International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 22, Issue 5 (May 2026), PP 124-143

Optimization of Hydrogen Production Through Waste Gasification

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ABSTRACT
Globally, the two major environmental challenges faced are waste generation and dependency on fossil fuels. With the significant rise in industrialization and population, the quantities of both industrial and municipal waste have increased, while fossil fuels remain the dominant energy source. This challenge has created a need for sustainable waste management methods, along with advancements in the cleaning of alternative fuels.

Gasification tends to be a prominent solution for converting carbon-based waste material into a valuable synthetic gas, also called as syngas, which primarily consists of hydrogen(H_2), carbon monoxide (CO), carbon dioxide (CO_2) and methane (CH_4). This process enables the energy recovery in a more efficient and environmentally friendly manner, not only reducing the volume of the waste. Thus, the contribution to reduced greenhouse gas emissions had increased as the hydrogen extracted from syngas is a clean fuel, as it only produces water as its byproduct.

The thermochemical process of gasification, in which, under limited oxygen conditions, a carbonaceous feedstock is partially oxidized. The restricted oxygen supply ensures that the fuel is not fully burned, unlike in complete combustion, which allows the formation of combustible gases. The process involves different reactions, such as ***pyrolysis, drying, oxidation and reduction stages.*** *The process can be exothermic or endothermic depending upon the oxidizing agent used (Air, Oxygen or Steam). External heat input is required in steam gasification that results in higher hydrogen yield and better- quality syngas. The chemical process is not completely different from combustion, and the fact is that combustion reactions also occur during the gasification process.*

The project focuses on the integration of a waste gasification system with an existing heat plant, which optimizes hydrogen production. The study involves an analysis of the parameters like temperature, oxidizing agents, and it estimates hydrogen yield and system efficiency by mass and energy calculations. The overall objective is to calculate the feasibility of producing hydrogen from the waste as a sustainable alternative to the fossil fuel methods.

The system aims to reduce environmental impact, improve energy recovery and sustainable energy in the future.

Date of Submission: 01-05-2026 Date of acceptance: 09-05-2026

I. INTRODUCTION

The use of fossil fuels has been shown to cause global problems, both climate and environmental, but also political problems. Despite this, fossil fuels still play an important role in the world's energy society, which leads to an increase in greenhouse gas emissions. Another globally growing problem is waste. The population on Earth is steadily increasing, and in line with this, global consumption and thus the amount of waste are also increasing. One of the most common waste treatment methods in the world is landfill, which causes pollution to both air, soil and water, while requiring large areas of land. A functioning system where the energy in waste is recovered to heat and electricity in combined heat and power plants through combustion exists, but historically, the alternative has been landfill [1].

It is important that countries that have access to technology and financial resources conduct research into alternatives to fossil fuels, but also into waste treatment, in order to find new ways to extract and convert energy. A possible method for treating waste is gasification. In gasification, the waste is oxidized with limited or no access to oxygen, which avoids the traditional oxidation and combustion taking place. One of the products from gasification is hydrogen, which has a high energy content, which gives it the potential to be used as fuel.

A potential market where hydrogen is starting to take up more space is the vehicle market, which is increasingly demanding alternative fuels. Vehicles can be powered by fuel cells, where hydrogen is converted into electricity, which powers the car. The exhaust gases from the fuel cells are pure water. Fuel cells are a relatively new technology, but have, to some extent, started to be produced on a commercial scale. Much research and development is being done on fuel cells, and car brands such as Ford, Hyundai and Toyota plan to deliver fuel cell cars in the near future [2].

The main area of application of hydrogen today is in the petroleum industry, where it is extracted from fossil fuels, which means that innovative and alternative methods for hydrogen production are sought after [3].

1.2 PURPOSE & OBJECTIVES

The purpose of this work is to investigate whether hydrogen production is possible in a scenario where an existing heating plant, whose production is at a standstill for large parts of the year, is supplemented with a waste-fed gasification process. Furthermore, the purpose is also to be able to classify both the system as a whole and also the produced hydrogen based on EU directives and previous environmental permit applications, where waste is used as fuel in gasification processes.

The goal of the study is to estimate the possibilities of producing hydrogen from waste when a gasification process utilizes heat from a nearby heating plant. This is to be able to determine whether hydrogen production of this type is feasible, which, in that case, could replace today's hydrogen production from natural gas. This shall be carried out by carrying out energy and mass balances for the combined system, and based on this, calculate hydrogen, electricity and heat production, but also calculate how much fuel is used in the boiler.

II. LITERATURE SURVEY

2.1 GASIFICATION

Gasification is a chemical recovery method where the product is a synthetic gas, hereinafter referred to as product gas, which consists of hydrogen, carbon monoxide, methane and carbon dioxide. Smaller amounts of tar and coke are also created. Depending on the gasification parameters, the composition of the product gas and its ratio to tar and coke vary. The product gas that is formed can be used, among other things, to produce fuels such as biogas, diesel and hydrogen [4] or to drive gas turbines for heat and electricity production [5].

The gasification process can look different, but each process is based on gasifying a material through thermal treatment. This can take place in an oxygen-free environment without an oxidizing agent, pyrolysis, or together with an oxidizing agent such as air or steam.

The first type of gasification emerged during the 18th-century Industrial Revolution in England, when coal was gasified into "town gas", which was used for streetlamps and also as a light source in homes. With the introduction of the lamp, there was no longer any major use for gasification technology, and gasification fell into the shadows. It was not until the 1920s, with the introduction of new gasification technology, where oxygen could be effectively separated using cryogenic technology, that gasification again received attention [6].

In gasification, a carbonaceous fuel is oxidized to gas; this is done by thermal treatment and in a deficit of oxygen. The process is complex, during which several chemical processes such as cracking, oxidation, steam reforming, water-gas shift and methanization occur. Some of the reactions that occur can be seen in the equations below (1-8) [7]. Although complete combustion is avoided, some oxidation occurs through the combustion reactions (1-3). The most important reactions in gasification of a carbon-rich fuel are (1), (4), (5) and (6), which have different significance depending primarily on the oxidant [6].

The oxidant plays a major role in the energy consumption of gasification. In the gasification reactions (1-8), it can be observed that the reaction enthalpies, ΔHr, vary, where certain reactions require or release energy. When oxygen or air is used as the oxidant, the first combustion reaction (1) is considered to be the most important reaction, in which energy is released. If carbon dioxide (uncommon) or steam is used instead as the oxidant, energy must be added to the gasification process, as the Boudouard reaction (4) and the Water-gas reaction.
(5) are considered to be the main gasification reactions.
The benefit of this, however, is a product gas with a higher calorific value than if oxygen/air is used as the oxidizer [6] [8]. Of note is the Steam Reforming Reaction (8), which is the reaction used when hydrogen production is from natural gas and is the most common method for hydrogen production today [7].

Combustion reactions:

$$C + \frac{1}{2}O_2 \rightarrow CO \qquad \Delta H_r = -111\,\frac{MJ}{kmol} \qquad (1)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \qquad \Delta H_r = -283\,\frac{MJ}{kmol} \qquad (2)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad \Delta H_r = -242\,\frac{MJ}{kmol} \qquad (3)$$

The Boudouard reaction:

$$C + CO_2 \rightarrow 2CO \qquad \Delta H_r = -172\,\frac{MJ}{kmol} \qquad (4)$$

The water-gas reaction:

$C+H_2 \rightarrow CO+H_2$ $\Delta H_r = +131 \frac{MJ}{kmol}$ (5)

The methanation reaction

$C+2H_2 \rightarrow CH_4$ $\Delta H_r = -75 \frac{MJ}{kmol}$ (6)

The CO-shift reaction

$CO+H_2O \rightarrow CO_2+H_2$ $\Delta H_r = -41 \frac{MJ}{kmol}$ (7) Steam reforming reaction:

$CH_4+H_2O \rightarrow CO+3H_2$ $\Delta H_r = +206 \frac{MJ}{kmol}$ (8)

Typically, the material being gasified undergoes four stages, the first of which is drying to avoid unnecessary energy being spent on evaporating water. The remaining three are described in simplified form in Figure 1.

The first stage, pyrolysis, involves the thermal decomposition of large complex molecules into smaller gas molecules, tar and coke [9]. In the next stage, the pyrolysis gases and tar are broken down into smaller gases with the help of the oxidant. In the third stage, the gases and oxidant react with the coke, which mainly converts the coke into a gaseous form.

In the fourth and final stage, the gas products react with each other; here, the water-gas reaction (5), steam reforming (8) and methanation (6) are of importance. The final product gas has a complex composition that depends on the amount of oxidant as well as the residence time and temperature in the gasification reactor [10] [11].

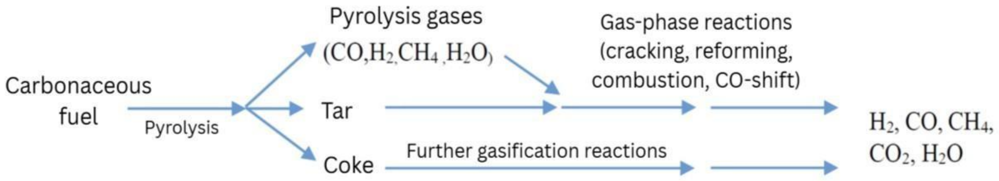


Figure 1: Simplified reaction sequence during gasification of carbonaceous fuels [6]

There is already a well-developed infrastructure for waste incineration. This may speak against the introduction of waste gasification, which thus also creates competition for the waste.

However, a comparison of the two methods carried out by Consonni & Viganò (2012) [13], table 1, shows that gasification can compete with waste incineration. Another comparison measure is to examine the underlying goals behind the processes.

For incineration, this goal is considered to be to maximize energy conversion from waste to high-temperature combustion products, carbon dioxide and water, and to utilize the energy from them. The goal of gasification is instead considered to be to maximize energy conversion from waste to synthetic gas with a high calorific value that can be used for several different processes [12].

Table 1: Advantages and disadvantages of gasification versus incineration of waste as listed by [13]

ADVANTAGES	DISADVANTAGES
-Gasification produces a synthetic gas that can be handled and burned or further processed as needed. For example, the gas can be stored and then efficiently and quickly burned in a gas turbine when electricity demand arises in the market. -Gasification reduces the levels of dioxins and furans compared to combustion. -The synthetic gas can be used to produce high-quality fuels such as hydrogen, methane, diesel or gasoline. -Gasification at high pressure can lead to higher energy efficiency.	-Synthetic gas is toxic and explosive. Raises questions about safety and control of production. -A gasification plant tends to be more complex than an incinerator with more processes involved that must work together. -The combustion of the synthetic gas can give rise to dioxins. -Overall energy efficiency is often lower for gasification. However, the synthetic gas obtained has a higher energy quality than combustion.

2.2 TAR

The tar produced in an initial stage of gasification is often a collective name for organic pollutants with a molecular weight higher than that of benzene. The fact that tar remains as a product after the gasification process is often a sign that incomplete gasification has occurred. It is important to prevent tar formation as much as possible in the gasification process or to remove the tar from the product gas using purification technology. Tar can have different properties depending on the type of compounds it consists of, but a recurring problem is the risk of condensation on sensitive equipment such as a turbine [14].

There are different methods to avoid tar formation or to purify tar from the synthetic gas. The most explored method is thermal cracking where the gasification process is carried out at high temperature, which breaks down the long hydrocarbon chains of the tar. A more sophisticated method is to use a catalytic bed where the bed material acts as a catalyst for the gasification reactions that occur during gasification.

A proven material for this is calcined dolomite, which has been shown to be able to reduce tar formation completely or to a large extent [4] [15]. Coke, which is formed naturally in the gasification process, also acts catalytically on tar. However, coke is consumed in the gasification reactions, which makes it unsuitable for use as a bed material [16].

Methods for purifying the product gas from tar can also be carried out after the gasification reactor and then by mechanical or physical means. Tar purification with a mechanical method can be of a similar type that performs particle separation, such as filters or wet scrubbing. However, separation of tar and other particles should be avoided in the same mechanical cleaning process as particles can easily get stuck in the viscous tar and cause damage to the equipment [17].

2.3 COKE

Coke is also formed in the gasification stage and is also the result of incomplete gasification. Coke is formed in the same way as tar in an initial pyrolysis stage [6]. As mentioned above, coke can act as a catalyst to break down tar with the disadvantage that it is itself consumed in the process.

Too much coke can cause damage to sensitive equipment, so it is important that the amount of coke in the product gas is kept as low as possible for the same reason as tar. Coke can be cleaned from the product gas in the same way as other particles are cleaned from the product gas, for example with a cyclone or with a filter. A common technique used is to transport the coke to the incinerator where it is burned [5].

2.4 OTHER CONTAMINANTS

Just as with waste incineration, contaminants can also occur when waste is gasified. These include compounds such as sulphur oxides, dioxins and furans. The contaminants accompany the product gas when it leaves the gasification reactor. This means that effective cleaning of the product gas is required to ensure that human health and the surrounding environment are not harmed by the process. Carbon monoxide can also be interpreted as a pollutant because it is fatal to inhale, but it is generally not interpreted as a pollutant in gasification processes.

It is worth noting that a gasification process is considered cleaner than a pure combustion process because it is easier to control [12].

2.5 GASIFICATION TECHNIQUES

There are different techniques for gasifying materials. The most popular and well-known methods are fixed-bed gasifiers, fluidized-bed gasifiers and indirect gasification. In a fixed-bed gasifier, left in Figure 2, the fuel is fed into the top of the reactor. Gasification occurs as soon as the fuel falls to the grate where it then remains to be further gasified.

The flow of oxidant can either be counter current or concurrent. A fluidized bed gasifier, center in Figure 2, fluidizes the fuel using a bed material and the oxidant, creating a liquid-like state. Indirect gasification or double-bed gasifiers, on the right in Figure 2, are constructed of two separate chambers that are connected by the circulating bed material.

Gasification occurs in the gasification chamber from which the bed material and coke are then fed to the combustion chamber. A problem with this technology is that the temperature in the gasification chamber is limited to the temperature in the combustion chamber if no additional heat source is supplied to the gasification reactor [18] [5].

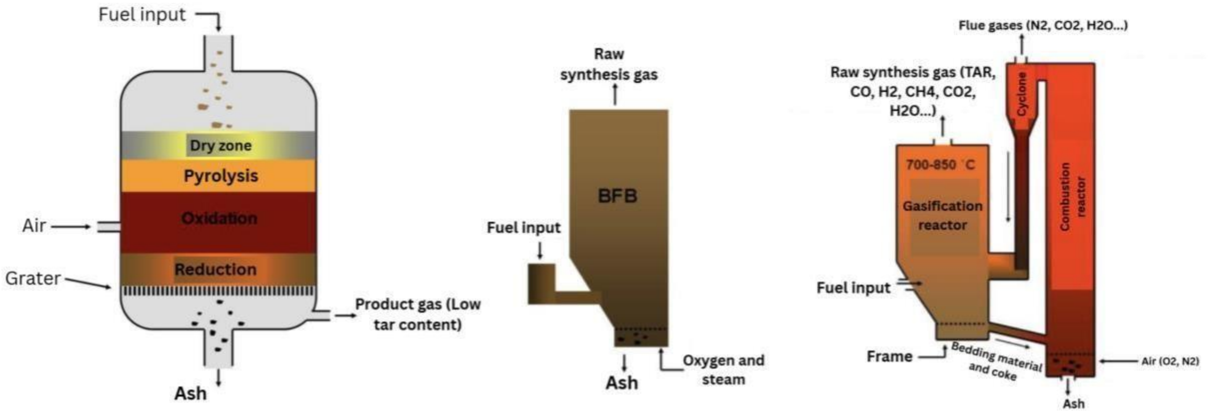


Figure 2: The left image shows a fixed bed gasifier of the counter current reactor type. The middle image shows a bubbling fluidized bed gasifier. The right image shows an indirect gasifier of the double bed gasifier type [18]

2.6 ELECTRICITY PRODUCTION

The design of the proposed system includes two turbines, a steam turbine in a steam cycle and a gas turbine. These are briefly described in the sections below.

2.6.1 STEAM CYCLE

High temperature and high-pressure steam are produced in a steam boiler which is then allowed to expand in a turbine to produce electricity. Connected to the turbine is also a heat exchanger or condenser that utilizes the heat in the steam from the turbine exhaust and sends it out to a district heating network or similar. The condensed water is then pumped back to the steam boiler [19].

2.6.2 GAS TURBINE

A gas turbine can be simply described as a gas with a high calorific value being combusted, which increases the temperature of a compressed air stream which is allowed to expand through a turbine from which electricity is produced. Synthetic gas produced in a gasification process is suitable for combustion in a gas turbine, provided that the gas has a sufficiently high calorific value [19].

2.7 PRESSURE SWING ADSORPTION (PSA)

Pressure Swing Adsorption, hereafter referred to as PSA, is an isothermal gas separation method. The gas to be separated is first compressed to a desired pressure, the optimal pressure for hydrogen separation is usually in the range of 15-30 bar [6]. After compression, the gas is introduced into an adsorption chamber where the materials with the highest adsorption capacity are adsorbed on a porous carrier material. The gas with the lowest adsorption capacity is separated from it in the process. Once the separation has taken place, the remaining gas is desorbed by reducing the pressure in the chamber [20].

To obtain an effective hydrogen separation by PSA from a synthetic gas containing CO, H_2, CO_2, CH_4 and H_2O, two pairs of chambers are required, Figure 3. In the first bed pair, bed A, which contains activated carbon, virtually all carbon dioxide and water vapor in the gas are adsorbed.

This provides opportunities to handle the carbon dioxide via, for example, carbon capture and storage if the method proves to be feasible in the future. The remaining gas is then passed on to the second bed pair, bed B, containing a type of zeolite that effectively adsorbs the remaining substances in the synthetic gas and lets through up to 86% of the hydrogen. The separated hydrogen gas has a purity of up to 99.999% [20] [21].

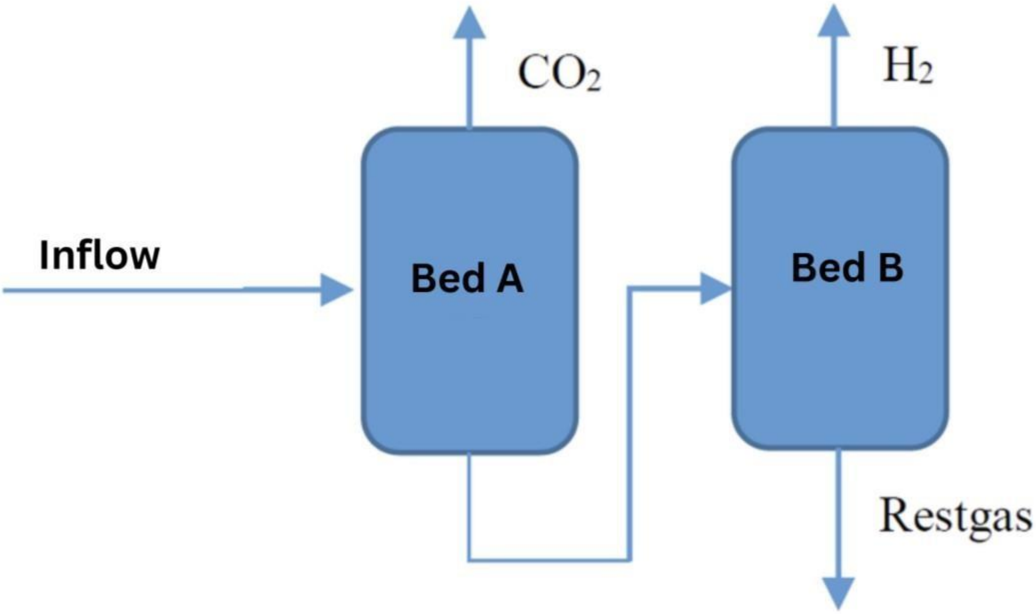


Figure 3: Hydrogen separation using PSA [20]

2.8 HYDROGEN AS AN ENERGY CARRIER

Hydrogen is a lightweight, difficult to condense and energy-rich gas consisting of two hydrogen atoms. When hydrogen is oxidized, energy is released, and the only residual product is water vapor. Hydrogen can be used as a fuel for vehicles through clean combustion in special combustion engines or via fuel cells [3]. This means that hydrogen is being discussed as one of the alternatives to replace fossil fuels in today's vehicle fleet.

Most of the research and new car models today are based on fuel cell technology, as the efficiency is higher than for combustion engines. The disadvantage, however, is that fuel cells are a complex and expensive technology that still has problems to overcome. One of these problems is the lifetime of the fuel cells, which is currently too short to be able to compete fully with today's combustion engines [22].

Another major challenge in reforming today’s vehicle infrastructure to one where hydrogen cars have a large market is the production, storage and distribution of hydrogen. Today’s hydrogen production, as already briefly described in chapter 1.2, is mostly from steam reforming (8) of natural gas.

The disadvantage of the steam reforming of natural gas is that the produced hydrogen costs more per kWh extracted than it would have cost to use pure natural gas, while at the same time, carbon dioxide is emitted because natural gas is a fossil fuel. Furthermore, there are also cleaner methods for hydrogen production, such as electrolysis, but these are also expensive. Therefore, alternative hydrogen production methods are desirable and necessary [22].

Another problem that must be overcome is the public’s opinion about hydrogen. In a study conducted by Cherryman et al. (2008) [23], people’s perceptions and opinions about the introduction of hydrogen as an energy medium in Wales were investigated. In this study, explosion risk was considered to be of great importance, and links were drawn to both the Hindenburg accident and the hydrogen bomb. Furthermore, the issue of today's fuels and their explosion risk was also touched upon, as well as what the discussion looked like, whether it was gasoline or diesel that was introduced today.

What is important to note is that hydrogen is not more dangerous than any other fuel if it is handled and distributed correctly [22].

The hydrogen market is relatively small today. Most of the hydrogen is used in the petrochemical industry and for the production of artificial fertilizers. The proportion of hydrogen consumed by vehicles today is very small, and the market share is almost nonexistent.

However, there is an effort to implement reforms.

The storage unit is an important part if hydrogen is to gain a greater role in the energy market. With today's technology, it is relatively difficult to transport and store hydrogen. A standard truck today can carry 400 kg of pressurized hydrogen, which corresponds to hydrogen for about 100-150 fuel cell cars, while the same truck can transport 26,000 kg of gasoline, which is enough for about 800 cars [24]. The reason hydrogen is so difficult to transport is that it takes up a large volume relative to its energy content. This poses difficulties not only in the transport of hydrogen but also in the storage tank in the vehicle in question [25].

A study by Meibom & Karlsson (2010) examines a model that predicts the role of hydrogen in the energy system of Northern Europe in 2060 [26]. The result assumed that the price of oil would rise above $100 per barrel, which would result in alternative energy sources becoming cheaper than oil. According to the result, hydrogen would play the role of the energy carrier that can be used when needs arise in the market, not entirely different from the role that oil often has today.

In addition, it was assumed that half of the vehicle fleet would be powered by hydrogen. Furthermore, a study by Ball et al. (2007) claims that hydrogen could become economically competitive in Germany against fossil fuels when the price of oil exceeds $50-$70 per barrel and when strict carbon dioxide emission restrictions apply [27].

2.9 REFERENCE ARTICLE

He et al. (2009a) investigate a gasification technique where household waste is gasified together with calcined dolomite as a catalyst and steam as an oxidiser [28]. Their results show a product gas with a high hydrogen content and low tar content. Furthermore, the product gas composition is also presented for a gasification temperature of 800 °C, which is consistent with temperatures in a typical boiler that could act as a heat producer for the gasification reactor. The above factors are the reasons why this work is widely used as a reference in this study. The full composition and amount of coke and tar in the product gas for [28] is presented in the model.

2.10 LAW

A highly topical topic today is the question of when waste ceases to be waste and instead becomes a resource. This chapter presents excerpts from legislation and EU directives that deal with the definition and management of waste and addresses the question of when waste can cease to be waste.

2.11 ENVIRONMENTAL CODE

When waste is used as fuel, it is covered by the Environmental Code's provisions on waste management. In general, it is stated that an activity must follow the general rules of consideration. This is even if no authority has set specific requirements for the activity. The rules of consideration state that an activity must acquire sufficient knowledge to be able to guarantee that it does not pose a risk to human health and the surrounding environment.

In addition to this, there are also requirements for precautionary measures, which state that the activity must ensure that its processes undergo the protective measures required to ensure that its facility does not harm human health or the environment. Furthermore, there are also requirements that operators must assess and take a position on how they can counteract or prevent negative environmental impacts from their facility and how the facility's environmental impact can be documented.

The Environmental Code's definition of waste is: "Waste refers to any object or substance that the holder disposes of or intends or is obliged to dispose of." Furthermore, the first paragraph also mentions that: “A substance or object that has become waste ceases to be waste if it has been handled in a manner that involves recycling and meets the requirements for continued use in accordance with regulations issued under Section 9 or 28.” [29].

2.12 EU DIRECTIVE 2008/98/EC

In November 2008, it was decided that a new framework directive on waste would be adopted and would enter into force by December 2010 for all members of the European Union. This directive lists various requirements for waste, and Article 6 deals with when waste ceases to be waste. The article states that waste can legally cease to be waste if it has undergone a recovery process and meets the new conditions set out in the directive. These conditions are:

a) “that the substance or object is to be used generally for specific purposes”

b) “that there is a market for or demand for the substance or object”

c) “that the substance or object meets the technical requirements for the specific purposes and existing legislation and standards for products”

d) “that the use of the substance or product will not lead to generally negative consequences for the environment or human health”

Based on these conditions, the European Commission, together with the Member States, wants to develop detailed criteria for when specific waste ceases to be waste. These criteria have not yet been developed and are therefore not to be found in any EU directives. At present, the Member States are allowed to judge in each case whether a waste has ceased to be waste, based on the case law of the Court of Justice of the EU. (Directive 2008/98/EC of the European Parliament and of the Council).

2.13 GASIFICATION PLANTS

Gasifying household waste for the production of hydrogen is a technology that does not exist on a commercial scale globally. In fact, gasification of waste on a commercial scale is a relatively new technology, and the only relevant gasification plant with household waste as a substrate is in Lahti, Finland [30]. Lahti Energia's Kymijärvi boiler 2 produces a synthetic gas that is combusted on site for the production of electricity and heat. Mälarenergi had an ambition to build a similar plant and received a permit for it, but ultimately chose not to carry out the project. There are also gasification plants that gasify biomaterial partly for biofuel, GoBiGas in Gothenburg [31], but also for electricity and heat production, cyclone gasifiers in Piteå [32].

2.14 HOVHULTS HEATING BOILER

A gasification reactor of the double-bed gasifier type can utilize the heat of a combustion boiler by circulating the bed material. The Hovhults heating boiler in Uddevalla is a relatively old heating boiler where biofuel is burned for the production of district heating. The combustion boiler is of the CFB (Circulating Fluidized Bed) type and uses a bed material that makes it possible to connect the boiler to a gasification reactor and circulate the bed material between them.

The main purpose of the Hovhults heating boiler is today to act as a reserve when the heat demand is high, which means that the boiler is used during winter but otherwise stands still for large parts of the year. This, combined with the CFB boiler technology, motivates the use of the Hovhults heating boiler as a model for heat supply in this study.

III. LITERATURE REVIEW

3.1 INTRODUCTION TO THE LITERATURE REVIEW

Global environmental decline, surging waste levels, and the thinning of fossil fuel reserves have forced us to rethink how we convert energy. **Hydrogen** stands out as a serious contender for a clean energy future, largely because of its high energy density and the fact that its only "exhaust" in a fuel cell is water. Yet, there is a lingering irony: most hydrogen today is still produced via steam methane reforming—a process tethered to fossil fuels that releases significant greenhouse gases.

We need a cleaner way forward, and that’s where waste gasification comes in. It’s a dualpurpose strategy: we take what society throws away and thermally convert it into synthesis gas (syngas) to extract hydrogen. This isn't just about waste disposal, it’s about turning a liability into a high-value fuel.

The problem is that most current research feels stuck. It’s either confined to small-scale lab experiments or buried in broad theoretical reviews that don't account for the messiness of the real world. We noticed a major gap here—there’s very little work that actually steps out of the 'test tube' phase to figure out how these systems plug into existing infrastructure.

3.1.1 Bridging the Gap

This study addresses the disconnect. We are proposing a design that integrates waste gasification directly with an **existing heat plant**. Moving beyond basic chemical equations, this work focuses on the "nuts and bolts" of system design and practical feasibility. By tapping into the heat recovery of a pre-existing plant, we can slash external energy demands, making the entire process more efficient and economically viable.

3.1.2 Comparative Framework

To test the weight of our findings, we benchmarked our approach against three pillars of current research:

- **He et al. (2009):** For its experimental groundwork on catalytic steam gasification of municipal waste.
- **Arena (2012):** For its birds-eye view of industrial gasification technologies.
- **Consonni & Viganò (2012):** For their critical comparison between gasification and standard incineration.

We evaluated these studies against our own based on H2 yield, gasifier geometry, and energy efficiency. But we also looked at the bigger picture: **scalability and environmental footprint.** 3.1.3 Contribution of our research What sets this work apart is the focus on **system-level synergy.** By calculating precise mass and energy balances and exploring how machine learning can optimize hydrogen output, we aim to move the needle from "theoretical possibility" to a "practical reality." Ultimately, this analysis validates our design choices and offers a clearer roadmap for sustainable, waste-tohydrogen energy systems.

3.2 COMPARISON WITH HE ET AL. (2009) [36]

In their research work, He et al. (2009) have explored in detail hydrogen-rich gas generation from municipal solid waste (MSW) via catalytic steam gasification. In their experiment, He et al. (2009) have tried to maximize hydrogen content through optimization of operational parameters such as temperature and catalyst selection, wherein calcined dolomite was employed as an efficient catalyst for minimizing tar content and improving the quality of generated gases.

The experiment designed by He et al. (2009) involves operations at high temperatures ranging between 800°C and above, whereby steam serves as the gasifying agent. At such operational conditions, reactions like water gas reaction and steam reforming reactions become dominant, which result in maximizing hydrogen content within the product gas stream. The experiment performed by He et al. (2009) provides a comprehensive account of the gas composition, indicating that operational parameters like temperature and catalytic action can effectively increase hydrogen content while decreasing tar content.

While the work of He et al. is highly valuable from a reaction engineering and experimental perspective, it is primarily limited to laboratory-scale analysis. The study emphasises understanding the chemical behaviour of gasification reactions rather than addressing systemlevel design or industrial implementation.

On the contrary, the current study utilizes a broader approach. Apart from the validation of the hydrogen production via experimental testing, it includes theoretical modelling and system designs as well. Moreover, the designed system involves not only hydrogen generation but also the assessment of the processes of mass and energy balances as well.

One of the major distinctive elements in the present study is the utilization of the gasification process together with the existence of the heat plant. In this way, it contrasts with the research by He et al., in which heat input should be provided externally in order to conduct gasification processes.

The current study further expands on the previous one since it includes not only the analysis of gas composition but also the estimation of the hydrogen generation rate. For example, the current study calculates that the hydrogen yield from the gasification of 100 kg/hr of the waste is about 8–12 kg/hr.

Therefore, the study by He et al. (2009) offers a powerful experimental justification for hydrogen production via gasification. However, the present research develops the previous one by considering system integration and scalability issues as well.

3.3 LIMITATIONS OF HE ET AL. (2009) AND IMPROVEMENTS [36]

Despite being a great source of information regarding the catalytic gasification method used for the production of hydrogen, the research performed by He et al. (2009) can be criticized based on its numerous weaknesses that arise from the industrial aspect of the application of such findings.

Firstly, the problem of system-level integration should be raised as one of the most important issues to consider while developing a certain energy-producing system. It is worth noting that the research of He et al. does not provide any information about system-level integration that could help understand the performance of the energy-producing mechanism after its integration in the existing energy infrastructure.

Secondly, the authors fail to provide any data related to the problem of energy consumption while performing steam gasification, which is the main focus of the article. Indeed, the steam gasification method can hardly be considered efficient due to the high amount of energy consumption associated with its endothermic nature.

Moreover, there is no information related to the mass and energy balance in the process. Although all possible outputs have been described in the article, their relationship with input energy and mass was not provided in detail.

In contrast to the discussed paper, the following features of the current investigation are worth mentioning. Firstly, the incorporation of the gasification system into an existing heat plant ensures proper heat exchange and allows for reducing external energy needs. Secondly, the current analysis considers mass and energy balance. These concepts help to quantitatively evaluate the input and output values of the system.

Moreover, the study considers scalability. To be specific, the researchers suggest analyzing the case of a waste feed rate equal to 100 kg/hr. Such a rate is realistic because the system can work under these conditions. Therefore, the estimation of hydrogen production and overall efficiency in such a way becomes possible.

Finally, one of the most critical differences between He et al.'s research and the current investigation is related to the consideration of optimization possibilities. In particular, the current researchers recommend using machine learning. It helps to forecast the yield of hydrogen based on the results provided by this technology.

To conclude, He et al. (2009) make significant contributions to science due to their experimental research. However, there is room for improvement when considering scalability, optimization, and other aspects.

3.4 COMPARISON WITH ARENA (2012) [12]

Arena's (2012) review paper covers the field of municipal solid waste gasification technology quite extensively and considers multiple factors related to it. This paper can be regarded as an essential basis for research and further discussion regarding the issues connected to this topic.

This review discusses several types of gasifiers, such as fixed-bed, fluidized-bed, and entrained-flow systems. In addition, this review touches upon such important factors as temperature, pressure, and residence time that influence the gas production significantly.

The main feature of Arena's paper that makes it useful for any research in this area is its emphasis on environmental issues. Thus, this paper considers emissions, tar production, and pollution control in detail.

Nevertheless, even in spite of the comprehensive character of this paper, it cannot be considered as a practical one as it does not focus on any particular system development or design.

Contrastingly, while the current paper makes use of the theoretical knowledge that Arena (2012) provides, it advances further and puts this information into practice through application to a concrete design. Choosing to use the fluidized bed gasifier system in the current study is based on benefits such as enhanced mixing process, equal temperature distribution, and efficiency of operation mentioned by Arena.

While the former article provides a review, the current paper concentrates more on implementation, which requires additional calculations of all aspects of system functioning, including design, operational conditions, and performance.

Furthermore, another novelty brought by the current study concerns heat integration. This technique allows the use of the heat released in an industrial setting in order to achieve energy efficiency and lower costs.

Therefore, while Arena (2012) has proven its worth in providing theoretical insight, the current paper goes beyond and applies it to a practical case study.

3.5 LIMITATIONS OF ARENA (2012) AND IMPROVEMENTS

While Arena (2012) is considered one of the most complete reviews of different gasification technologies, there are several drawbacks of the paper that should be taken into account when analysing it from the point of view of practical design and implementation.

First of all, the lack of concreteness can be considered the key limitation of the study. As a review article, it deals with numerous questions; however, it cannot provide any information concerning a certain system.

Moreover, there is no quantitative analysis in the work under discussion. In other words, mass balance, hydrogen yield and other important characteristics of a certain gasification system are not calculated.

Finally, the paper does not discuss the problem of integration of the gasification process into the existing energy infrastructure. In practice, this step is necessary to enhance its effectiveness.

Unlike Arena (2012), the current paper overcomes the above-mentioned drawbacks of the previous article. Thus, it presents an analysis of a certain gasification system and gives the results of relevant numerical calculations.

In addition, the selection of the fluidized bed gasifier is grounded in its benefits, and the operation conditions are selected in such a way as to maximize hydrogen generation. The level of elaboration is much higher than in Arena's paper.

The integration of the gasification system into the existing heat plant is also a considerable enhancement. This contributes to better utilization of the energy resources, which is one of the crucial problems associated with the development of gasification technologies. Furthermore, the current research includes novel components like AI-based optimization, making it relevant to the contemporary state of affairs.

In summary, while Arena (2012) provides valuable theoretical insights, the present study offers a more practical, detailed, and application-oriented approach.

3.6 COMPARISON WITH CONSONNI & VIGANÒ (2012) [38]

Comparative assessment of waste gasification and incineration of municipal solid waste was carried out by Consonni & Viganò (2012). This paper mainly examines the effectiveness of both waste processing technologies. The main goal pursued by the authors is an attempt to define the possibility of using gasification as an alternative technology to the incineration of municipal waste. The results of the research indicate the feasibility of gasification use, despite some drawbacks associated with this method, such as increased complexity of the process and some energy loss due to incomplete conversion of waste.

Nevertheless, the scope of research performed by Consonni & Viganò (2012) is narrow and confined to the comparative assessment of two technologies rather than the study of the potential of gasification. No further investigation of system design issues and hydrogen separation was included in the study.

This paper deals with the issue of hydrogen production from gasification, which is more beneficial compared to waste-to-energy conversion. The study reflects global trends in the transition towards sustainable energy resources.

Yet another important distinction that can be made is that the current paper features heat integration. Where Consonni & Viganò analyze separate systems, in the current paper, efficiency is improved by utilizing the waste heat produced by an already established system.

It should also be noted that the current paper makes use of technology in its future projections, specifically in relation to AI optimization techniques. This consideration is not accounted for in the comparative paper.

3.7 COMPARISON AMONG DIFFERENT RESEARCH PAPERS

Research Paper	**Methods Used**	**Advantages**	**Limitations**
He et al. (2009) – Hydrogen-rich gas from catalytic steam gasification	- Experimental study - Steam gasification process - Use of catalyst (calcined dolomite) - High temperature operation (~800°C)	- High hydrogen yield - Effective tar reduction using a catalyst - Detailed experimental validation	- Limited to laboratory scale - No system integration - High external heat requirement - No economic or scalability analysis

	- Gas composition analysis	- Provides accurate gas composition data	
Arena (2012) – MSW gasification review	- Comprehensive literature review - Comparative study of gasifier types - Analysis of process parameters - Environmental impact evaluation	- Broad understanding of gasification technologies - Covers multiple reactor designs - Strong theoretical foundation - Useful for selecting gasifier type	- No specific system design - No experimental validation - No hydrogen yield calculation - Lacks practical implementation details
Consonni & Viganò (2012) –	- Comparative analysis of technologies	- Clear comparison between two major technologies	- Does not focus on hydrogen production
Gasification vs incineration	- Evaluation of energy efficiency - Environmental performance comparison - Techno-economic perspective	- Highlights the environmental benefits of gasification - Useful for policy and decisionmaking - Identifies strengths of syngas utilization	- No reactor-level or system design - No integration with existing systems - Limited technical depth in the gasification process

IV. GASIFIER DESIGN AND OPERATING PARAMETERS

4.1 INTRODUCTION

The Gasifier is an important component in this project because it converts the waste into useful gas. The hydrogen production efficiency mainly depends on how well the gasifier is designed and operated [6][7]. If the design has an error, problems such as high Tar formation, incomplete conversion and low hydrogen yield can occur [14]. Now, in this section, we are discussing the design of the gasifier, including basic calculations and assumptions to provide more understanding of how such a system would work in real conditions.

4.2 SELECTION OF GASIFIER TYPE

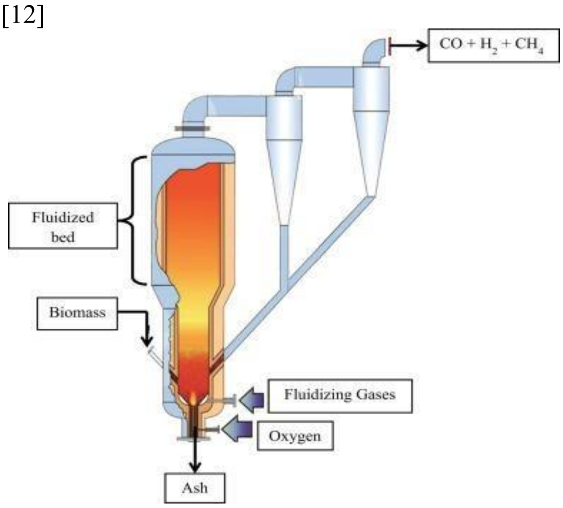
In the different industrial applications, there are different types for gasifier are used, such as:

- Fixed bed gasifier
- Fluidised bed gasifier
- Flow gasifier

We have opted for the **Fluidised bed gasifier** for our project.

The main reason for the selection of the fluidised bed gasifier is that it provides better mixing between the reacting gas and the waste material. Other reasons for this selection are mentioned below :

- Handle different types of waste materials.
- Temperature inside the reactor remains uniform.
- Higher conversion efficiency.
- Lower tar formation.[12]



4.3 WORKING PRINCIPLE

The fluidized bed gasifier contains a bed of solid particles, usually ash or sand. When air or steam is passed upward at a certain velocity, the fluid behaviour of the particles begins, which is termed fluidisation.[6]

The waste is then introduced into the particle bed, and it gets heated quickly and starts reacting. This process generally happens in a few steps, as mentioned below:

- First, moisture is removed by drying
- The material is broken down into gases and solid residue, called as **Pyrolysis.**[8]
- Combustion partially takes place to provide heat.
- Reduction reactions produce gases like CO (carbon monoxide) and H (hydrogen).[7]

The reactions occur more uniformly because of this continuous mixing compared to the other gasifier.

4.4 GASIFIER DESIGN CONSIDERATIONS

4.4.1 Nature of waste:[12]

The waste ideally should have the following:

- Low moisture content
- Particle size should not be too large.
- High carbon content

4.4.2 Temperature

Temperature is one of the important parameters

- Typical range : 700°C to 900°C
- Hydrogen production can be improved if the temperature is higher.[15]
- Very high temperatures may also damage the material.

So, it is advised that a balance should be maintained.

4.4.3 Air supply

Limited oxygen is required for the process of gasification. As the process becomes combustion instead of gasification is the air supplied is way too much.[6]

In simple terms:

- Less air – incomplete reaction
- Too much air – burning instead of gas formation

So, a controlled air supply is necessary.

4.4.4 Residence Time

The time for which the waste stays inside the reactor is termed as **Residence Time**.

- If the residence time is short, the conversion is said to be incomplete.
- If the residence time is very long, the conversion is not at all economical.

So, an optimum value is selected.[45]

4.5 BASIC DESIGN CALCULATIONS

For better understanding, we have done some approximate calculations; these are not exact industrial values.

4.5.1 Assumptions

The following assumptions are being carried out :

- Waste feed rate: 100kg/hr
- Operating content: 800°C
- Carbon content ≈ 50%
- Efficiency ≈ 70%

4.5.2 Reactor Volume

The size of the reactor depends on the factor of how long the material stays inside

Volume= Flow rate × Residence Time

Assuming:

- Gas flow rate ≈ 0.5 m^3/s
- Residence time = 2 seconds

$$\text{Volume} = 0.5\times 2 = 1\ m^3$$

So, approximately 1 m3 is the required reactor volume.

4.5.3 Air requirement:

For complete combustion, gasification uses only a fraction of the air.
If stoichiometric air = 6 kg per kg fuel, then,

$$\text{Air used} = 30\% \approx 1.8\text{kg/kg}$$

4.5.4 Hydrogen production

The literature values for the hydrogen production were found to be:

$$1\text{ kg waste} = 0.08 - 0.12\text{ kg } H_2\ [15]$$

So, for 100 kg/hr:

$$H_2 \approx 8 - 12\text{ kg/hr}$$

These calculations depict that even waste can produce a useful amount of hydrogen.

4.6 EFFECT OF OPERATING PARAMETERS

The gasifier performance can vary with different operating conditions.

4.6.1 Temperature

- The higher the temperature, the higher will be the production of hydrogen.[15]
- Higher temperature often reduces tar formation.[14]

4.6.2 Pressure

- Gas quality can be improved with slightly higher pressure.
- Higher pressure can increase the cost.

4.6.3 Steam Addition

Adding steam helps in producing more hydrogen through reactions like the **water – gas reaction**.[7]

4.6.4 Bed material

Generally, the materials used are sand and dolomite. Dolomite is used for the following reasons:

- It helps to reduce tar formation.
- It also improves the gas quality.[14]

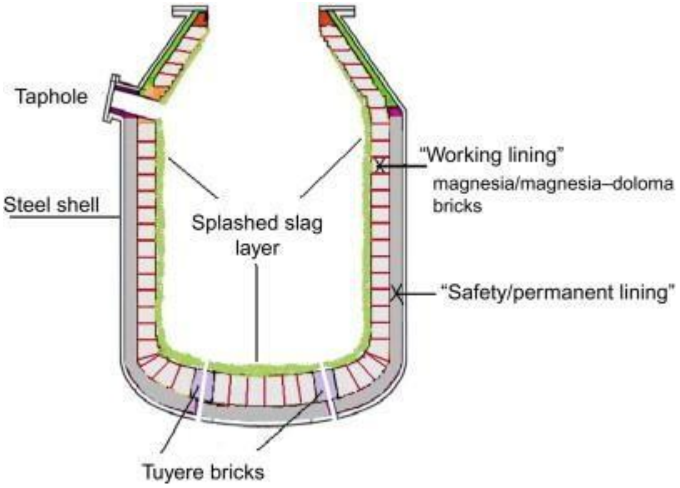
4.7 MATERIAL SELECTION

Material selection is very crucial as gasifiers operate at high temperatures.
The required properties for the material selection are:

- High temperature resistance
- Corrosion resistance
- Good mechanical strength

Some commonly used materials for gasifiers are mentioned below:

- Stainless steel
- Alloy steel
- Refractory lining inside the reactor[45]



4.8 ADVANTAGES OF THIS DESIGN

There are numerous advantages, some of which are mentioned below:

- It is suitable for different types of wastes • It provides better mixing and heat transfer.
- Continuous operations are possible.
- It has higher efficiency as compared to the simple systems.

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4.9 LIMITATIONS

There are certain limitations also, such as:

- The initial cost is much higher than that of other systems.
- The system is slightly complex
- There should be proper control of parameters.
- It requires the cleaning of gas.

V. MASS AND ENERGY BALANCE

5.1 INTRODUCTION

The thermochemical process of gasification helps to understand how mass and energy are distributed throughout the system. Mass and energy balance states about the efficiency of the process and helps in estimating the amount of useful output, especially hydrogen in this case.[3]

Gasification is a combination of several reactions happening simultaneously, not a single-step reaction. Because of this, performing an exact balance becomes complex.[7]

5.2 BASIS OF CALCULATION

The entire analysis is based on a waste input of 100kg per hour. This value is chosen for simplicity and can be scaled up or down later.

The composition of waste is assumed as follows:

- Carbon: 50%
- Hydrogen: 06%
- Oxygen: 44%

The efficiency of the gasification process is assumed to be around 70%, as these values represent an average composition of municipal solid waste after basic segregation.

5.3 MASS BALANCE

The mass balance is based on the law of conservation of mass. It states that

“ **Mass cannot be created or destroyed”**

Therefore, the total mass entering the system must be equal to the mass leaving the system.

In the process of gasification, the input consists of waste and air, while the output consists of different gases along with ash and some losses.[19]

5.3.1 Input to the system The total input includes:

- Waste feed: 100 kg/hr
- Air supply: 180kg/hr

So, the total mass entering the system is:

Total input = 100 + 180 =280 kg/hr

The requirement of air is done on partial oxidation, which is around 30% of the air required for complete combustion.

5.3.2 Output from the system

The gasifier output is in the form of synthesis gas with several components. [7] Based on gasification data, the distribution is as follows:

1. Hydrogen(H_2): 8-10 kg/hr
2. Carbon monoxide(CO): 20-25 kg/hr
3. Carbon dioxide(CO_2): 15-20 kg/hr
4. Methane(CH_4): 3-5 kg/hr
5. Ash and residue: 10-15 kg/hr
6. Other minor gases 7. System losses

5.4 HYDROGEN YIELD

Hydrogen yield indicates how effectively the waste is converted into hydrogen.

It is calculated as:

$$\text{Hydrogen yield} = \frac{\text{Mass of hydrogen produced}}{\text{Mass of waste input}}$$

Taking an average value: 0.1kg/kg

This means that for every kg of waste, 0.1 kg of hydrogen can be produced.[3][15]

5.5 ENERGY BALANCE

Energy balance helps in determining how much of the input energy is converted into useful output.[19]

5.5.1 Energy Input

The calorific value of waste varies depending on composition; for now, it is assumed to be 15MJ/Kg.

So, the total input energy is: 100 × 15 = **1500 MJ/hr**

5.5.2 Energy output

Some energy is lost due to heat losses, incomplete reactions, and inefficiencies. This useful energy is mostly present in the form of syngas.

Assuming a system efficiency of 70%: 0.7 × 1500 = **1050 MJ/hr**

5.5.3 Energy in Hydrogen

Calorific value of hydrogen is approximately 120MJ/kg.[25] So, the energy contained in the hydrogen produced is:

Energy in H_2 = 10 × 120 =**1200 MJ/hr**

5.6 EFFICIENCY OF THE SYSTEM:

$$\text{Efficiency} = \frac{\text{Useful output energy}}{\text{Input energy}} \times 100$$

$$= \frac{1050}{1500} \times 100 \approx 70\%$$

Thus, the efficiency of the system is 70% approximately that indicates that the system performs well.

VI. HEAT INTEGRATION WITH EXISTING PLANT

6.1 INTRODUCTION

The approach to utilise the waste heat from an existing heating plant to support the gasification process for improving the overall system efficiency is known as heat integration. [6]

6.2 HEAT REQUIREMENT IN GASIFICATION

The gasification process involves both endothermic and exothermic reactions.

In particular, reactions involving steam require additional energy. If this heat is supplied externally, it increases the operating cost of the system.[6]

Therefore, utilising available waste heat becomes beneficial.

6.3 HEAT RECOVERY METHOD

Heat exchangers are used to transfer and recover heat, as a heat exchanger allows heat transfer between two fluids without mixing them.[17]

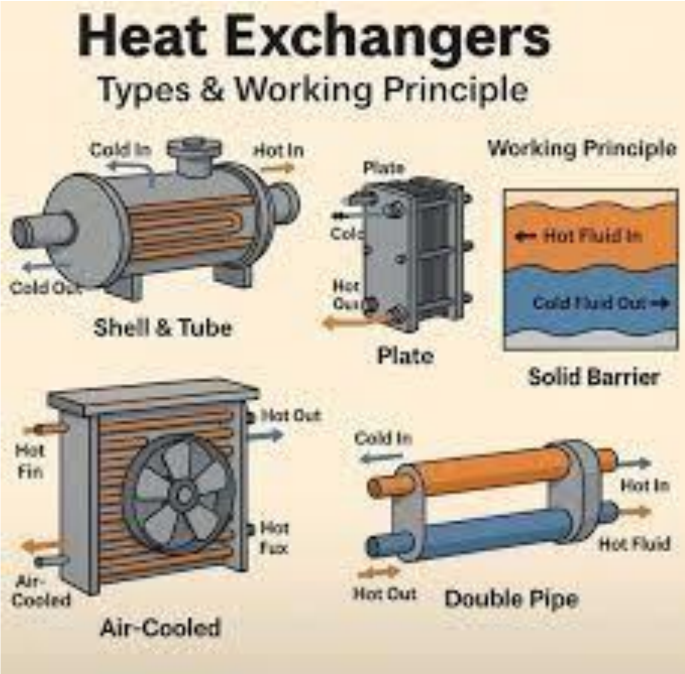
- Hot exhaust gases from boiler – heat exchanger
- Cold air/ steam – heated before entering gasifier

6.4 BASIC HEAT TRANSFER CALCULATION

The amount of heat transferred can be calculated using:[19] $Q = m \cdot Cp \cdot \triangle T$

Where:

- Q = Heat transfer
- m = mass flow rate
- Cp = specific heat
- $\triangle T$ = temperature difference



6.5 ADVANTAGES OF HEAT INTEGRATION

There are many advantages of heat integration mentioned below:

- It improves the overall efficiency of the system.[12]
- Lowering operating cost [18]
- Makes better use of available resources
- Reduces external fuel requirement

6.6 PRACTICAL CHALLENGES

There are some challenges involves is the heat integration process mentioned below:

- Proper insulation is required to avoid heat loss[17]
- Heat exchanger design must be efficient
- Temperature control is necessary

VII. ECONOMIC ANALYSIS

7.1 INTRODUCTION

Practical implementation of a gasification system depends largely on the economic feasibility. For Real – world applications, a very high-cost system that produces hydrogen efficiently is not suitable. Therefore, it's mandatory to evaluate the overall cost of operating the system as well as setting up the system.

An approximate economic analysis for the waste gasification system integrated with a heating plant. Estimating capital cost, cost of hydrogen production and operating cost.

7.2 COST COMPONENTS OF THE SYSTEM

The system cost components can be broadly divided into the following two parts:

1. Capital cost

An initial investment is required for the installation process.

2. Operating cost

The cost of the system requires daily or periodic running of the system.

7.3 CAPITAL COST ESTIMATION

For setting up the gasification–based hydrogen production plant, the cost that covers all the major components is the **capital cost.** Considering the system at a small to medium scale.

7.3.1 Gasifier Unit

The gasifier is the primary unit as it converts waste into syngas. It consists of the following parts:

- Feeding mechanisms
- Reactor body
- Air supply system
- Basic instrumentation

For a small-scale fixed-bed gasifier, the cost varies between **₹3–5 lakhs.** A similar cost range has been reported for small biomass gasification systems.[3]

7.3.2 Gas cleaning system

The gas cleaning system is responsible for ensuring the smooth operation of downstream units like PSA. The system includes the following parts:

- Scrubbers
- Filters (to remove tar, particulate matter)
- Cyclone separators

Depending on the level of purification, the estimated cost of the system lies in the range of **₹2–3 lakhs.** [12]

7.3.3 Pressure swing adsorption (PSA) unit

The unit is used for hydrogen purification by separating hydrogen from other gases like CO, CO_2 and CH_4.

Due to the use of specialised adsorbents and pressure vessels. The estimation of the cost ranges from **₹4–6 lakh** for a small-scale hydrogen purification system.

7.3.4 Heat integration system

The heat integration system involves the following parts:

- Heat exchangers
- Piping
- Insulation (to use the existing waste heat from the plant)

According to the material and design, the heat integration system ranges between **₹1–2 lakh.**

7.3.5 Miscellaneous Cost

This includes the control systems, valves, and safety equipment installation.

This cost approximately varies between **₹1–2 lakh.**

7.3.6 Total capital cost

After evaluating all the factors mentioned above:

Total Capital Cost ≈ ₹ 10–₹15 lakh

This cost is moderate when compared to large-scale hydrogen production plants.

7.4 OPERATING COST

The cost depends on the system size, level of automation and operating conditions.

7.4.1 Labor cost

A minimum of two operators is required to run a small-scale plant. Therefore, the estimated cost for daily labour is around **₹300–₹500.**

7.4.2 Maintenance cost

The estimated cost for maintaining a small-scale plant is around **₹200–₹300 per day.** It can also vary in usage. Maintenance includes the following:

- Replacement of filters
- Periodic cleaning of the gasifier
- Inspection of equipment

7.4.3 Electricity cost

Electricity is required for the following parts:

- operating PSA systems
- pumps
- compressors.

The estimated electricity cost is around **₹200–₹400 per day.**

7.4.4 Total operation cost

Total Operating Cost ≈ ₹ 700–₹ 1200per day

7.5 COST OF HYDROGEN PRODUCTION

To calculate the cost of hydrogen production, the total operating cost is divided by the amount of hydrogen produced.

Assuming;

- hydrogen production = 10 kg/day
- operation cost = ₹ 9000 per day

Cost per kg of hydrogen=9000 ÷ 10 =₹ 90/kg

S.NO.	METHODS	COST OF HYDROGEN PRODUCED
01.	Steam methane reforming (**SMR)**	₹80–₹120/kg
02.	Electrolysis (**green hydrogen) [5]**	₹300–₹500/kg

7.6 PAYBACK PERIOD

The time required to recover the capital investment cost is known as the payback period.
Assuming:

- Selling price of hydrogen = ₹150/kg
- Daily production = 10 kg
- Daily revenue = ₹1500
- Daily profit = ₹500

Payback Period= 12,00,000/500 ≈ 2400days ≈ 6.5 years

7.7 Economic benefits

The proposed system offers several economic advantages:

- Utilisation of waste reduces disposal cost
- Generates value from low-cost feedstock
- Produces hydrogen, which has a growing market demand
- Reduces dependency on fossil fuels

Additionally, future government incentives for clean energy may further improve economic viability [40].

7.8 Environmental Cost Advantages

The system also offers indirect economic advantages by reducing environmental impact.

- Lower greenhouse gas emissions compared to fossil fuels
- Reduction in landfill waste
- Cleaner energy production

Such benefits are becoming increasingly important due to stricter environmental regulations [12].

7.9 Limitations of Economic Analysis

- The analysis is based on approximate values
- Actual cost may vary with scale and location
- Market price of hydrogen may fluctuate
- Technological advancements may reduce costs in future

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