and cattle conveniences in rural zones [8].

Inside the MATLAB model, the sum of recoverable heat is considered by means of energy equilibrium calculations joint with heat exchanger efficiency limitations. The entire non-use heat is expressed as the quantity of contributions from the exhaust gases and the freezing system:

$$Q_{rec} = Q_{exh} + Q_{cool}, \quad (2)$$

where Q_{exh} denotes the heat extracted from the exhaust gases, and Q_{cool} denotes the heat obtained from the freezing system. This design permits a clear assessment of each source's input to the overall thermal production.

2.2.3. Use of recovered heat in rustic requests

A recovered thermal energy is chiefly utilized in requests necessitating low-temperature heat, which are mutual in rustic surroundings. Space heating characterizes a main part of request, particularly throughout cooler seasons, while cattle conveniences necessitate incessant heat supply to uphold appropriate interior circumstances [24]. Additionally, the system ropes local hot water making, dropping the necessity for distinct heating components such as boilers or electric heaters. This leads to inferior fuel ingesting and abridged working prices. Preceding scholarships authorize that mixing hot water making into CHP systems advances both competence and financial presentation [39].

Agrarian requests, counting hot house heating, harvest drying, and housework processes, can likewise advantage from the obtainable thermal energy. The suppleness of the LDP-based system lets real usage of heat crossways dissimilar subdivisions, minimalizing energy waste through the year [18].

2.2.4. Influence on energy efficacy and main energy reserves

The real usage of left-over warmth theatres a dominant role in refining both general competence and main energy investments. By using heat that would then be misplaced, the system upsurges the sum of valuable

energy gotten from the similar fuel involvement. The general efficacy can be articulated as the sum of electric and thermal competences [57]:

$$\eta_{overall} = \eta_{el} + \eta_{th}. \quad (3)$$

This groundwork is consistent with normal CHP valuation approaches and managerial senses of high-efficiency cogeneration [19]. Main energy reserves occur when recovered heat substitutes energy that would then be produced by conservative systems such as boilers.

Though the outcomes propose high efficacy, this may be contingent sturdily on functioning circumstances, chiefly fuel inconsistency. CHP systems can attain energy reserves of about 30-40% likened to distinct making [26].

2.2.5. Incorporation with MATLAB-based presentation investigation

The waste heat retrieval policy is fully cohesive into the MATLAB-based model advanced in this paper. The model assesses the sum of recoverable heat below diverse operating situations and likens it with the thermal request characteristic for rustic users.

Parametric studies are carried out to scrutinize how distinctions in apparatus consignment and recovery effectiveness touch thermal production and general system presentation.

By including heat recovery right into the modelling outline, it is preserved as an essential component of system action rather than a subordinate feature. This method guarantees a more truthful picture of CHP presentation in dispersed surroundings and provides both technical and financial study [7]. Furthermore, well-organized usage of recovered heat donates to dropping the price of useful energy, taming the economic feasibility of the organization.

2.3. Energy and financial presentation pointers

A system presentation is assessed by means of main energy pointers, counting electrical efficacy, thermal efficacy, general efficacy, and main energy investments. Prime energy reserves are considered by linking the CHP system with conservative separate group of electricity and heat, subsequent to recognized practices [35]. The financial presentation is measured through pointers such as yearly investments, decrease in working prices, and reimbursement period.

These systems of measurement offer a strong foundation for assessing the viability of LDP-based CHP schemes, chiefly in rustic settings where dispersed resolutions can propose important rewards [33]. Preceding scholarships have likewise emphasized that small- and medium-scale CHP technologies, particularly those using low-temperature heat bases, hold substantial potential in contemporary energy arrangements [37]. Figure 5 shows both the real LDP engine combined within the CHP organization and a basic thermodynamic picture of its working cycle.

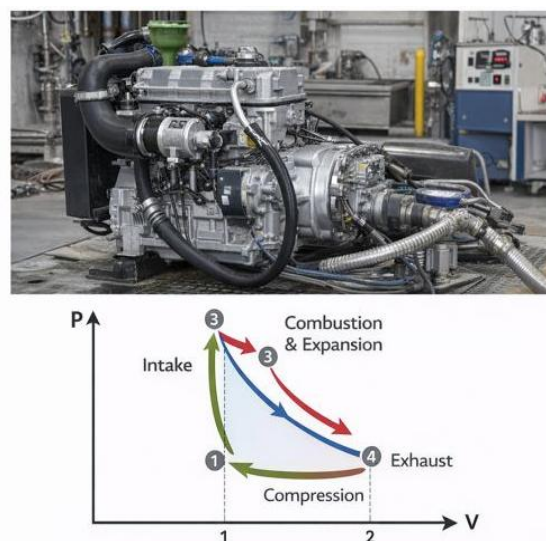


Figure 5. A thermodynamic design of the LDP operating sequence, screening the chief phases of energy change during piston process

The higher portion of Figure 5 displays the physical apparatus, while the inferior unit exemplifies the main stages of the piston procedure, counting consumption, density, burning, development, and use.

The thermodynamic performance of the system is branded over distinctive diagrams (such as P–V or T–s), which capture the essential energy modifications in the course.

These variations can be expressed by the energy symmetry sums:

$$Q_{in} - Q_{out} = W_{net}, \quad (4)$$

where Q_{in} represents the heat input throughout burning, Q_{out} represents the heat lost through cooling and exhaust, and W_{net} is the net mechanical work of the generator.

This shared picture offers a strong connexion within the physical device progression and the thermodynamic exhibiting background utilized in the reproductions. It shows how chemical energy from the petroleum is altered into mechanical making and recoverable thermal energy, branding the base for system performance valuation. Such visualization shows the functioning of low-temperature piston apparatus performance in CHP applications and provides the explanation of effectiveness and energy steadiness marks.

Prior papers on micro-CHP technologies have recognized their aptitude to reach computable energy reserves and CO₂ releases reduction, essentially in detached rural systems [40]. By linking Figures 3, 4, and 5 with the reliable leading calculations, the strategic process creates a consistent and see-through analytical background, ensuring replicability in both energy and fiscal assessments.

2.4. Economic examination

The financial practicability of the projected LDP-based CHP system is assessed over an inclusive price–benefit tactic that reflects both electricity and heat manufacture.

In dispersed rural requests, financial routine plays a serious role, as investment pronouncements are sturdily predisposed by fuel savings, functioning prices, and the predictable reimbursement period.

By proficiently using recovered waste heat, the system decreases the general price of carried energy (€/kWh) and recovers asset revenues, making it an applied resolution for real-world application [18].

2.4.1. Price structure of the LDP-CHP system

The full price of the CHP system is divided into capital expenses (CAPEX) and working expenses (OPEX), resulting in average performs in techno-economic valuations of cogeneration systems [10].

CAPEX contains the primary asset essential for system connexion, top key mechanisms such as the LDP engine, electrical generator, heat exchangers, secondary subsystems (counting with refrigeration and regulator components), as well as connexion and commission prices.

OPEX characterizes the frequent incidentals related with system operation, with fuel use, preservation doings, labor, and supplementary electricity usage. In rural settings, the accessibility of resident fuels or remaining energy bases can meaningfully reduce fuel-related prices, thereby taming the general economic attractiveness of the system [37].

2.4.2. Yearly energy production

The whole yearly energy production of the CHP system comprises both electrical and thermal mechanisms. Grounded on the MATLAB model, yearly electricity and heat generation are considered by means of the next formulas:

$$E_{el, year} = P_{el} \cdot hop; E_{th, year} = Q_{rec} \cdot hop, \quad (5)$$

where P_{el} denotes electrical power production, Q_{rec} denotes recovered thermal power, and hop refers to yearly operating hours.

The entire useful energy is consequently got as:

$$E_{tot, year} = E_{el, year} + E_{th, year}. \quad (6)$$

This design guarantees that all valuable energy streams, with space heating and local hot water stock, are measured in the economic calculation.

The replication context allows for correct assessment of yearly presentation under changing operating circumstances, constant with similar CHP studies [7].

2.4.3. Fee of useful energy (€/kWh)

The fee of valuable energy is a chief pointer for assessing the competitiveness of the CHP system associated to predictable energy source possibilities. It is defined as:

$$C_{energy} = C_{annual} / E_{tot, year}, \quad (7)$$

where C yearly embraces all yearly fees, such as fuel expenses, procedure and conservation, and investment recovery.

For assessment resolutions, the fee of electricity-only production can be articulated as:

$$C_{el} = C_{annual} / E_{el, year}. \quad (8)$$

The occurrence of thermal energy meaningfully decreases the actual fee per unit of energy, meanwhile both electricity and heat are shaped from the similar fuel involvement. This benefit is chiefly applicable in country zones, where thermal request is unceasing and can be resourcefully met by means of recovered heat.

Prior papers postulate that micro-CHP systems with heat retrieval can cut overall energy charges by up to 30%, representing the economic advantage of cogeneration [17].

2.4.4. Comparison with separate energy production

To better assess the economic performance of the CHP system, it is compared with a conventional approach based on separate generation of electricity and heat. In such cases, electricity is typically supplied by the grid or diesel generators, while heat is produced using standalone boilers.

The full yearly price of isolated making is demarcated as:

$$C_{sep} = C_{el, sep} + C_{th, sep}, \quad (8)$$

where $C_{el, sep}$ denotes the price of electricity, and $C_{th, sep}$ denotes the price of heat production.

The fiscal benefit of the CHP system is assessed through yearly savings, intended as:

$$S_{annual} = C_{sep} - C_{CHP}, \quad (9)$$

where a positive value of S_{annual} designates that the CHP system is more price-effective.

Practically it confirms that important price discounts can be attained when recovered heat is efficiently applied, particularly in dispersed requests [24], [25].

2.4.5. Reimbursement period

The reimbursement period signifies the time compulsory to recuperate the initial asset grounded on yearly funds. It is considered:

$$PB = C_{APEX} / S_{annual}. \quad (10)$$

A temporary repayment period designates more attractive benefit forecasts.

In country CHP systems, the fee period is inclined by issues such as fuel fee, yearly functioning hours, and the effectiveness of heat retrieval. Furthermore, policy inducements and care mechanisms for high-efficiency or renewable-based organizations can further loan economic practicability [20].

2.4.6. Economic proposals for rural requests

The economic valuation legalizes that the projected LDP-based CHP system offers strong financial incomes for rustic users. By simultaneously making electricity and by means of recovered heat for domestic heating, local hot water, and agrarian requests, the system meaningfully decreases the general fee of energy. This leads to inferior energy expenditures, improved energy autonomy, and improved pliability of country energy systems.

The integration of economic inspection within the MATLAB model guarantees transparency and reproducibility, letting the process to be transformed to diverse country setups and supportive informed decision-making.

3. Results and discussion

The results gotten from MATLAB reproductions display that an LDP-based shared heat and control system can offer a clear enhancement in overall recital likened to traditional systems where electricity and heat are produced separately. Under the investigated operational settings, the electrical effectiveness remnants within the distinctive range found in small-scale systems. From an applied viewpoint, LDP technology seems to be chiefly appropriate for low-temperature cogeneration requests. The practical routine is usually reliable with results found for comparable technologies, counting ORC-based systems [21].

For a more complete valuation of the system efficiency, core energy savings (PES) are utilized as a critical system of measurement. The planned PES standards are confident, representing that the system can meet the measures for highly effective cogeneration demarcated in European Directive 2004/8/EC. Related to distinct power generation, the system establishes a 35-40% decrease in main energy ingesting, though this figure may differ reliant to functioning settings.

This enhancement is mostly connected to the actual retrieval and inferior energy application, in link with preceding revisions on micro- and small-scale CHP systems [26]. Enhancements in energy effectiveness are likewise reproduced in energy productivity. By necessitating fewer usage of primary fuel, CO₂ releases per unit of supplementary heating can be condensed. This recommends that LDP-based CHP systems can be a part in supportive decarbonization efforts, particularly in requests where low-temperature electricity and heat are desirable, such as constructions or small trade amenities [29].

In totaling to effectiveness, the system offers precise applied advantages in compactly settled country locations. These comprise dipping broadcast losses and refining dependability, particularly in zones where feeble grid organization is more dominant. Similarly, some limits should be recognized. LDP technology is quickly developing, and queries persist about long-term presentation and optimization under explicit functioning circumstances. For this aim, it would be necessary to practice appropriate energy sources, as was also detected in current scholarships on developing CHP technologies [30].

The economic examination offers supplementary vision into the presentation of the system. As shown in Table 5, electricity produced on its own prices 0.116 €/kWh, while electricity shaped at an inferior price, around 0.058 €/kWh. When the two productions are joint, the operative price of energy effectiveness cuts to around 0.072 €/kWh. This determines the economic benefit of cogeneration, particularly in requests where there is a shared request for energy [24].

A contrast of revenue with age and gender displays a usual yearly revenue of €17,000. These investments are frequently related to condensed fuel ingesting and well-organized usage of the recovered heat. When taking preliminary prices into consideration, the assessed chief time is around 3.8 years, which is parallel to the variety stated in analogous scholarships on small-scale CHP systems in country settings [18]. Total, the outcomes propose that economic efficacy is thoroughly related to how competently renewable thermal energy is kept in the commerce.

3.1. Economic study results and MATLAB-based assessment

The economic assessment is grounded on constraints resulting from the thermodynamic model, joint with characteristic operating circumstances characteristic of country surroundings. The examination assumes continuous yearly functioning hours and complete use of recovered thermal energy, situations that are generally assumed in similar techno-economic revisions of small-scale CHP systems [31]. Table 2 displays the main technical and financial involvement strictures used in the MATLAB-based investigation.

Table 2. Chief economic and functioning input parameters

Parameter	Symbol	Value	Unit
Electrical power output	P_{el}	30	kW
Recovered thermal power	Q_{rec}	45	kW
Electrical efficiency	η_{el}	0.28	–
Thermal efficiency	η_{th}	0.42	–

Parameter	Symbol	Value	Unit
Overall efficiency	η_{overall}	0.70	–
Annual operating hours	η_{op}	6,500	h/year
Fuel cost	–	0.045	€/kWh _{fuel}
Discount rate	–	6	%

The system is similar to a micro-scale CHP unit with an electrical volume of 30 kW and a thermal recovery capacity of 45 kW, which are characteristic standards for country households and agrarian requests. A yearly functioning time of 6,500 hours is expected, reflecting comparatively constant and incessant energy request in rural zones. The selected fuel price of 0.045 €/kWh is related with locally accessible energy funds, while the expected general effectiveness of 70% highlights the rank of left-over heat retrieval in enlightening system performance. In practical terms, the system makes about 195,000 kWh/year of electricity and 292,500 kWh/year of recovered thermal energy, leading to a complete valuable energy making of 487,500 kWh/year (Table 3).

Table 3. Yearly energy production of the LDP-CHP system

Energy output	Symbol	Value	Unit
Electrical energy	$E_{\text{el, year}}$	195,000	kWh/year
Thermal energy (recovered)	$E_{\text{th, year}}$	292,500	kWh/year
Total useful energy	$E_{\text{tot, year}}$	487,500	kWh/year

A thermal energy shows approximately 60% of the entire production, emphasizing the leading role of heat retrieval in CHP systems intended for country requirements. Table 4 recapitulates the investment and working price structure of the system. The entire asset price is assessed at around 65,000 €, with the main donations pending from the LDP apparatus, generator, and heat retrieval mechanisms. Fuel charges reason for the major share of yearly functioning expenditures, representing that system presentation is highly subtle to fuel efficacy.

Table 4. Price structure of the LDP-CHP system

Component	Cost (€)
LDP engine	28,000
Generator	10,000
Heat exchangers	12,000
Control & auxiliaries	6,000
Installation & commissioning	9,000
Total CAPEX	65,000 €
Fuel	19,000
Maintenance	2,500
Auxiliary electricity	1,000
Total OPEX	22,500 €

From a financial viewpoint underscore the rank of exploiting left-over heat consumption, as it straightly decreases functioning prices and advances general economic presentation. Table 5 displays the considered fee of energy indicators for electricity, thermal energy, and total valuable energy. When electricity is measured as a separate production, the price impacts about 0.116 €/kWh, reflecting the influence of fuel ingesting and working prices characteristic of small-scale associations.

Table 5. Price of energy indicators

Indicator	Value	Unit
Cost of electricity only	0.116	€/kWh
Cost of thermal energy	0.058	€/kWh
Cost of total useful energy	0.072	€/kWh

In divergence, the price of recovered thermal energy is meaningfully inferior, about 0.058 €/kWh, representing the financial advantage of using left-over heat. When both productions are joint, the actual price of valuable

energy cuts to about 0.072 €/kWh. This decrease obviously demonstrates the benefit of cogeneration, where concurrent manufacture of electricity and heat leads to enhanced fuel use and inferior general prices.

From an economic viewpoint authorize that the financial feasibility of the system sturdily rests on on the beneficial usage of recovered thermal energy, chiefly in country zones with incessant heat request. Consequently, the joint energy price offers a more accurate percentage of system presentation than electricity-only pointers and assists as a main limitation for the reimbursement study. To further assess the financial profits of the planned system, the CHP shape is likened with a predictable scenario grounded on separate electricity making and heat making by means of a boiler. Table 6 distributes a comparative financial assessment amid the projected LDP-based CHP system and a traditional outline stuck on separate electricity and heat manufacture.

Table 6. Economic comparison	
Energy system	Annual cost (€)
Separate electricity + boiler	39,500
LDP-based CHP system	22,500
Annual savings	17,000 €

A significant remark is that display that the traditional tactic (characteristically concerning a separate generator joint with a boiler) brings to an advanced yearly operative price. This is generally due to augmented fuel consumption and the non-appearance of waste heat recovery.

In dissimilarity, the CHP system significantly reduces total energy costs by simultaneously generating electricity and utilizing the recovered thermal energy. The assessed annual savings of approximately 17,000 € clearly demonstrate the economic advantage of the proposed system, chiefly in rural environments where both electricity and heat are required throughout the year. These findings authorize that improved fuel utilization, which is inherent to cogeneration systems, directly interprets into lower operating costs. As a result, the CHP configuration represents a more efficient and sustainable alternative to separate energy production, providing the basis for the payback period analysis obtainable in the following section. Table 7 summarizes the estimated payback period of the proposed LDP-based CHP system, calculated based on the initial investment cost and the annual savings achieved compared to conventional energy production.

Table 7. Payback period	
Parameter	Value
Total CAPEX	65,000 €
Annual savings	17,000 €/year
Payback period	3.8 years

From an economic perspective, a total capital investment of approximately 65,000 €, combined with annual savings of about 17,000 €, results in a payback period of around 3.8 years. The payback period is determined using the following relation:

$$\text{Payback Period} = C_{APEX} / \text{Annual savings}. \quad (11)$$

Substituting the corresponding values:

$$\text{Payback Period} = 65,000 \text{ €} / 17,000 \text{ € per year}. \quad (12)$$

The relatively short recovery time falls within the range commonly reported for small-scale CHP systems in decentralized and rural applications. The favorable economic performance is mainly attributed to the efficient utilization of recovered waste heat, which reduces fuel consumption and operating costs. In addition, continuous demand for both electricity and heat in rural households and agricultural activities contributes to stable system operation and consistent economic outcomes.

Overall, the calculated payback period confirms the financial feasibility of the proposed system and supports its suitability as a sustainable solution for decentralized energy supply. Figure 6 demonstrates the delivery of the entire yearly valuable energy shaped by the system. Electricity accounts for about 195,000 kWh/year (40%), while improved thermal energy donates around 292,500 kWh/year (60%), subsequent to a total useful energy production of 487,500 kWh/year. Figure 6 highpoints the main share of thermal energy, accenting the rank of unused heat retrieval in attaining high general effectiveness.

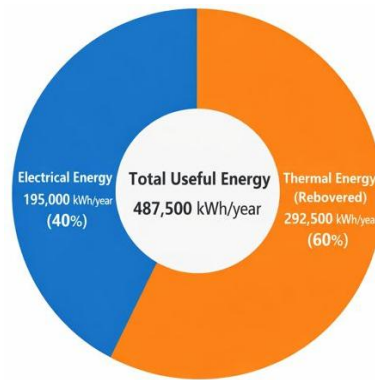


Figure 6. Supply of yearly valuable energy production

Figure 7 compares the prices of diverse energy production by the system.

An electricity-only making fallouts in a price of around 0.116 €/kWh, while thermal energy is provided at a meaningfully inferior cost of around 0.058 €/kWh. When both electricity and heat are measured together, the operative price of valuable energy reductions to about 0.072 €/kWh. Related to that the use of recovered heat plays a main part in dropping overall energy prices and taming system financial side.

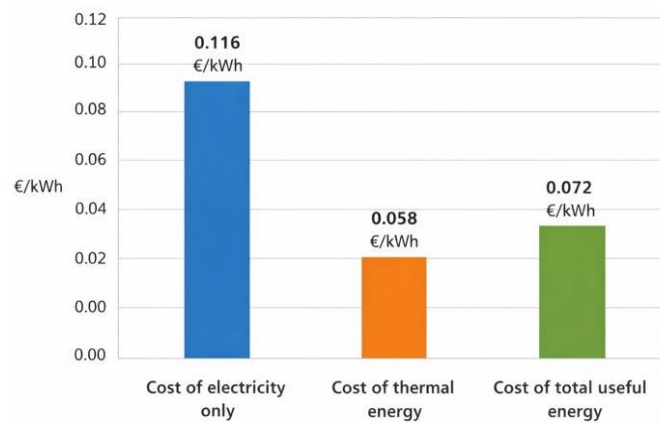


Figure 7. Assessment of energy prices

Figure 8 presents the estimated payback period of the LDP-based CHP system, based on the relationship between total investment cost and annual savings.

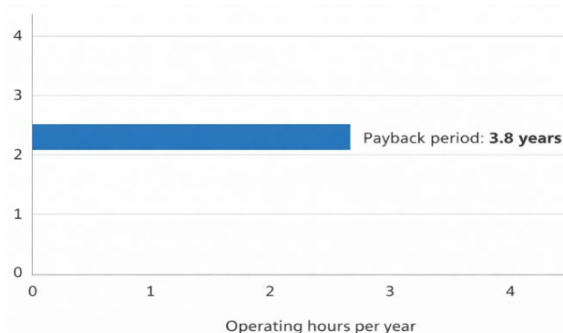


Figure 8. Reimbursement period of the CHP system

Figure 8 confirms that effective use of recovered thermal energy significantly improves economic performance by lowering both operating costs and the cost of useful energy. These results further support the suitability of the proposed system for decentralized rural applications.

3.2. Discussion of economic results and sensitivity considerations

From a financial viewpoint, the presentation of the projected LDP-based CHP system appears to hinge on powerfully on how efficiently the recovered heat is applied. Though the numerical data (Tables 3–6) designate a decrease in the general price of valuable energy, this consequence is thoroughly related to the statement that thermal energy is unceasingly utilized. If this state is not completely met in rehearsal, the financial assistances

may be fewer distinct. Comparable remarks have been stated in preceding scholarships, where the part of heat retrieval was recognized as a serious issue in defining system viability [17], [26]. A nearer aspect at the price structure proposes that fuel use leftovers the chief donor to functioning expenditures. This is not unforeseen, but it does highpoint a confident understanding of the system to petroleum value variations.

In actual situations, even reasonable variations in petroleum price or functioning times could affect the financial consequence more than the model might advocate. For this motive, the efficacy advances related with heat retrieval should be observed not as secure benefits, but as performance-dependent assistances that contrast with working settings [40], [41]. In rustic locations, where energy request is frequently dispersed crossways both electrical and thermal usages, the system seems to function more favorably. One conceivable clarification is that the concurrent request rises the probability that recovered heat will be utilized rather than missed.

Though, this supposition may not grip similarly crossways all periods. For instance, throughout heater stages, the request for thermal energy may cut, possibly touching general system efficacy. This cyclical inequity is likewise distinguished in other scholarships on dispersed CHP applications [18]. It is similarly worth observing that the current study is founded on a basic depiction of functioning settings. Even though this tactic is valuable to considerate wide-ranging tendencies, it unavoidably presents some limits. Real systems are topic to variations in consignment request, dissimilarities in user behavior, and working restrictions that are problematic to seizure in a numerical way. As debated in connected papers [43], [44], such features can lead to unconventionalities amid forecast and real presentation.

4. Conclusions

The results suggest that combining electricity generation with heat recovery can improve overall energy efficiency and reduce the cost of useful energy. Similarly, these enhancements seem to be contingent on how the system is worked and how successfully the recovered heat is utilized. One of the core explanations is that fuel ingesting lasts to be leading in defining economic presentation.

While the system displays a comparatively constructive reimbursement period under the expected circumstances, this result should not be understood without seeing conceivable dissimilarities in fuel value and energy request. Comparable assumptions have been strained in preceding scholarships, which highlight the rank of background when assessing CHP systems.

Further work, especially investigational authentication or ground application, would be essential to authorize the pertinence of the outcomes. Future study could likewise discover the influence of mixing renewable energy bases, such as sun or wind, into the system. This could theoretically advance both sustainability and longstanding economic presentation, though it would likewise familiarize supplementary difficulty in system process.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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