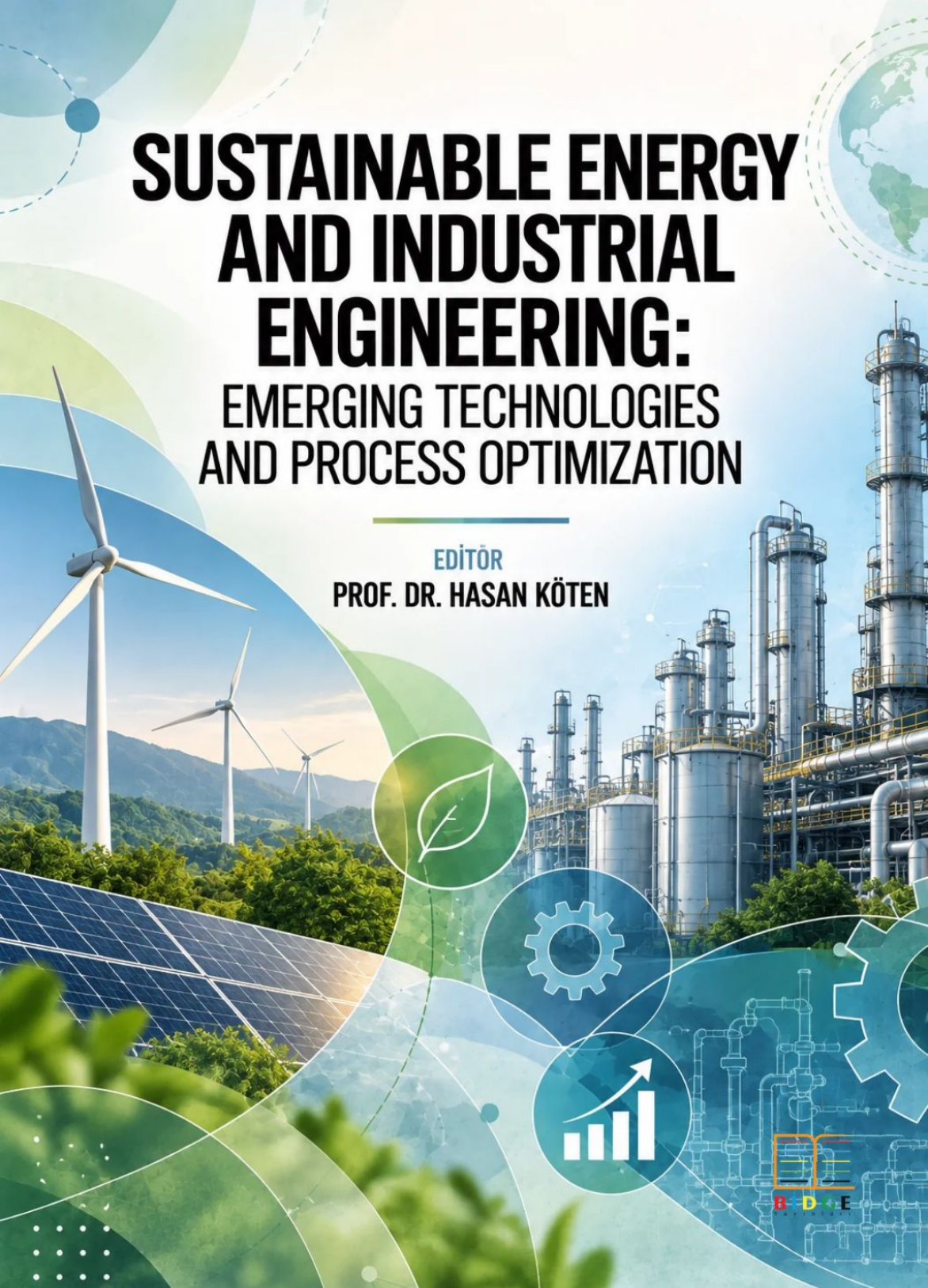
SUSTAINABLE ENERGY AND INDUSTRIAL ENGINEERING:

EMERGING TECHNOLOGIES AND PROCESS OPTIMIZATION

EDİTÖR
PROF. DR. HASAN KÖTEN



BİDGE Yayınları

Sustainable Energy and Industrial Engineering: Emerging Technologies And Process Optimization

Editor: Prof. Dr. HASAN KÖTEN

ISBN: 978-625-5436-06-1

1st Edition
Page Layout By: Gözde YÜCEL
Publication Date: 2026-10-25
BİDGE Yayınları

All rights reserved. No part of this work may be reproduced in any form or by any means, except for brief quotations for promotional purposes with proper source attribution, without the written permission of the publisher and the editor.

Certificate No: 71374
All rights reserved © BİDGE Yayınları
www.bidgeyayinlari.com.tr - bidgeyayinlari@gmail.com
Krc Bilişim Ticaret ve Organizasyon Ltd. Şti.
Güzeltepe Mahallesi Abidin Daver Sokak Sefer Apartmanı No: 7/9 Çankaya / Ankara

CONTENTS

HYDROGEN PRODUCTION METHODS: GREEN HYDROGEN, NANOMATERIALS, AND EMERGING DRUG DELIVERY APPLICATIONS 1
HASAN KÖTEN

PROCESS SELECTION AND FLOW OPTIMIZATION IN MANUFACTURING PROCESSES: TRADITIONAL AND MODERN APPROACHES FROM AN INDUSTRIAL ENGINEERING PERSPECTIVE 45
GÜLLÜ AKKAŞ

WASTE HEAT RECOVERY IN OIL INJECTED SCREW AIR COMPRESSORS 75
ARDA ZAİM

CHAPTER 1
HYDROGEN PRODUCTION METHODS: GREEN HYDROGEN NANOMATERIALS AND EMERGING APPLICATIONS

Ehsan kianfar[1], Hasan Koten[2], Behnaz Chaharbashi[3], Mahdiyeh Nosratabadi[4], Hamidreza Sayadi[5]

Abstract

Hydrogen connects sustainable power manufacturing with rising biomedical technology through advances in catalysis, garage, and managed launch. This bankruptcy severely examines hydrogen-manufacturing pathways and the jobs of nanomaterials in power conversion and hydrogen-mediated drug shipping, drawing on literature posted from 2010 to 2026. Conventional manufacturing routes are taken into consideration along renewable-powered electrolysis, photocatalytic and photoelectrochemical water splitting, thermochemical processes, and organic hydrogen manufacturing. Particular interest is given to the relationships among catalyst structure, interfacial fee transfer, response kinetics, and operational durability. Green hydrogen is evaluated inside a system-stage framework incorporating power supply, useful resource requirements, life-cycle emissions, and scale-up. The dialogue finally examines hydrogen-garage materials, precursor-loaded nanocarriers, and systems for localized hydrogen technology. Biomedical packages are prepared in step with their shipping mechanism, activation strategy, and integration with capsules or complementary treatments. Representative most cancers and wound-recovery research illustrate the ability of those tactics even as emphasizing the difference among preclinical hobby and scientific evidence. Carrier distribution, hydrogen exposure, response products, and organic responses are handled as separate however interconnected determinants of performance. Across power and biomedical packages, the evaluation identifies reproducible manufacturing, quantitative hydrogen measurement, application-applicable testing, and material-destiny evaluation as critical studies priorities. Nanomaterial engineering gives a not unusual place technological foundation, however environmental sustainability and healing effectiveness require unbiased validation. Future development relies upon on translating manage over hydrogen technology and launch into long lasting manufacturing structures and reproducible, biologically powerful shipping systems.

Keywords: Hydrogen production; green hydrogen; water electrolysis; photocatalysis; nanomaterials; hydrogen storage; controlled release; drug delivery; hydrogen therapy; life-cycle assessment.

---

[1]Young Researchers and Elite Club, Gachsaran Branch, Islamic Azad University, Gachsaran, Iran.
[2]Head of Mechanical Engineering Department Faculty of Engineering and Pure Sciences
Istanbul Medeniyet University.
[3]Department of chemistry, Central Tehran Branch, Islamic Azad University, Tehran, Iran.
[4]Department of Metallurgical Engineering, Shahid Bahonar University of Kerman, P. O. Box 76169-133, Kerman, Iran.
[5]Department of Chemical Engineering, Faculty Shahrood Branch, Shahrood Branch, Shahrood, Iran.

1. Introduction

1.1. Hydrogen in sustainable energy and biomedical research

The medical price of hydrogen lies within the courting between how it's far produced, how it's far handled, and the feature it in the end performs. In strength structures, molecular hydrogen gives a way of changing renewable strength right into a chemical feedstock or fuel. Its environmental price, however, relies on the whole manufacturing and shipping pathway. A life-cycle evaluation of 1,1/2 deliberate inexperienced hydrogen centers throughout seventy-two nations proven that renewable strength infrastructure, gadget manufacturing, and hydrogen shipping can make contributions drastically to the ensuing greenhouse fuel Oline footprint [1]. Consequently, assessing hydrogen technology calls for a transition from manufacturing labels closer to measurable overall performance throughout honestly described machine boundaries. Green hydrogen, taken into consideration right here mostly as hydrogen produced thru water electrolysis powered through renewable strength, is consequently a process-established designation in place of an intrinsic belongings of the molecule. Renewable strength can lessen the dependence of hydrogen manufacturing on fossil resources; however, it does now no longer do away with the fabric and environmental burdens related to infrastructure and deliver chains [1]. Recent studies have prolonged this evaluation past greenhouse fuel Oline emissions. Lejeune et al. tested hydrogen manufacturing pathways towards planetary boundaries, demonstrating the significance of comparing environmental pressures past weather extrude alone [2]. These findings set up a critical precept for this paper: enhancements in hydrogen manufacturing must be assessed thru their contribution to the overall performance of the whole machine, such as its aid necessities and environmental consequences. Alongside those developments, hydrogen has emerged as a topic of materials-primarily based biomedical studies. Here, the goal shifts from generating a recoverable bulk product to controlling hydrogen availability inside an organic environment. Zhao et al. investigated palladium hydride nanocrystals as a platform combining hydrogen launch with photothermal remedy in preclinical most cancers models [3]. A next look at tested a semiconductor Nano catalyst that coupled photocatalytic hydrogen technology with an extra oxidative mechanism for experimental most cancers remedy [4]. This research illustrates a rising connection between hydrogen chemistry and healing fabric design, at the same time as additionally displaying that located organic consequences can get up from numerous interacting features inside an unmarried platform. They offer experimental foundations for investigating hydrogen-associated shipping structures in place of setting up their medical effectiveness.

1.2. Nanomaterials as a link between hydrogen production and delivery

Nanomaterials offer a beneficial medical framework for connecting hydrogen manufacturing with its garage and managed launch. Their relevance extends past particle size: floor shape, interfacial chemistry, and the association of lively additives can have an impact on how hydrogen is generated or exchanged with a fabric. Johnson et al., for example, proven that the sides and vertices of palladium nanocrystals modify hydrogen uptake and launch [5]. This dating among shape and hydrogen change affords a mechanistic foundation for designing substances around a required feature instead of choosing them completely consistent with nominal composition. In sun hydrogen manufacturing, development has to in addition join fabric homes with reactor operation. Nishiyama et al. proven photocatalytic water splitting in a 100-m^2 panel array, integrating hydrogen technology with fuel Oline series and separation [6]. The take a look at mounted the feasibility of working a huge outside photocatalytic device, at the same time as additionally

figuring out boundaries in performance and typical power performance. In a special configuration, Zhou et al. pronounced a sun-to-hydrogen performance of 9.2% the use of an indium gallium nitride photocatalyst beneath Neath focused sunlight [7]. These achievements cope with special dimensions of technological development: working scale and conversion performance. Their consequences need to consequently be interpreted within the respective illumination situations, reactor configurations, and device boundaries, instead of being dealt with as interchangeable measures of readiness for deployment. The corresponding layout trouble in biomedical packages worries in which hydrogen turns into available, how swiftly it's far released, and what different methods accompany its transport. Palladium hydride nanocrystals illustrate a fabric-mediated launch strategy, while photocatalytic nanoplatforms illustrate nearby technology beneath Neath outside activation [3,]. These tactics need to be prominent from traditional drug co-transport. A platform combining hydrogen launch with heating is an aggregate treatment, however it does now no longer always deliver a separate pharmaceutical payload. Preserving this difference is important for appropriately comparing the contribution of hydrogen, the carrier, and any accompanying healing component. Taken together, those findings inspire the imperative organizing argument of this paper: the contribution of a hydrogen-associated nanomaterial needs to be judged with the aid of using how its shape controls hydrogen technology, change, or transport beneath the situations required with the aid of using its supposed application. This framework connects the power and biomedical literature without assuming that a fabric optimized for one placing will carry out accurately withinside the different. An important remedy of hydrogen technology ought to join proof acquired at one-of-a-kind ranges. Material characterization can screen a potential mechanism; a managed test can display a useful effect; and a reactor or organic look at can set up overall performance below greater disturbing conditions. None of those ranges independently resolves all questions in a sensible application. The evaluation of large-location photocatalytic operation and high-performance sun conversion illustrates this problem in electricity research [6,7]. Likewise, multifunctional healing systems require cautious attribution of effects whilst hydrogen launch happens along heating or photocatalytic reactions [3,]. Table 1 establishes the application-unique evaluation framework used in the course of the paper. It is supposed to be an analytical manual in preference to a numerical rating of technology. The paper considers literature posted from 2010 thru the literature-seek cutoff in 2026. It adopts an important narrative method, the use of authentic studies to help precise experimental findings and quantitative comparisons. The motive is to discover consequential trends and give an explanation for their importance in the situations below which they have been demonstrated. The dialogue starts with the basics and category of hydrogen manufacturing, observed through traditional and renewable pathways. It then examines inexperienced hydrogen technology and the jobs of nanomaterials in catalysis, storage, and managed release. The biomedical dialogue focuses specially on molecular hydrogen shipping, nearby hydrogen generation, and hydrogen–drug aggregate systems. General nanoparticle drug shipping is addressed simplest wherein it at once informs those functions. Across those topics, the evaluation follows a not unusual place sequence: cloth or system design, proposed mechanism, measured performance, and necessities for application. Environmental evaluation is prominent from catalytic activity, and preclinical healing findings are prominent from medical evidence. This method establishes a coherent foundation for comparing how advances in hydrogen-associated substances can make contributions to each sustainable manufacturing and rising biomedical technology.

Table 1. Assessment framework for hydrogen technologies in energy and biomedical applications [1-7].

Assessment dimension	Energy-oriented hydrogen systems	Biomedical hydrogen-delivery systems
Intended function	Produce and supply hydrogen as a feedstock or energy carrier	Establish a controlled hydrogen exposure at a biological target
Material contribution	Catalysis, light utilization, hydrogen uptake, or product separation	Hydrogen retention, local generation, triggered release, or integration with another treatment
Functional performance	Production rate, conversion efficiency, recoverable hydrogen, and operating stability	Release profile, local exposure, biological response, and duration of effect
Interpretation of results	Account for energy inputs, operating conditions, reactor scale, and system boundaries	Distinguish hydrogen effects from carrier effects, reaction products, and accompanying treatments
Practical assessment	Resource demand, manufacturing, life-cycle impacts, and scale-up	Biodistribution, material persistence, tolerability, manufacturing consistency, and evidence level

2. Fundamentals and Classification of Hydrogen Production

2.1. Physicochemical properties of molecular hydrogen

Molecular hydrogen is a diatomic species with a molar mass of about 2.016 g mol^{-1} [8]. Its low molecular mass contributes to a defining engineering characteristic: excessive power content material in keeping with unit mass along low power content material in keeping with unit extent beneath ambient situations. On a decrease heating fee foundation, hydrogen includes about one 120 MJ kg^{-1}, equal to 33.3 kWh kg^{-1} [9]. Consequently, the overall performance of a hydrogen gadget relies upon now not only on the amount produced but additionally on the power and infrastructure required to collect, condition, store, and supply it. The difference between decrease heating fee (LHV) and better heating fee (HHV) is specifically essential whilst reporting power performance. The HHV consists of the warmth recovered whilst the water shaped throughout hydrogen combustion condenses, while the LHV assumes that this water stays within the vapor phase. For hydrogen, the corresponding values are about 39.4 and 33.3 kWh kg^{-1}, respectively. A performance stated on an HHV foundation is consequently numerically more than the LHV-primarily based totally fee for the identical hydrogen output and power input. These conventions ought to be said explicitly every time manufacturing technology is compared [9,10]. For cloth-mediated garage and biomedical shipping, the applicable residences amplify past heating fee. Hydrogen uptake, retention, and launch depend upon interactions with the host cloth and the encircling environment. The impact of palladium nanocrystal aspects and vertices on hydrogen change demonstrates that cloth shape can regulate launch behaviors even if the nominal chemical composition is unchanged [5]. Consequently, the quantity of hydrogen saved in a fabric and the quantity eventually added beneath software situations are awesome quantities. A beneficial evaluation ought to set up each capability and launch kinetics, in place of infer shipping overall performance from garage capability alone.

2.2. Classification by feedstock, energy source, and carbon intensity

Hydrogen manufacturing is fully categorized the usage of 3 complementary descriptors: the hydrogen-containing feedstock, the conversion pathway, and the electricity deliver. Feedstocks encompass water, hydrocarbons, and biomass-derived compounds; conversion pathways encompass electrochemical, thermochemical, photochemical, and organic processes. These descriptors become aware of the bodily process, while environmental overall performance calls for a separate evaluation of emissions and aid use throughout the deliver chain [1,10]. Colour terminology presents handy shorthand but does now no longer accurately describe all of those dimensions. Grey hydrogen usually denotes fossil-derived manufacturing without carbon seize, whilst blue hydrogen denotes fossil-primarily based totally manufacturing incorporating carbon seize and storage. Green hydrogen usually refers to renewable-powered water electrolysis. However, a shade label does now no longer specify energy consumption, upstream methane leakage, the fraction of carbon dioxide captured, or the remedy of delivery and infrastructure emissions [1,11]. The difference is consequential for each fossil-primarily based totally and electrolytic pathway. Bauer et al. confirmed that the weather overall performance of blue hydrogen relies heavily on upstream methane emissions, carbon dioxide elimination at the manufacturing facility, and the weather metric used [11]. Similarly, the life-cycle evaluation via means of de Kleijne et al. confirmed that renewable-powered hydrogen manufacturing keeps emissions related to its infrastructure and shipping chain [1]. Thus, neither carbon seize nor renewable energy must be handled rather for quantifying the environmental overall performance of a described system. Methane pyrolysis illustrates why chemical type and environmental type must continue to be distinct. Its idealized response produces hydrogen and strong carbon:

$$\mathrm{CH_4(g) \rightarrow C(s) + 2H_2(g)} \qquad (1)$$

Upham et al. established this conversion by the usage of catalytic molten-steel structures that enabled the separation of strong carbon [12]. Although the response itself does now no longer generate carbon dioxide, a whole environmental evaluation has to nevertheless account for methane supply, method electricity, and the eventual destiny of the carbon product. The absence of carbon dioxide within the essential response equation consequently establishes a chemical distinction, in place of a whole life-cycle conclusion. Throughout this paper, technology is therefore recognized with the aid of using their feedstock, conversion method, and electricity source. Carbon depth is dealt with as a calculated outcome, expressed with a said purposeful unit and machine boundary.

2.3. Thermodynamic and kinetic fundamentals

2.3.1. Energy requirements of water splitting

The overall reaction for splitting liquid water is:

$$\mathrm{H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g)} \qquad (2)$$

At about 25 °C and standard-nation situations, the Gibbs free-electricity energy change is 237.1 kJ mol^{-1} of hydrogen, at the same time as the enthalpy energy change is about 285.eight kJ mol^{-1}. Their courting is:

$$\Delta H = \Delta G + T\Delta S \qquad (3)$$

The Gibbs free-electricity energy change represents the minimal reversible electric work; the last electricity may be furnished as warmth. With electrons transferred consistent with the hydrogen molecule, the reversible and thermoneutral voltages are:

$$E^{\circ}_{rev} = \frac{\Delta G^{\circ}}{2F} \approx 1.23\ V \qquad (4)$$

$$E^{\circ}_{tn} = \frac{\Delta H^{\circ}}{2F} \approx 1.48\ V \qquad (5)$$

Where (F) is the Faraday constant. The reversible voltage and thermoneutral voltage consequently describe exceptional electricity balances. Operation underneath the thermoneutral voltage can require warmth absorption; it does now no longer suggest that the general electricity requirement has disappeared [13]. These values observe the said reference situations and ought to now no longer be transferred unchanged to high-temperature steam electrolysis.

2.3.2. Electrode reactions and practical voltage losses

In acidic media, the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) can be written as:

$$2H^{+} + 2e^{-} \rightarrow H_2(g) \qquad (6)$$

$$H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^{+} + 2e^{-} \qquad (7)$$

In alkaline media, the equivalent half-reactions are:

$$2H_2O(l) + 2e^{-} \rightarrow H_2(g) + 2OH^{-} \qquad (8)$$

$$2OH^{-} \rightarrow \frac{1}{2}O_2(g) + H_2O(l) + 2e^{-} \qquad (9)$$

Although the general response is unchanged, the electrolyte adjustments the response surroundings and catalyst requirements. McCrory et al. tested the significance of comparing HER and OER catalysts below explicitly described acidic or alkaline situations the use of a not unusual place experimental protocol [1]. A realistic electrolyze calls for extra voltage to maintain a finite manufacturing rate. A beneficial engineering illustration is:

$$V_{cell} = E_{rev} + \eta_{act,a} + \eta_{act,c} + IR_{\Omega} + \eta_{mt} \qquad (10)$$

Here, the activation overpotentials describe kinetic losses, IRΩ represents ohmic losses, and ηact, represents attention and transport-associated contributions. This decomposition is a version of the mobileular voltage in place of an assertion that the contributions can continually be measured independently. Catalysts can lessen kinetic losses; however, they do now no longer regulate the equilibrium strength requirement of the identical average response [13]. Alternative architectures can redistribute the response steps. Slobodkin et al., for example, proven a decoupled procedure wherein hydrogen and oxygen had been produced in separate cells thru an electrochemical–chemical cycle [15]. Such structures ought to be evaluated over the whole cycle, inclusive of regeneration of intermediates and auxiliary operations. The voltage measured at some stage in one step on my own is inadequate to set up the performance of the general procedure.

2.4. Performance indicators and principles of comparison

2.4.1. Electrochemical production and efficiency

Faradaic efficiency measures the fraction of charge that produces the target electrochemical product. For hydrogen:

$$FE_{H_2} = \frac{2F\, n_{H_2}}{Q} \times 100\% \qquad (11)$$

in which nH2 is the measured quantity of hydrogen in moles and (Q) is the price surpassed for the duration of the corresponding dimension interval. An excessive Faradaic performance shows powerful price usage however does now no longer set up low power intake, due to the fact the working voltage stays relevant. Both product quantification and electric measurements are consequently required [1,15]. At the gadget level, particular power intake is described as:

$$SEC_{el} = \frac{E_{el,system}}{m_{H_2}} \qquad (12)$$

with units of kWh kg^{-1}. The corresponding electricity-based LHV efficiency is:

$$\eta_{LHV,el} = \frac{m_{H_2}\, LHV_{H_2}}{E_{el,system}} \times 100\% \qquad (13)$$

The numerator and denominator have to use regular power units. The gadget boundary has to perceive whether or not energy conversion, pumping, fuel Oline drying, purification, and compression are included. Where outside warmness is supplied, it has to additionally be reported; an electricity-handiest performance isn't a complete power performance [10]. Catalyst screening introduces an extra stage of comparison. Overpotential at a distinct modern-day density is beneficial handiest while electrode area, loading, electrolyte, temperature, and resistance correction are reported. The extensively used benchmark of 10 mA cm^{-2} changed into hired through McCrory et al. withinside the context of sun water-splitting devices [1]. Performance at this screening situation must now no longer be interpreted as proof of sturdiness at business running modern-day densities.

2.4.2. Photochemical production and photon utilization

Photocatalytic hydrogen production needs separate ways to measure how fast the reaction happens, how well it uses light, and how efficiently it converts energy. A mass-normalized hydrogen evolution rate shows how productive a catalyst is compared to its weight, but it still depends on light, the shape of the reactor, and the type of solution used. For a specific light wavelength or a small range of wavelengths, the apparent quantum yield for making hydrogen is usually written as:

$$AQY = \frac{2N_{H_2}}{N_{ph,inc}} \times 100\% \qquad (14)$$

Where N_{H2} is the number of hydrogen molecules made and (N_photons, incident) is the number of photons that hit during the same time period. The factor of two shows that two electrons are needed to form a hydrogen molecule. The basis based on incident photons should be different from the basis based on absorbed photons. Takata etal found that their special type of photocatalyst, which is made with aluminium-doped strontium titanate, can achieve an external quantum efficiency of 96% when light with wavelengths between 350 and 360 nanometers is used [16]. This result shows that the system is using photons very efficiently in the ultraviolet range; however, it does not mean that 96% of all sunlight is being turned into hydrogen. To achieve fair solar water splitting, the efficiency of converting sunlight into hydrogen can be expressed as:

$$\eta_{STH} = \frac{\dot{n}_{H_2}\, \Delta G^{\circ}}{P_{solar,inc}} \times 100\% \qquad (15)$$

Where H_2 is the rate at which hydrogen is produced in moles per second, and the incident solar power is measured across the defined collection area. This phrase explains how sunlight is turned into chemical energy stored in hydrogen. Other things like extra electricity, outside heating, or using up special chemicals need to be considered on their own. Otherwise, the reported value cannot be considered as showing how well sunlight is used to split water into its parts. The different ways of showing large-area photocatalytic activity and high-efficiency performance when using strong sunlight highlight the importance of reporting both how well the conversion works and the setup used in the experiments [6,7]. These differences form the starting point for assessing the production methods in the next part. Comparisons will keep the original operating conditions and normalization rules, and they will connect material findings to process performance only when there is enough evidence to support that link(Table 2).

Table 2. Principal performance indicators and the information required for their interpretation [1,6,7,10,11,14–16].

Indicator	Primary meaning	Essential reporting conditions
Hydrogen production rate	Quantity of hydrogen produced per unit time	Temperature, pressure, collection method, operating duration, and gas composition
Mass-normalized production rate	Productivity relative to catalyst mass	Catalyst loading, reactor geometry, illumination or electrical input, and reaction medium
Overpotential at a specified current density	Electrode polarization required to sustain a reaction rate	Electrolyte, reference scale, temperature, area basis, loading, and resistance correction
Faradaic efficiency	Fraction of charge recovered as hydrogen	Charge integration interval, gas quantification, and collection losses
Specific electricity consumption	Electricity consumed per unit mass of hydrogen	Stack or system boundary, auxiliary loads, outlet pressure, and purity
LHV- or HHV-based efficiency	Hydrogen heating value relative to energy input	Heating-value convention and inclusion of electrical and thermal inputs
Apparent quantum yield	Electron-equivalent hydrogen production relative to incident photons	Wavelength, photon flux, irradiation area, and measurement interval
Solar-to-hydrogen efficiency	Solar energy converted into hydrogen chemical free energy	Solar spectrum, collection area, bias, external heat, and absence or accounting of sacrificial reagents
Operational stability	Retention of performance during operation	Test duration, operating load, cycling protocol, and degradation criterion
Life-cycle carbon intensity	Greenhouse gas emissions per unit of hydrogen supplied	Functional unit, system boundary, electricity supply, upstream emissions, and allocation assumptions

3. Hydrogen Production Pathways

There are different ways to make hydrogen, and each method uses a different chemical source for the hydrogen, requires a different kind of energy, and involves different steps to get a useful product. Hydrocarbon reforming and gasification create mixtures that contain hydrogen, which need more processing and separation to get pure hydrogen. Water-splitting technologies use electricity, light, or heat to create hydrogen and oxygen. Another way involves biological processes, where microbes break down substances or plants use sunlight to transfer electrons, which helps in making hydrogen. These differences affect where energy is lost, how materials

impact the performance, and which limits become important when scaling up. The next parts look at these paths by explaining how the reactions work and by showing the main studies that have been done on them. The comparison shows how well a single reaction works compared to a whole production system.

3.1. Steam reforming, partial oxidation, and autothermal reforming

Steam methane reforming converts methane and steam into a hydrogen-rich synthesis gas. The principal reforming reaction is:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \qquad (16)$$

Additional hydrogen is obtained through the water–gas shift reaction:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad (17)$$

Combining these reactions gives the idealized overall conversion:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \qquad (18)$$

The reforming process needs heat, and the steps that come after that help get hydrogen and separate carbon dioxide. Antonini etal looked at different setups that combine steam-reforming and autothermal-reforming processes. They showed that how well carbon is captured depends on how the entire production system is arranged [17]. Partial oxidation uses a hydrocarbon and a limited amount of oxygen to produce heat through a chemical reaction. For methane, the idealized reaction is:

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \qquad (19)$$

Autothermal reforming uses both oxidation and steam reforming in the same reactor, and the oxidation process helps provide the heat needed for the reforming reaction. How well it works with low-emission hydrogen depends on how well it fits into the overall process and how the carbon-containing streams are handled [17]. A high capture efficiency in one part of the plant doesn't mean the same efficiency is happening everywhere else in the whole plant. Even with a lot of carbon capture, there are still important issues like emissions from plants and methane leaks from earlier stages that need to be addressed [11]. When evaluating different reform paths, it's important to use overall carbon balances for the entire plant and keep the same life-cycle boundaries throughout the comparison.

3.2. Coal and biomass gasification

Gasification converts carbonaceous feedstocks into a mixture containing hydrogen, carbon monoxide, carbon dioxide, methane, and other constituents. A representative steam–carbon reaction is:

$$C + H_2O \rightleftharpoons CO + H_2 \qquad (20)$$

After the water–gas shift process, the amount of hydrogen increases. The amount of useful hydrogen you get depends more on the steps like gasification, cleaning the gas, separating the hydrogen, and getting it back, rather than just how much hydrogen was there to begin with. Biomass adds another layer of reliance on the features of the raw material and the assumptions

made about how it's supplied. Antonini etal looked at three different ways to make wood gas and found that choosing the right method affects both how well the process works and the chances of capturing carbon [18]. Their analysis shows that biomass hydrogen could lead to a net-negative effect on greenhouse gases in certain cases, but it doesn't mean it's always carbon-negative. For both coal and biomass, gas cleanup is an important part of the process. From a process design point of view, a catalyst improvement is only useful if its advantages work well with the real feed and can be combined with removing impurities and purifying hydrogen. Coal-based and biomass-based hydrogen might use some of the same steps in making hydrogen, but when assessing their environmental impact, you have to consider their sources and how carbon moves through the process differently. The comparison unit should be a set amount of clean hydrogen given at a certain pressure, including all the steps before and during its preparation.

3.3. Methane pyrolysis

Methane pyrolysis is a process that breaks down methane into hydrogen and solid carbon, as shown in Equation (1). What makes this method unique is that instead of turning carbon into carbon dioxide, it produces solid carbon as a usable byproduct. Researchers like Upham etal showed that using molten-metal alloys can help in breaking down methane through a catalytic process, allowing the solid carbon to be separated from the liquid mixture [12]. This technique helps tackle a major issue in methane decomposition, where the formation of carbon can both be a useful product and cause problems for the catalyst's performance over time. Their findings highlight how the choice of reactor medium can impact both the efficiency of the catalytic reaction and the ease of handling the final products. Despite these benefits, the environmental advantages of methane pyrolysis depend on the entire process being well-managed. Important factors to consider include the source of heat used, preventing methane leaks, purifying the hydrogen produced, and properly handling the solid carbon. Especially important is where the carbon will end up in the long run—because if it gets oxidized later on, it could reverse some of the environmental benefits. When evaluating the economic side, it's important to clearly distinguish between the revenue generated from a specific carbon product and the potential market value of all the carbon created during large-scale hydrogen production. Therefore, methane pyrolysis should be viewed as a combined process for producing both hydrogen and carbon. High conversion rates of methane are important, but they are not enough on their own; ongoing removal of carbon, consistent operation of the system, and a realistic plan for managing the carbon are also essential.

3.4. Water electrolysis

Water electrolysis is a process that uses electrical energy to produce hydrogen, and this process happens through a pair of chemical reactions that take place at the electrodes, as explained in Section 2. There are several main types or families of this technology, including alkaline electrolysis, proton-exchange-membrane (PEM) electrolysis, anion-exchange-membrane (AEM) electrolysis, and solid-oxide electrolysis. Each of these technologies has its own unique features, such as the type of charged particles that move through the system, the kind of material used as the electrolyte or membrane, the temperature at which it operates, and the materials that work best with the electrodes [10]. Renewable sources of electricity, like solar power, can be used to run electrolysis systems, but this usually involves a separate stage where the electricity is generated. In one study, Jia and colleagues developed a system that combined photovoltaic cells with electrolysis units. They used a triple-junction solar cell connected in series with two polymer-electrolyte-membrane (PEM) electrolyzers.When exposed to concentrated sunlight, this system

achieved an average efficiency of about 30% in converting solar energy into hydrogen over a 48-hour period [19].This result highlights the importance of aligning the electrical output of the solar cells with the energy needs of the electrolysis system. However, it's worth noting that this study didn't test the full performance of a real commercial setup that includes all the additional components and steps required for actual operation. Recent research has emphasized the need to combine good catalytic performance with an efficient electrode design. For example, Kim and colleagues created a nickel-iron porous electrode that serves both as a catalyst and helps move ions through the system in an anion-exchange-membrane (AEM) electrolyzer [20]. Their findings indicate that even if one part of the system, like the catalyst, isn't the best, improvements in other areas—like reducing resistance between layers or making the transport of ions more efficient—can lead to better overall performance. Therefore, water electrolysis requires a balanced and coordinated approach that optimizes the performance of catalysts, electrodes, membranes, power sources, and any other supporting equipment. Section 4 of this report provides a more detailed look at the specific requirements for each technology and the broader system-level considerations that need to be taken into account.

3.5. Photocatalytic and photoelectrochemical water splitting

Photocatalytic water splitting is a process that uses a material capable of absorbing light to create charge carriers, which are essential for driving the reduction and oxidation reactions needed to split water into hydrogen and oxygen. For this process to work effectively, it's important that the generation, separation, movement, and reaction of these charges happen efficiently, without them recombining and losing their energy. Takata etal showed how placing certain catalysts in specific positions on specially modified aluminium-doped strontium titanate particles can greatly improve the use of ultraviolet light. Their work highlights how positioning the sites where reduction and oxidation occur can significantly affect the overall efficiency of water splitting. However, even if a system can use a lot of light in a narrow range of wavelengths, this doesn't necessarily mean it can make effective use of the entire sunlight spectrum, which includes a wide range of wavelengths. At a larger scale, Nishiyama and their group created a photocatalytic panel array that was over 100 square meters in size, complete with systems for collecting and separating the gases produced. This innovation helped in dealing with the challenges of operating on a larger scale and recovering the products, but there were still issues with efficiency and the balance between energy input and output. On the other hand, Zhou etal managed to achieve a solar-to-hydrogen efficiency of 9.2% using a photocatalyst made of indium gallium nitride under concentrated sunlight. These examples show the importance of reporting performance in terms of efficiency, the size of the illuminated area, the operating conditions, and the ability to recover the products, as these all represent separate aspects that influence the overall effectiveness of the system. Photoelectrochemical systems are designed in such a way that light absorption is integrated into an electrode structure. This allows for the separation of charges and the operation of electrochemical reactions to be designed and optimized together, which can enhance the overall process. Landman etal developed a setup where hydrogen and oxygen were generated in separate cells, which helped in overcoming challenges related to the collection and separation of these gases that are produced in different parts of the system, when using solar energy for water splitting. In both photocatalytic and photoelectrochemical systems, it's crucial to differentiate between the production of hydrogen through the process and the actual overall splitting of water. When certain chemicals are used as sacrificial reagents, the chemical reactions involving these reagents are part

of the input into the process. While such experiments can help in understanding and testing the catalytic behavior of materials, the amount of hydrogen produced in these cases should not be directly compared to the results obtained from systems that split water without the use of any additional chemicals.

3.6. Thermochemical water-splitting cycles

Thermochemical cycles break down water into different steps that help restore the material used in the process. In two-step metal-oxide cycles, when the process is done at high temperatures, oxygen is released and the solid becomes less rich in oxygen. After using steam for oxidation, oxygen is added back to the solid and hydrogen is created. For an idealized ceria cycle, these steps are:

$$CeO_2 \rightarrow CeO_{2-\delta} + \frac{\delta}{2}O_2 \qquad (21)$$

$$CeO_{2-\delta} + \delta H_2O \rightarrow CeO_2 + \delta H_2 \qquad (22)$$

In this case, δ stands for the lack of oxygen that happens during the reduction process, assuming that the material is fully returned to its original oxidized state as shown in Equation (22). Chueh et al showed how solar energy can be used to split water and carbon dioxide into fuels, using a reactor made with ceria, and they were able to make fuel repeatedly for more than 500 cycles [22]. The study showed that mixing reversible oxygen exchange with how the reactor is built is important. The material's performance needs to find a good balance between how much it is reduced, how quickly it reoxidizes, and how stable its structure remains. Increasing oxygen release doesn't always lead to better system efficiency if it needs much more heat or harder oxygen removal conditions. Heat recovery, reactor losses, and auxiliary requirements need to be included when measuring the amount of hydrogen produced in each cycle. Chueh and Haile's experiment and study about ceria show how the material works and what conditions are needed for the cycle to function [23].

3.7. Biological hydrogen production

Biological processes use microorganisms' metabolic activities or photosynthesis to help create hydrogen. Their performance is affected by how well they use the substrate, the competing ways their body processes things, the conditions of the culture, and—when relevant—the way light is spread out.

3.7.1. Dark fermentation

The process of dark fermentation enables the generation of hydrogen from organic substrates without illumination. An idealized glucose-to-acetate pathway is:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \qquad (23)$$

Equation (23) shows a specific pathway's stoichiometric yield, not a general result from an experiment. Real cultures give some of their resources to making body parts and also to creating different kinds of dissolved substances. So, the amount of hydrogen produced depends more on how the organism uses its metabolism rather than just how much carbohydrate it eats. Studies on photo fermentation using dark-fermentation byproducts show that leftover organic acids can also be used to make more hydrogen [24].

3.7.2. Photo fermentation and sequential processes

Photo fermentation can use light to help turn the leftover organic materials from dark fermentation into more useful products. Combining the two stages can help use the substrate better, but it also requires proper lighting and makes sure the stages work well together. Lo et al.set up a combined dark and photo fermentation system and linked the gas stream, which had carbon dioxide, to a culture of autotrophic microalgae [25]. Their research shows how making hydrogen and taking in carbon through living processes can work together. Using carbon dioxide in biomass is different from permanently removing carbon; after that, using the biomass still affects the overall carbon balance.

3.7.3. Photosynthetic hydrogen production

Photosynthetic microorganisms provide ways to link light-powered electron movement with the production of hydrogen. A big problem in design is keeping the local environment suitable for making hydrogen while still supporting the life processes of the system. Xu etal arranged algal cells inside microreactors made from droplets, which helped form small environments that allowed hydrogen to be produced even when there was oxygen in the surrounding air [26]. The work shows how the way space is arranged and changes in oxygen levels can affect how living things work. Its importance comes from managing the tiny environment inside cells; applying this idea to a bigger reactor also needs constant output, consistent light spread, and dependable gas collection. Therefore, biological hydrogen production needs to be studied by looking at how the materials used, the energy involved, and the final product are all connected. Hydrogen yield, how much hydrogen is produced, the amount of hydrogen made in a given space, what needs to be done before starting the process, and how well the process works over time all give different but useful information.

3.8. Comparative assessment of production pathways

The various methods discussed earlier address different challenges related to converting materials into usable forms of energy. For instance, reforming and gasification rely heavily on how carbon is handled and how gases are purified. Methane pyrolysis stands out because it focuses on recovering solid carbon as a key part of the process. Electrolysis connects the production of hydrogen to the availability of electricity and the durability of electrochemical components. On the other hand, direct solar and thermochemical methods demand progress in both the materials used and the operation of the reactors, while biological approaches need to combine efficient metabolic processes with effective ways to grow and separate the desired products. The use of nanomaterials plays a significant role in these processes, as they can help with catalytic reactions, manage the flow of substances through electrodes, guide the movement of light-generated charges, or alter the immediate chemical environment where reactions occur. The important question here is whether these material improvements lead to more hydrogen being produced or if they reduce the amount of resources needed when considering real-world conditions (Table 3). This process-focused viewpoint serves as the basis for the in-depth evaluation of green hydrogen technologies presented in Section 4.

Table 3. Comparative assessment of principal hydrogen production pathways.

Pathway	Feedstock and principal energy input	Main conversion feature	Principal development or integration requirement	Representative references
Steam methane reforming	Methane, steam, and heat	Reforming followed by water–gas shift and hydrogen separation	Heat integration, plant-wide carbon capture, and upstream emissions control	[11,17]
Partial oxidation and autothermal reforming	Hydrocarbon, oxygen, and, for autothermal reforming, steam	Oxidation supplies part or all of the reforming heat requirement	Oxygen supply, reactor integration, and treatment of carbon-containing streams	[17]
Coal and biomass gasification	Carbonaceous solids, gasifying agents, and heat	Production of synthesis gas followed by conditioning and separation	Feedstock handling, gas cleanup, hydrogen recovery, and carbon accounting	[18]
Methane pyrolysis	Methane and process energy	Coproduction of hydrogen and solid carbon	Sustained conversion, continuous carbon removal, and carbon disposition	[12]
Water electrolysis	Water and electricity; heat also supplied in some configurations	Electrochemical hydrogen and oxygen production	Electricity supply, cell efficiency, durability, and auxiliary consumption	[10,19,20]
Photocatalytic water splitting	Water and light	Light absorption and surface redox reactions on photocatalytic materials	Broadband photon utilization, charge separation, gas recovery, and reactor scale	[6,7,16]
Photoelectrochemical water splitting	Water and light; electrical	Coupled photoelectrode	Stable interfaces, sufficient	[21]

	assistance in some configurations	and electrochemical operation	photovoltage, and product separation	
Thermochemical cycling	Water, regenerable reactive material, and high-temperature heat	Sequential reduction and steam oxidation	Heat recovery, oxygen removal, material stability, and cycling performance	[22,23]
Dark fermentation	Organic substrates	Metabolic hydrogen production without illumination	Substrate allocation, residual organics, culture stability, and gas recovery	[24,25]
Photofermentation	Organic substrates and light	Light-supported conversion of fermentation products	Light distribution and integration with upstream biological processing	[24,25]
Photosynthetic microbial production	Light and a suitable cultivation medium	Biological electron transfer coupled to hydrogen evolution	Oxygen management, sustained activity, and photobioreactor scale-up	[26]

4. Green Hydrogen Production: Technologies and System Integration

Green hydrogen production involves careful planning and coordination across several key components, including the electrochemical conversion unit, the supply of renewable electricity, the water treatment system, and the hydrogen conditioning equipment. Just because an electrode is efficient on its own doesn't mean the entire plant will be efficient. There are many other factors that affect how much hydrogen is produced and how much it costs, such as electrical conversion losses, the use of auxiliary systems, the way the plant operates over time, and when parts need to be replaced. Because of this, it's important to choose the right technology based on how well it works within the specific energy system it's part of. This section looks closely at the main types of electrolysis technologies and the decisions made during their integration, which ultimately determine how well they perform in real-world settings. A special focus is placed on how the physical properties of materials, the conditions they operate under, and the overall system performance are connected.

4.1. Alkaline water electrolysis

Alkaline water electrolysis relies on an aqueous solution of an alkaline electrolyte, typically potassium hydroxide, with a separator that keeps the hydrogen and oxygen-producing areas apart. In this setup, hydroxide ions help move the electric charge through the solution. The alkaline environment makes it possible to use nickel-based electrodes and other materials that aren't as expensive as those from the platinum group, which is a big plus when choosing materials [10]. However, the efficiency of this process isn't just about how well the catalysts work. Other factors like how far apart the electrodes are, how well the electrolyte conducts electricity, how effectively gases are removed, and how much resistance the separator offers all play a role in determining the voltage needed to run the system. It’s also important that the system can manage the electrolyte and separate the gases well, no matter what conditions it's operating under. Therefore, when trying to improve the performance of the electrodes, it's essential to also look at how changes in resistance and the movement of liquids and gases in the whole cell affect things. Research on integrated alkaline electrode systems shows how important this is. A study on an interconnected catalyst-layer design, for instance, showed how the way the active materials are arranged and how transport paths are set up impact the overall performance of the cell [27]. These approaches link the design of catalysts at the nanoscale with how substances move through the system at a larger scale. To properly evaluate how useful these methods are, they should be tested over a long period of time during steady hydrogen production under defined conditions, not just by looking at the electrode alone.

4.2. Proton-exchange-membrane water electrolysis

Proton-exchange-membrane electrolysis relies on a solid, proton-conducting membrane that separates the electrode sections and allows protons to move from the anode to the cathode. Because this process takes place in an acidic setting, the materials used must be very stable, especially at the oxygen-evolving electrode. As a result, traditional setups often use platinum at the cathode, iridium-based materials at the anode, and parts that are resistant to corrosion on the oxygen side [10]. The membrane and electrode assembly must handle several important tasks at the same time, including allowing protons to pass through, providing good electrical contact, delivering water, and removing gases. Lowering the amount of catalyst used can be helpful, but only if the system continues to work properly over time. If reducing the amount of precious metals leads to quicker breakdown or higher energy use, then the cost might shift from making the system to using electricity and replacing parts. When the system is run in a changing or dynamic way, there needs to be specific evidence about how it performs under different operating conditions. Rakousky etal studied constant versus intermittent power use and found that how much the system breaks down depends on the history of current density applied. In their tests, certain patterns of intermittent power use led to less degradation compared to running the system continuously at high current density [28]. This shows that fluctuating power isn't always worse for the system; its impact depends on the specific operating conditions and the causes of degradation.

4.3. Anion-exchange-membrane water electrolysis

Anion-exchange-membrane electrolysis uses a hydroxide-conducting polymer membrane along with an alkaline electrode setup. This method aims to keep the system compact and based on a membrane while also making it possible to use catalysts that don't contain platinum or other expensive group metals. However, how well the system works depends on several factors, including the membrane itself, the ionomer used in the catalyst layer, the electrodes, and the liquid feed that's being used. It’s important to note that operating with pure water is different from using

an alkaline electrolyte that contains dissolved ions. The presence of these dissolved ions affects how ions move through the system and changes the environment where reactions take place. Because of this, results from experiments using potassium hydroxide as the feed cannot be directly applied to situations where pure water is the feed. In a study by Zheng and their team, they showed that it's possible to carry out pure-water electrolysis without using platinum-group metals by carefully selecting the ionomer and designing the electrode [29].Their work shows that the polymer part in the catalyst layer plays a direct role in how the device operates, not just holding everything together mechanically. Another example comes from the research by Kim and their colleagues, who developed a nickel-iron porous electrode that works well in practical conditions. The performance of this electrode depends on how well the catalytic and transport functions are working together. Overall, these studies highlight the importance of looking at anion-exchange-membrane systems as a whole, considering the combined structure of the membrane and electrodes, as well as factors like resistance at the interfaces, how water is distributed, and how the system holds up under real operating conditions.

4.4. Solid-oxide electrolysis

Solid-oxide electrolysis operates at elevated temperature and commonly uses steam as the hydrogen-containing reactant (Table 4). For an oxide-ion-conducting cell, the steam-electrode reaction is:

$$H_2O(g) + 2e^- \rightarrow H_2(g) + O^{2-} \qquad (24)$$

Oxide ions migrate through the electrolyte and release oxygen at the opposite electrode:

$$O^{2-} \rightarrow \frac{1}{2}O_2(g) + 2e^- \qquad (25)$$

The overall reaction remains water splitting. When the temperature rises, the way electricity is used and heat is added changes, which means combining heat in the system becomes very important for the technology to work well. Electricity use should be reported along with the needs for steam generation and heating [10]. Dynamic compatibility is influenced by how the cells are built and the kind of charging and discharging they undergo. Zhu etal studied metal-supported solid-oxide electrolysis cells that were subjected to steam, thermal, redox, and power cycling. In the tested conditions, the rate at which the material broke down was about the same as the rate for the baseline cell [30]. This shows that the architecture can be adapted as needed, but it still leaves the task of managing heat at a large scale and setting limits based on specific uses for future work.

Table 4. Functional comparison of principal water-electrolysis technologies [10,29-30].

Technology	Electrolyte and principal charge carrier	Material-design opportunity	Main integration requirement	Important comparison condition
Alkaline electrolysis	Aqueous alkaline electrolyte; hydroxide ions	Use of nickel-based and other non-platinum-group materials	Electrolyte circulation, gas separation, and resistance reduction	Report electrolyte concentration and operating range

Proton-exchange-membrane electrolysis	Proton-conducting polymer; protons	Compact membrane–electrode assemblies and catalyst-layer optimization	Water quality, corrosion-resistant components, and operating-profile management	Report precious-metal loading and durability conditions
Anion-exchange-membrane electrolysis	Hydroxide-conducting polymer; hydroxide ions	Non-platinum-group catalysts within a membrane-based architecture	Membrane–ionomer stability and water/ion transport	Distinguish pure-water and alkaline-electrolyte feeds
Oxide-ion-conducting solid-oxide electrolysis	Ceramic electrolyte; oxide ions	Coupling electrical conversion with high-temperature heat	Steam supply, heat recovery, sealing, and thermal management	Include thermal input alongside electricity consumption

4.5. Integration with renewable electricity

Renewable electricity and the electrolyze need to be planned and designed at the same time. The amount of electrolyze capacity that is installed decides how much renewable energy can be used at any given moment, and the pattern of energy generation affects how effectively the electrolyze is used. Hydrogen demand adds another limitation since making and using it might happen at different times. There are three main options: connecting directly to a specific renewable energy source, operating by linking to the power grid, and using a mix that includes both a dedicated energy source and interaction with the grid. These setups vary in how much electricity they have, how they use it, how much they need to store, and how they track emissions. Terlouw etal showed that the way hydrogen is made and where it is produced both affect how much it costs and how much harm it causes to the environment [31].

For time-dependent operation, hydrogen production can be represented by:

$$m_{\mathrm{H_2}} = \int_0^T \frac{P_{\mathrm{el,system}}(t)}{\mathrm{SEC}_{\mathrm{el,system}}(t)}\, dt \qquad (26)$$

In this case, the system's electrical power is shown in kilowatts, the specific electricity use is given in kilowatt-hours per kilogram, and time is measured in hours. The expression is used during the time when hydrogen is being produced; the electricity needed for standby and starting up the system should be added separately to the total energy calculation. It explains that just having enough electricity every year doesn't mean you'll produce a lot of hydrogen each year: how efficiently and how much electricity is used can change depending on how the system is running. Grid connection also requires careful environmental interpretation. Ricks and others did a study on the U.S. power system and found that matching electricity use hour by hour with extra, physically available clean energy sources can greatly lower the emissions from making hydrogen using the grid [32]. Their study shows that keeping track of renewable energy each year might not

show the real effects of using electricity when it happens. The result should be understood based on the study's local area and the way the model was set up.

4.6. Water quality, purification, and resource requirements

Water is both a reactant and a process resource. From the reaction stoichiometry, the theoretical water consumption is:

$$m_{\mathrm{H_2O,stoich}} = \frac{M_{\mathrm{H_2O}}}{M_{\mathrm{H_2}}} m_{\mathrm{H_2}} \approx 8.94\, m_{\mathrm{H_2}} \qquad (27)$$

So, about 8.94 kilograms of water is used chemically for every kilogram of hydrogen that is made. This calculated value does not include losses from purification, cooling needs, blowdown, or other uses within the plant. When evaluating a site, it's important to also differentiate between water withdrawal and net water consumption. The need for water treatment depends on the type of electrolyze being used and the make-up of the source water. Impurities can influence how well electrochemical processes work, make components less stable, and impact how the plant runs. Direct seawater electrolysis involves a different kind of engineering challenge compared to electrolysis that uses purified water. Xie etal created a system that uses a membrane to move water from seawater into another part of the process, and they also used electrolysis. This helped solve some of the problems that happen when using salty water, like unwanted chemical reactions and damage to materials [33]. This work shows a combined approach for supplying water instead of proving that regular electrolysis can work directly with seawater as it is. A plant-level comparison should look at the entire water management process. It's only better to not use a separate desalination unit if the other option can match or beat it in terms of how much hydrogen it gets back, how long it lasts, how easy it is to keep working, and how much of everything it uses overall.

4.7. Techno-economic assessment

The levelized cost of hydrogen expresses the discounted cost of production relative to discounted hydrogen output over a defined project lifetime. A general formulation is:

$$\mathrm{LCOH} = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{m_{\mathrm{H_2},t}}{(1+r)^t}} \qquad (28)$$

In this case, C_t stands for the costs that happen in year t, like the first cost, running costs, replacement costs, and any costs at the end of the life if needed; r is the rate used to reduce future costs to today's value; N is the number of years we're looking at; and $m(H_2,t)$ is the amount of hydrogen produced during that year. Any income from coproducts or residual values has to be clearly addressed. The equation makes two relationships clear. Using less electricity cuts down on the cost of running the system, and using the system more throughout the year helps spread out the fixed costs over a larger amount of hydrogen produced. These goals can clash when using more electricity during times that are either more costly or produce more pollution. Terlouw etal discovered that the costs and environmental effects of big electrolysis projects depend on the type of setup used and the availability of renewable resources [31]. So, a cost estimate should explain the assumptions about electricity prices, how much the system will be used, how it will be funded, how long each part will last, and where the hydrogen delivery starts. A value measured at the stack outlet cannot be directly compared to one that includes compression, storage, and transport.

4.8. Life-cycle environmental performance

Life-cycle assessment looks at the different problems that come up with materials, building, energy use, how the product is used, when it needs to be replaced, and what happens when it's no longer needed. For hydrogen, the basic unit also needs to mention the quality of the product and the conditions for delivering it. A general carbon-intensity expression is:

$$\mathrm{CI}_{\mathrm{H}_2} = \frac{G_{\mathrm{infrastructure}} + G_{\mathrm{energy}} + G_{\mathrm{operation}} + G_{\mathrm{delivery}}}{m_{\mathrm{H}_2,\mathrm{delivered}}} \qquad (29)$$

The top part includes the amount of greenhouse gases, measured in carbon-dioxide-equivalent units, and each part is counted only once within the chosen area. The denominator is the amount of hydrogen provided during the relevant time period. De Kleijne etal showed that the systems used to produce renewable energy and move hydrogen can significantly affect the overall environmental impact of green hydrogen [1]. Ricks and others looked at a related question: how increased demand for electrolysis affects emissions from the power system [32]. Attributional footprints and the effects on the power system address different issues and should be clearly recognized on their own, instead of being mixed together without any explanation. Environmental assessment should also look beyond just greenhouse gases. The study by Lejeune and others highlights the need to take into account wider challenges when hydrogen production grows [2]. So, when we develop new technologies, we need to link better performance of cells with how much materials are needed, how much water is used, the kind of infrastructure required, and how much hydrogen can be produced over time. These system requirements set the background for looking at nanomaterials in Section 5: a material improvement is considered important when it helps make production more efficient and longer-lasting under the full system conditions.

5. Nanomaterials for Enhanced Hydrogen Production

Nanomaterials allow scientists to design hydrogen-producing reactions by carefully managing various aspects like the makeup of the surface, the arrangement of atoms around active sites, the way different parts of the material interact, and how charges move through the material. Their role goes beyond just increasing the surface area available for reactions. For example, a well-designed interface can help break apart water molecules more efficiently, a good conductive support can help move electrons more effectively to where they are needed, and a cocatalyst can guide the energy from light into useful reactions on the surface. It’s important to understand that these different functions can each contribute to improved hydrogen production, but they do so in different ways. Sometimes, similar improvements in hydrogen output can come from different underlying processes. The main challenge in this field is linking how a material is made with how it behaves during the actual reaction. This becomes especially crucial when the catalyst changes its structure while it's working or when the performance is influenced by how the catalyst interacts with other components such as the support, the electrolyte, and the reactor itself.

5.1. Nanoscale structure–activity relationships

The way a nanostructured catalyst works depends on how many places are available for reactions to happen and how good those places are at making the reactions happen. A larger current over the same area of an electrode can happen because of more surface being exposed, better connection for electricity, or each point on the surface working more effectively. These contributions should

be split apart as much as possible by using different ways to normalize them, like considering the amount of catalyst used, the surface area that can take part in electrochemical reactions, and the number of active sites that are clearly supported by their own reasoning. Standardized benchmarking is important for understanding these comparisons [14]. For hydrogen evolution to happen, the surface chemistry needs to help create and remove hydrogen intermediates that are stuck on the surface. In alkaline environments, water splitting adds another necessary condition. A simplified adsorption step is:

$$H_2O + e^- + * \rightarrow H* + OH^- \qquad (30)$$

Here, * represents an available surface site and H* denotes adsorbed hydrogen. Hydrogen can subsequently form through electrochemical desorption:

$$H* + H_2O + e^- \rightarrow H_2 + OH^- + * \qquad (31)$$

or through recombination of two adsorbed hydrogen intermediates:

$$2H* \rightarrow H_2 + 2* \qquad (32)$$

These steps offer a way to understand how a catalyst is designed, but they don't tell you exactly what determines the reaction speed in every case. Subbaraman and their team showed that adjusting the interfaces between lithium-ion, nickel hydroxide, and platinum improved the production of hydrogen in alkaline conditions. This was because the changes helped break apart water molecules more effectively, leading to better hydrogen generation [34]. Their research shows how nearby parts can help with different basic steps in the same chemical process.

5.2. Noble-metal and transition-metal-based catalysts

Noble-metal catalysts are important for understanding how hydrogen is produced, but their performance can be influenced by the environment around them. For instance, Subbaraman etal studied a system that combines nickel-hydroxide with platinum and found that improving the efficiency of hydrogen production in an alkaline environment doesn't always mean replacing platinum. Instead, changing the processes that happen near platinum can also boost its performance [34]. Transition-metal compounds provide different options when it comes to making materials for this purpose. They offer varied chemical compositions, surface properties, and are more widely available than noble metals. Popczun etal showed that nanostructured nickel phosphide can be effective for producing hydrogen, especially when the material has a large surface area and specific crystal faces are exposed [35]. Their work introduced a new way to design materials by combining nickel and phosphorus in different chemical forms, rather than simply swapping one metal for another. It’s important to assess the value of these alternatives at both the electrode and device levels. Replacing a precious metal like platinum could be beneficial if the new material still works well under similar conditions, such as maintaining a good voltage, low material usage, long-lasting performance, and being easy to make. This idea is supported by the integrated nickel-iron electrode discussed in Section 4, which shows that real-world performance depends on how well the active material is connected to the structures that help with transporting electrons and collecting current [20].

5.3. Metal oxides, sulfides, phosphides, nitrides, and carbides

Transition-metal compounds offer a wide range of possibilities for design because adjusting the non-metal component can influence how atoms bond together, how well the material conducts electricity, how the surface interacts with other substances, and how it behaves during chemical reactions. However, when you measure the composition of a material before testing, it might not

be the same as its active form during the reaction. For example, Xu etal showed this difference with nickel selenide under conditions where oxygen is being produced. The material actually changed into a state that included hydroxides, and they used nickel-iron Di selenide as a starting material to create an active oxide catalyst [36]. Therefore, any improvement in performance should be linked to the material that forms during the reaction, not to the original selenide surface that didn't change. Nitrides and carbides show different strategies for creating catalysts that help in splitting water to produce hydrogen. Chen and their group made carbon-supported nickel-molybdenum nitride nanosheets, which had easily accessible places where reactions could happen [37]. In another study, nanostructured molybdenum carbide supported on carbon nanotubes performed better in hydrogen production than the bulk version of molybdenum carbide [38]. These findings highlight how important it is to consider not just the chemical makeup, but also how well the material is spread out and the structure of the support material. If we only classify materials based on their starting form, we might miss important details. To get a clearer picture, it's better to compare how the material behaves during the reaction. We should check which specific form is actually active, whether the components dissolve or redistribute, and whether the support material plays a role in the reaction. This method helps prevent mistakes, like confusing improvements in oxygen production with results from hydrogen production tests.

5.4. Carbon-based and two-dimensional materials

Carbon-based materials can act as conductive supports, while certain carbon-containing semiconductors can also serve as light-absorbing components. These two roles are different and should not be confused. For instance, graphene used as a support for a hydrogen evolution catalyst does not perform the same function as a carbon nitride material that is used for photocatalytic reactions. In a study conducted by Li and colleagues, hydrogen evolution was achieved using molybdenum disulfide nanoparticles that were grown on graphene [39]. This hybrid structure combined the dispersed MoS_2 nanoparticles with a conductive support, showing how a two-dimensional substrate can affect the availability and electrical connectivity of the catalytic sites. Therefore, when comparing different materials, it is important to look at the entire structure, including how well the different components are connected and interact with each other. In the case of photocatalysis, the design challenges go beyond just the support structure and include efficient light absorption and effective charge separation. Zhao etal designed a Z-scheme system using boron-doped, nitrogen-deficient carbon nitride nanosheets for overall water splitting [42]. They reported the production of hydrogen and oxygen in the correct stoichiometric ratios using platinum and cobalt hydroxide as cocatalysts [42]. This study illustrates a system that includes multiple components working together rather than showing that carbon nitride alone can perform all the necessary functions. The two-dimensional structure should be seen as a design choice rather than a guaranteed performance feature. The actual contribution of this structure must be shown through how the materials are assembled and how they interact during the reaction process.

5.5. Metal–organic frameworks and framework-derived materials

Metal-organic frameworks have the ability to arrange catalytic elements inside a porous structure, which allows for better control over how active sites are accessed and how protons move likelihood etal used a porous framework as a support structure for a nickel-sulfur electrocatalyst and showed that this setup significantly improved the rate of electrochemical hydrogen production [40].The framework's role wasn't just about holding the catalyst in place; it also influenced the overall

reaction environment and how the catalytic material was spread out in space. There's an important difference between a catalyst that is made entirely from the framework and one that is derived from the framework. In the first case, the original framework remains part of the working material and contributes to the overall function. In the second case, the framework undergoes some sort of heat or chemical change, creating a new material that needs to be studied on its own. Just because a catalyst starts from a framework doesn't automatically mean it still has all the special properties that the framework originally had. Covalent organic frameworks are a similar type of material, but they work through different chemical reactions. Stegbauer etal showed that a hydrazone-based framework, combined with a platinum cocatalyst and a sacrificial electron donor, could drive hydrogen production using visible light [41]. This experiment showed that an ordered organic framework can function as a key part of a photocatalytic system. However, since the reaction used up a sacrificial reagent, the results should be compared carefully with processes that split water without needing any extra chemicals.

5.6. Heterostructures, cocatalysts, and interfacial engineering

Interfaces let different materials work together to do things more effectively. In electrocatalysis, nearby parts can help with different steps of a reaction or make it easier for electricity to flow. In photocatalysis, the space between materials can affect how electrons and holes move, and where chemical reactions happen. Takata and others showed that putting certain helpers, called cocatalysts, in the right places on aluminum-doped strontium titanate particles can make water splitting very efficient when using ultraviolet light [16]. Zhao and others used a special Z-scheme design made from carbon-nitride to control how charges move and use different helpers [42]. These examples show that how materials are arranged at their edges is just as important as what kind of main material is used. However, just having better hydrogen production doesn't mean we know exactly how the electricity is moving. To really understand how something works, we need proof that shows it's not just other factors, like more light being absorbed, a bigger surface area, more helpers, or different electron behaviors. A good explanation of how an interface works is one that can explain both the results and how the system changes when the material or structure is altered in a controlled way(Table 5).

Table 5a. Representative electrocatalytic nanomaterials and the design principles demonstrated.

Material or architecture	Reaction or application	Design strategy	Research finding and interpretation	Reference
Li^+–$Ni(OH)_2$–Pt interfaces	Alkaline hydrogen evolution	Couple water-dissociation promotion with hydrogen-active sites	Demonstrated interfacial enhancement of hydrogen evolution; the effect depends on the local chemical environment	[34]
MoS_2 nanoparticles on graphene	Hydrogen evolution	Integrate dispersed catalytic domains with a conductive support	Demonstrated a hybrid catalyst architecture; support and active-phase contributions must be considered together	[39]

Carbon-supported Ni–Mo nitride nanosheets	Hydrogen evolution	Combine compound formation with nanosheet morphology	Established a non-noble-metal nitride route with accessible reactive sites	[37]
Ni_2P nanoparticles	Hydrogen evolution in acidic solution	Control particle structure and exposed facets	Demonstrated hydrogen-evolution activity of nanostructured nickel phosphide	[35]
Carbon-nanotube-supported Mo_2C	Hydrogen evolution	Disperse carbide domains on a conductive support	Improved activity and stability relative to bulk Mo_2C under the reported conditions	[38]
Framework-supported Ni–S	Hydrogen evolution	Modify catalyst distribution and proton-transfer environment	Demonstrated that a porous framework can contribute to reaction promotion	[40]
Nickel–iron diselenide-derived oxide	Oxygen evolution	Use a reconstructing precursor to generate an active oxide	Identified the distinction between the synthesized precursor and the operational catalyst	[36]
Integrated Ni–Fe porous electrode	Anion-exchange-membrane electrolysis	Combine catalytic and transport functions	Demonstrated the importance of electrode architecture for practical cell performance	[20]

Table 5b. Representative photocatalytic systems and the conditions governing interpretation.

Photocatalytic system	**Design strategy**	**Demonstrated result or contribution**	**Essential interpretation condition**	**Reference**
Hydrazone-based covalent organic framework with Pt	Ordered organic light-absorbing framework	Visible-light-driven hydrogen evolution	Sacrificial donor was used; distinguish from overall water splitting	[41]
Modified Al-doped $SrTiO_3$ with selectively positioned cocatalysts	Spatial control of reduction and oxidation sites	External quantum efficiency up to 96% at 350–360 nm	Narrow-band quantum efficiency is not broadband solar efficiency	[16]
Boron-doped, nitrogen-deficient carbon-nitride Z-scheme system	Defect, composition, and interface engineering	Overall water splitting with complementary cocatalysts	Evaluate the complete multicomponent system	[42]

Particulate photocatalyst panel array	Integration of catalyst sheets and gas recovery	Outdoor operation at a 100-m^2 scale	Scale, energy balance, and separation performance remain distinct measures	[6]
InGaN-based photocatalytic system	Material and operating-condition integration	Reported solar-to-hydrogen efficiency of 9.2%	Concentrated illumination and experimental conditions must accompany the value	[7]

5.7. Synthesis, characterization, and mechanistic investigation

Synthesis controls how the material starts—like how it's made, the size of its pieces, any flaws, where parts meet, and how much space is open inside. A good way to make the material should figure out which of these things it wants to change and how to check if it worked. Changing one thing during making might affect many other things at once, so it's hard to say exactly what caused a change without proper checks. When testing the material, you need to look at it in three ways: how it was first made, how it behaves during a reaction, and how it looks after the test. For example, in some oxygen-making catalysts made from selenium, the active part isn't clear just from the first check, which shows why more work is needed. When doing electrical tests, you must control things like how much material is used, the size of the area being tested, the liquid used, any resistance issues, and how much product is made. A method by McCrory and others helps separate how active the material is, how much surface area is available, and how long it lasts. For materials that use light, you also need to report on the light used, how much help from other materials is there, what liquid is used, and how light efficiency was calculated. To understand why a material works better, you need to use these tests to tell apart different possible reasons. For example, a material placed on a surface may work better than powdered material because it spreads out better or connects better electrically, without needing to change how active the material's spots are. Similarly, a faster reaction might be because it catches more light, not because it moves charges better. Knowing where the improvement comes from makes the results easier to use for making new materials and better equipment.

5.8. Catalyst stability, degradation, and scalable manufacturing

Activity and durability need to be looked at together. A catalyst that starts with a high reaction speed might not be very useful in real situations if its shape, makeup, or electrical connection changes too quickly while it's working. On the other hand, if the catalyst is activated or changes in a controlled way, it can work well. This is different from it getting worse over time. For electrolysis, how the material is used over time is important. A study by Rakousky et al. found that how much current is used affects how the material breaks down in proton-exchange-membrane cells [28]. These findings suggest that tests should be done under conditions that match how the catalyst will actually be used, including changes in how much load is applied, instead of only using short tests with fixed conditions. Making the material also brings another challenge: the good structure of the material needs to stay the same when it's put into an electrode, coating, or reactor. The integrated nickel-iron electrode made by Kim et al. shows a way to think about both how the material is prepared and how the electrode is designed [20].At a bigger scale, the 100-square-meter

photocatalytic test by Nishiyama et al.shows that how the catalyst is used must be matched with how the product is collected and separated [6].So, the best way to develop new materials is by linking how they are made with how they are used, how long they last, and how much hydrogen they can produce. These ideas also apply to materials used for storing and delivering hydrogen, even though the conditions they need to work under and what makes them successful can be different. Section 6 looks at how these materials move from being made to being used, focusing on how much hydrogen they can take in, keep, release in a controlled way, and produce locally.

6. Hydrogen Storage, Controlled Release, and Local Generation

Hydrogen production and hydrogen availability are different engineering issues. A material might make hydrogen very efficiently, but it might not control how much hydrogen is kept, moves around, or is released later. On the other hand, a material used to store hydrogen might hold a lot of it, but it might only give out a small part of that amount within the time, pressure, and temperature needed for a specific use. This difference is especially important when moving from energy systems to medical applications. For energy storage, the main goals are to get as much hydrogen as possible back, use it efficiently over time, and keep the system small or light. In medical uses, the focus is on how much hydrogen is exposed locally, how long it stays, where it goes in the body, and any chemical changes that happen. The main challenge is to understand how the properties of the material affect how much hydrogen is actually available under certain conditions.

6.1. Storage and delivery requirements across applications

Hydrogen storage performance needs to clearly show the highest amount of hydrogen it can take in compared to how much can actually be released. Maximum uptake means the amount of hydrogen that is kept under certain conditions of loading. Deliverable capacity is the amount of hydrogen that can be released when moving from one charging condition to another discharging condition. For a material where the amount taken in is measured based on a consistent mass basis:

$$q_{\text{deliverable}} = q\left(P_{\text{charge}}, T_{\text{charge}}\right) - q\left(P_{\text{discharge}}, T_{\text{discharge}}\right) \qquad (33)$$

In this case, q stands for hydrogen uptake, P represents pressure, and T stands for temperature. The equation includes the operating window as part of the performance definition. Chen etal looked at this balance in materials that have lots of tiny spaces, and they found that these materials can hold a lot of hydrogen when both temperature and pressure change together [43]. These results can't be understood on their own without considering how the device was charged and discharged, and they can't be used directly in applications that operate at normal room temperature. Material-level capacity must also be separated from the overall system capacity. Containment, heat exchange, insulation, and other supporting parts add weight and take up space without having to increase the amount of hydrogen stored. So, just because a single material can hold a lot of energy on its own, it doesn't mean the whole system that uses it can do the same. In biomedical uses, the important result is usually a graph showing how concentration changes over time at a specific place. The total amount of hydrogen linked to a given material that is given does not by itself show how much someone is exposed to it. Hydrogen that is released outside the intended area, stays inside the carrier, or is lost before it is given can affect the amount that actually reaches the target. This encourages doing separate tests for loading, release, and local availability.

6.2. Adsorption- and hydride-based hydrogen storage

6.2.1. Adsorption in porous materials

Porous materials hold hydrogen by interacting with the internal surfaces of the material. How well they work depends on factors like the amount of space inside the pores, how strongly hydrogen sticks to the material, how dense the structure is, and the conditions under which they operate. Making the material more porous can increase how much hydrogen is stored per unit weight but may also reduce how much material fits into a certain space. Because of this, both how much hydrogen is stored per weight and how much is stored per volume need to be considered together. Chen and others showed this challenge in very porous material structures [43]. Recently, Zhang and others reported on supramolecular crystals that can store a lot of hydrogen when conditions like temperature and pressure are changed [44]. These studies show that the design of the pores affects both how much hydrogen is stored per weight and per volume, but it still depends a lot on the operating conditions. For clear comparisons, adsorption data should include details like temperature, pressure, and whether the hydrogen storage is measured as excess, absolute, or total. The way density is calculated to convert weight-based storage to volume-based storage should also be clearly stated.

6.2.2. Hydrogen storage in hydrides

Hydrides keep hydrogen by mixing it chemically into a material that holds it. For magnesium, the idealized reversible reaction is:

$$\mathrm{Mg} + \mathrm{H_2} \rightleftharpoons \mathrm{MgH_2} \qquad (34)$$

The maximum amount that can be stored and how it is released rely on factors like thermodynamics, how fast reactions happen, how easily the surface can be reached, and how heat is moved. Nanoscale design can change how fast reactions happen and how materials move, but better reaction speeds don't always mean the reaction needs to reach a different final state. Jeon etal showed that magnesium nanocomposites can stay stable in air while still quickly storing hydrogen, and they did this without using heavy metal catalysts [45]. Their work shows how a surrounding material can guard reactive substances while helping hydrogen move around. Palladium provides a different hydrogen-host system. Johnson etal found that the different faces and corners of nanocrystals affect how much hydrogen they can take in and let out [5]. In this case, the way something looks on the surface affects how people exchange things. These results suggest that particle shape and the boundaries between materials should be considered as important design factors, not just focusing on the overall makeup of the storage material.

6.3. Hydrogen-containing and hydrogen-generating platforms

A helpful difference is between platforms that have hydrogen already loaded and those that make hydrogen by having a reaction happen right where it's needed. Some systems include these functions together, but each one's role should still be clear. Hydrogen-containing platforms release an existing supply of hydrogen, which can be dissolved, attached to surfaces, or part of a material that holds hydrogen. Their operation is limited by how much they can carry, how well they hold on during handling, and the conditions that allow them to be released. The palladium-hydride

nanocrystals studied by Zhao et al. show a combination of material-assisted hydrogen release and photothermal properties [3]. Hydrogen-generating platforms instead consume reactants locally. For magnesium reacting with water, the simplified overall reaction is:

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 \qquad (35)$$

Equation (35) shows how magnesium is used up in a chemical reaction, not how hydrogen stored in a magnesium hydride can be released again. Yang etal created magnesium rods coated with platinum. These rods kept producing hydrogen by speeding up the reaction with water through a process called galvanic acceleration [46]. The system also changed the nearby chemical environment by forming magnesium reaction products. Therefore, you can't fully understand its biological effects just by looking at how much hydrogen it produces. The rods are an implantable platform, not a nanoparticle carrier, and are included here as an example of how local generation works. Photocatalytic platforms offer another way to generate energy locally. Zhao etal studied a nano catalyst that was able to produce hydrogen and also showed extra photocatalytic effects in early-stage cancer models [4]. These systems need to find where the electrons come from, figure out the oxidation reaction that goes with it, and also identify any other substances that are involved in the reaction. Just having hydrogen evolution doesn't mean water is being split overall, and it doesn't prove that hydrogen is the only reason for a biological reaction.

6.4. Release kinetics and stimulus-responsive control

Controlled release needs more information than just the total amount collected at the end of the experiment. Two systems can release the same total amount of something, but they might create very different levels of exposure. Important factors to consider are when the effect starts, the initial strong response, how long the effect lasts, and how much is still present after the time being observed. For a hydrogen-loaded carrier, the total amount released can be written as:

$$f_{\text{released}}(t) = \frac{n_{H_2,\text{released}}(t)}{n_{H_2,\text{loaded}}} \qquad (36)$$

This definition needs a starting list that is set up on its own. For a material that produces hydrogen as a result of a reaction, it's better to use a conversion yield based on the chemical amounts of the reactants rather than a value based on the amount of hydrogen already stored. The ability to release hydrogen can be affected by factors like temperature, pressure, exposure to radiation, and the type of solution or environment in which the reaction takes place. The palladium-hydride platform looked at by Zhao et al.had the ability to respond to near-infrared light [3]. However, the release of hydrogen that depends on a stimulus and the heating that also depends on a stimulus are two different results and should be measured separately when figuring out how each one contributes. A local concentration balance offers a helpful way to think about things.

$$\frac{dn_{H_2,\text{local}}}{dt} = R_{\text{generation}} + R_{\text{release}} - R_{\text{outflow}} - R_{\text{consumption}} \qquad (37)$$

All terms are given in mol s^{-1} for a specific compartment. The balance shows that the generation rate alone doesn't fully explain the local concentration because factors like removal, redistribution, and chemical reactions also play a role. In a real living system, the right transport terms need to be

figured out for the experiment model, not just taken for granted based on what happens in a basic lab solution(Table 6).

Table 6. Comparison of hydrogen-storage, release, and local-generation platforms.

Platform	Hydrogen source or inventory	Principal control variables	Appropriate performance measures	Important interpretation boundary	references
Porous adsorbent	Previously adsorbed molecular hydrogen	Pressure, temperature, and pore architecture	Deliverable gravimetric and volumetric capacity	Specify the operating swing and uptake convention	[43,44]
Reversible magnesium-hydride system	Hydrogen chemically incorporated during charging	Temperature, pressure, interfaces, and heat transfer	Recoverable capacity, kinetics, and cycling retention	Distinguish reversible storage from magnesium hydrolysis	[45]
Palladium-based hydrogen host	Hydrogen incorporated into palladium	Hydrogen content, surface structure, temperature, and activation conditions	Uptake, retention, and time-resolved release	Material mass does not independently establish hydrogen dose	[3,5]
Magnesium-based local generator	Reaction of magnesium with the surrounding medium	Surface condition, galvanic coupling, and solution chemistry	Hydrogen-generation rate, conversion, and reaction-product formation	The metal is consumed and local chemistry also changes	[46]
Photocatalytic local generator	Light-driven redox chemistry	Illumination, charge transfer, and available reactants	Hydrogen rate, reaction balance, and accompanying products	Separate hydrogen effects from other photocatalytic effects	[4]
Hydrogen-containing aqueous phase	Dissolved molecular hydrogen	Partial pressure, temperature, composition, and containment	Dissolved concentration and retention over time	Equilibrium solubility does not establish sustained exposure	[47]

6.5. Hydrogen quantification and measurement limitations

Hydrogen measurements must distinguish gas-phase accumulation, dissolved concentration, and hydrogen retained in a material. A measurement of one compartment does not necessarily represent the total inventory or the amount delivered to a biological target. For dilute aqueous solutions at equilibrium, Henry's law relates dissolved concentration to hydrogen partial pressure:

$$c_{\mathrm{H_2}} = H_{\mathrm{s}}^{cp}\, p_{\mathrm{H_2}} \qquad (38)$$

In this case, the solubility-form Henry constant is measured in units of mol per cubic meter per pascal when concentration is given in mol per cubic meter and pressure in pascals. Sander's collection shows values close to 7.8×10^{-6} mol per cubic meter per pascal for hydrogen in water at 298.15 K [47]. At a hydrogen partial pressure of 1 bar, this equals about 0.78 millimoles per liter, or 1.6 milligrams per liter. These are equilibrium values under the mentioned conditions, not the concentration found in water under normal air conditions. Therefore, gas and liquid measurements should be considered together when hydrogen moves between different phases. Factors like temperature, the amount of gas space, how samples are taken, and how gas is removed can influence the amount of hydrogen observed. It's also important to tell the difference between hydrogen partial pressure and total pressure. For closed experiments, a helpful way to keep track is:

$$n_{\mathrm{H_2,accounted}} = n_{\mathrm{gas}} + n_{\mathrm{dissolved}} + n_{\mathrm{retained}} + n_{\mathrm{removed}} \qquad (39)$$

The term that has been removed refers to hydrogen that is taken out either through sampling or by intentionally collecting it. If there is any leakage or chemical reaction happening, these extra factors need to be taken into account before someone can say that there is a closed balance. In the context of biomedical interpretation, if someone is presenting a bulk release curve, they should also provide evidence that relates to where the action is happening in the body. It's important to remember that carrier accumulation, hydrogen production, and the therapeutic results are all separate things to observe. To figure out how these things are connected, it's necessary to have proper controls for the carrier, the reaction byproducts, and any other treatments that might be involved. This clear distinction forms the foundation for Section 7, which looks at hydrogen-based delivery systems and the biological evidence that supports them.

7. Hydrogen-Related Nanoplatforms for Drug Delivery and Biomedical Applications

Using hydrogen in medicine has different design needs compared to making it as an energy source. In industry, they care about how well hydrogen is made, how much is made, how long it lasts, and how much it costs. For medicine, there are more things to think about, like how much hydrogen reaches the body, how it is released, how the material breaks down, and how the body reacts. So, a material that makes a lot of hydrogen in a lab isn't good enough for medicine unless it can actually deliver the right amount of hydrogen to the right part of the body. There are three main ways to use hydrogen in medicine: giving hydrogen that's already been stored, making hydrogen right where it's needed from another substance, and giving hydrogen along with other medicine. Each

method works differently, has different effects on the body, and needs different steps to be used in real medical situations. The next parts of this discussion look at studies from 2010 to 2026, focusing on the difference between what works in experiments and what is actually helpful in real medical treatment.

7.1. Biological Rationale and Proposed Mechanisms

The reason for studying molecular hydrogen is based on its possible effects on oxidative damage, inflammation, and how cells manage their balance of chemicals. But just saying hydrogen is an antioxidant doesn't explain everything about how it works. To understand how it works, we need to find out which molecules it interacts with, how much of it is needed for those interactions, and how that leads to the changes we see in the body. Jin and others looked at a system called oxidized iron-porphyrin and found that hydrogen can cause certain chemical reactions under specific lab conditions. Their research suggests that hydrogen might be involved in important chemical reactions in the body. However, showing that these reactions happen doesn't mean the same process is happening the same way in all parts of the body, in different diseases, or with different ways of delivering hydrogen. More studies are needed, especially ones that use clear and measured amounts of hydrogen. In the field of nanomedicine, a big challenge is figuring out exactly what part each part of the treatment plays. A treatment might release hydrogen, change the pH, make heat, give out metal ions, or affect how cells take in the medicine. So, if we see a drop in markers of oxidative stress, we can’t be sure it’s only because of the hydrogen. To properly understand how it works, experiments should compare the whole treatment with the carrier without hydrogen, the hydrogen by itself, and other controls that match up with other active parts of the treatment.

7.2. Conventional Administration and Delivery Barriers

Conventional methods involve breathing in hydrogen or using liquids that contain hydrogen. These ways of giving hydrogen don't need nanoparticles to carry it, but the amount given and the amount that actually reaches a certain part of the body are not the same. As talked about in Section 6, factors like how hydrogen dissolves, how much escapes as a gas, how it spreads through the body, and when it's given, all affect how much hydrogen is actually available. One example of this is the HYBRID II trial, where patients who had a cardiac arrest outside the hospital were given a gas mix with 2% hydrogen for 18 hours [49]. This is a clear way of giving gas, but it doesn't show what happens when hydrogen is made by nanoparticles. So, the idea behind giving hydrogen directly to the affected area is based on the idea that keeping the hydrogen source close to the problem area might create a better pattern of hydrogen levels over time. To prove this idea, we need to compare it directly with simpler ways of giving hydrogen. Making things more complicated in the formula is only worth it if it leads to real improvements in how much hydrogen gets to the right place, how well it works, or how well the patient handles it.

7.3. Nanocarriers for Hydrogen Delivery

Nanocarriers can feature as hydrogen reservoirs, shielding packing containers for reactive precursors, or scaffolds that integrate transport with imaging and outside activation. These capabilities must be diagnosed one by one due to the fact they decide what the components clearly transport. Palladium hydride nanocrystals illustrate the reservoir approach. Zhao et al. evolved $PdH_{0.2}$ nanocrystals that blended hydrogen garage with near-infrared absorption, photothermal conversion, and photoacoustic imaging [3]. The platform enabled externally managed hydrogen launch along the warmness era in experimental most cancers treatment. Its healing interest should

consequently be interpreted because the reaction to a multifunctional cloth, which includes the contribution of photothermal treatment. An opportunity is to encapsulate a hydrogen-producing compound. He et al. loaded ammonia borane into ultrasmall amino-changed mesoporous silica nanoparticles and integrated the debris right into a gelatin–polyethylene glycol assembly [50]. Here, the transported shipment turned into a chemical hydrogen precursor. This difference subjects due to the fact the carrier, precursor, generated hydrogen, and response merchandise all require characterization. Carrier overall performance must therefore be pronounced thru each cloth and publicity measurements: precursor loading, untimely launch, hydrogen-era kinetics, colloidal stability, and hydrogen availability below situations applicable to the meant application.

7.4. Nanomaterials for In Situ Hydrogen Generation

Local hydrogen technology gives a method of linking fuel Oline manufacturing to the tissue surroundings or an outside stimulus. Its realistic price relies upon whether or not the activating situations are reachable and whether or not the accompanying chemical differences are biologically acceptable. Photocatalytic structures show each the possibilities and interpretive complexity of this approach. Zhao et al. said a $SnS_{1.68}$–$WO_{2.41}$ Nano catalyst that generated hydrogen and oxidative holes below near-infrared irradiation [4]. The proposed remedy blended reductive and oxidative processes. Accordingly, the organic reaction can't be defined because of the motion of hydrogen alone. A 2026 examine prolonged neighborhood technology to an enzyme-containing biomaterial. Ji et al. designed a peptide–nanocluster hydrogel that created an oxygen-depleted microenvironment to help hydrogenase activity [51]. The paintings illustrate how the neighborhood chemical surroundings can decide whether or not a hydrogen-generating catalyst stays practical in a biomedical setting. For each chemical and enzymatic platforms, the applicable evaluation consists of the supply of lowering equivalents, catalyst stability, byproduct formation, and hydrogen manufacturing below sensible tissue situations. Hydrogen evolution measured in an optimized response vessel is inadequate proof of powerful manufacturing after administration.

7.5. Targeting and Stimulus-Responsive Release

Targeting includes numerous awesome processes: achieving the diseased tissue, penetrating its inner structure, getting into applicable cells, and activating the hydrogen supply at the precise location. Success at one level does now no longer show achievement on the others. The size-switchable machine advanced with the aid of using He et al. illustrates this sequential design [50]. Matrix metalloproteinase-2 degraded the gelatin component, exposing smaller silica nanoparticles, even as acidic situations promoted hydrogen launch from ammonia borane. The authors suggested tumor-increase suppression in the aT1 tumor-bearing model. These outcomes assist similarly research of sequential activation, despite the fact that the identical shipping conduct can't be assumed for human tumors with specific extracellular matrices and enzyme distributions. Stimulus responsiveness has to be evaluated quantitatively. For a pH-responsive machine, launch measurements have to distinguish situations in blood, extracellular diseased tissue, and intracellular acidic compartments. For externally activated systems, experiments have to specify the strength achieving the remedy web page and distinguish stimulus-triggered hydrogen launch from different consequences of activation.

7.6. Hydrogen–Drug Co-Delivery Systems

Hydrogen–drug co-shipping calls for a formula that supplies each a hydrogen supply and a pharmacologically energetic drug. Combining hydrogen with light, heat, or an imaging

characteristic does now no longer fulfill this definition. Wang et al. evolved polyethylene glycol-changed hole mesoporous polydopamine nanoparticles containing ammonia borane and doxorubicin [52]. The formula becomes designed for acid-responsive hydrogen era and chemotherapy of drug-resistant tumors. The authors related the remedy reaction with adjustments in intracellular shipping and mitochondrial strength metabolism. These findings offer a particular experimental instance of hydrogen-assisted chemotherapy, whilst their applicability stays depending on the examined formula and sickness model. An important problem is the connection between drug publicity and hydrogen publicity. Loading each additive into one particle does now no longer assure simultaneous launch or the right neighborhood ratio. Formulation research has to consequently degree the discharge of every element independently and study how their timing affects healing activity. The minimal informative assessment incorporates the unloaded carrier, hydrogen-producing formula, drug-loaded formula, and entire co-shipping system. A free-drug comparator is also wanted whilst advanced drug shipping is claimed.

7.7. Hydrogen-Based Combination Therapies

Combination remedy incorporates a broader class than drug co-delivery. Hydrogen may be mixed with photothermal remedy or photocatalytic hobby without incorporating a traditional pharmaceutical. The palladium hydride platform defined via way of means of Zhao et al. mixed hydrogen launch with warmness generation [3], while the $SnS_{1.68}$–$WO_{2.41}$ machine mixed hydrogen manufacturing with oxidative photochemistry [4]. Together, those research displays materially unique approaches to integrating hydrogen into experimental remedy platforms. Evaluation must distinguish stepped forward mixed hobby from verified synergy. A mixture that outperforms element by me might also additionally nevertheless produce an additive response. A synergy declares calls for the appropriate interplay evaluation throughout applicable remedy levels. Controls need to additionally replicate the platforms bodily behavior. Photothermal comparisons require matched temperature histories, even as photocatalytic comparisons require evaluation of oxidative species and catalyst-related effects. These controls assist set up whether or not hydrogen contributes independently, modifies the accompanying remedy, or simply correlates with some other energetic process.

7.8. Selected Applications in Cancer, Inflammation, and Wound Healing

The most cancer research mentioned above looks at hydrogen as a part of structures meant to regulate tumor-mobiliary responses or enhance an accompanying treatment. Wound-recuperation packages place more emphasis on controlling inflammation, helping tissue restore, and handling infection. Bi et al. suggested a liquid-steel dressing combining antibiotic transport with hydrogen era for diabetic-wound packages [53]. This method hyperlinks a traditional antimicrobial feature with an experimental hydrogen-related anti-inflammatory feature. Evaluating the entire dressing calls for distinguishing those contributions from the consequences of the dressing fabric itself. In the 2026 hydrogenase study, Ji et al. suggested decreased oxidative-strain signals, modifications in macrophage polarization, and elevated restore in a diabetic wound model [51]. These findings aid the research of enzyme-enabled neighborhood hydrogen production. They continue to be preclinical observations, and wound closure by myself does now no longer set up recovery of regular tissue strength, resistance to reinfection, or long-lasting recuperation.

Table 7. Representative hydrogen-related delivery platforms and the principal questions governing their interpretation.

Platform	Hydrogen-related function	Additional function	Evidence discussed
$PdH_{0.2}$ nanocrystals [3]	Stored hydrogen with externally controlled release	Photothermal treatment and photoacoustic imaging	Preclinical cancer study
$SnS_{1.68}$–$WO_{2.41}$ nanocatalyst [4]	Photocatalytic hydrogen generation	Oxidative-hole generation	Preclinical cancer study
Size-switchable silica assembly [50]	Delivery of ammonia borane for local hydrogen generation	Enzyme-responsive carrier disassembly	4T1 tumor-bearing model
Ammonia borane/doxorubicin-loaded polydopamine [52]	Hydrogen generation from a co-loaded precursor	Chemotherapy	Experimental drug-resistant tumor treatment
Liquid-metal dressing [53]	Local hydrogen generation	Antibiotic delivery	Experimental diabetic-wound application
Hydrogenase-containing hydrogel [51]	Enzyme-mediated hydrogen generation	Local microenvironment control	Preclinical diabetic-wound model, 2026

7.9. Biodistribution, Clearance, and Biosafety

Evaluation of a hydrogen-transport platform needs to comply with the destiny of its character components. Hydrogen publicity, nanoparticle distribution, precursor conversion, and cloth clearance are associated with these awesome processes. The disappearance of hydrogen from a tissue can't set up the removal of the provider that brought it. For metal-containing formulations, applicable measurements encompass tissue-related metal, dissolution products, persistence, and repeated-publicity effects. For precursor-loaded systems, the evaluation needs to moreover account for unreacted precursor and response products. For enzyme-containing materials, retained pastime and components balance are critical overall performance variables. The research summarized in Table 7 encourages a component-resolved assessment framework. Within that framework, short-time period tolerability findings need to be interpreted in the report duration and measurements used. Establishing a positive protection profile calls for linking administered dose to neighborhood hydrogen publicity, systemic cloth publicity, and the period of provider retention.

7.10. Preclinical Evidence and Clinical Translation

Human evidence must be interpreted according to the intervention actually tested. HYBRID II randomized 73 patients to hydrogen-containing gas or control treatment after cardiac arrest [49]. Favorable neurological outcomes at 90 days occurred in 56% and 39% of patients, respectively, but the difference in the primary endpoint was not statistically significant ($P = 0.15$). Enrollment ended prematurely because of pandemic-related restrictions. Favorable secondary outcomes warrant further investigation, but they do not establish efficacy for nanoparticle-mediated hydrogen delivery. For nanoplatforms, translation requires a reproducible relationship between formulation properties, tissue exposure, biological mechanism, and clinically meaningful

outcomes. Priority should be given to studies that quantify hydrogen exposure at the treatment site, establish the contribution of each formulation component, and compare the complete platform with an appropriate standard treatment. The connection to green hydrogen is principally technological: catalysis, storage, interfacial chemistry, and release control inform both fields. Environmental performance and therapeutic performance nevertheless require separate evidence. A low-emission production route does not demonstrate biomedical suitability, and therapeutic activity does not establish the environmental sustainability of a nanomaterial's manufacture.

8. Scale-Up, Sustainability, and Translational Challenges

Progress in hydrogen technology relies upon connecting cloth overall performance with the necessities of the meant application. For inexperienced hydrogen manufacturing, this connection entails dependable operation, aid availability, production capacity, and environmental overall performance. For biomedical delivery, it entails reproducible formulation, managed tissue exposure, organic activity, and clearance. Although each field gains from advances in nanoscale materials, their measures of achievement vary substantially. This segment develops a comparative framework for comparing those challenges. The crucial goal is to discover which cloth upgrades stay beneficial whilst integrated right into a whole manufacturing gadget or healing platform.

8.1. From Laboratory Performance to Practical Operation

Laboratory experiments set up whether or not a proposed fabric or response pathway is promising. Practical implementation calls for demonstrating that the gain persists beneath the running situations of the entire system. In electrolysis, catalyst interest has to translate into electrode and stack performance. Relevant variables consist of catalyst loading, electrode thickness, ionic and digital resistance, fuel Oline removal, temperature, pressure, and running history. A decrease overpotential measured beneath one laboratory protocol does now no longer independently set up decrease power intake over the life of an electrolyser. Similarly, photocatalytic hydrogen manufacturing has to be evaluated past catalyst-normalized response rates. Reactor illumination, optical losses, product separation, and the chemical inputs required to hold the response have an effect on common performance. Results received with sacrificial electron donors have to be prominent from demonstrations of common water splitting. The broader implementation mission is illustrated with the aid of using Odenweller and Ueckerdt, who tested the distance among introduced inexperienced hydrogen initiatives and their realization [5]. Their evaluation suggests that technological deployment relies on coordinated improvement of manufacturing, demand, infrastructure, and funding situations. Project bulletins consequently constitute a one-of-a-kind stage of proof from running capacity. For biomedical systems, a similar difference exists between fabric interest and healing performance. Hydrogen era in a buffer establishes chemical feasibility; it does now no longer exhibit that enough hydrogen reaches the supposed tissue after administration. Translation calls for following the entire series from formula coaching to delivery, activation, exposure, and organic response.

8.2. Critical Materials and Resource-Efficient Design

Material choice impacts each tool overall performance and the feasibility of large-scale deployment. A considerable catalyst with slight interest can be appealing if it gives ok performance and sturdiness, while a fantastically energetic scarce-steel catalyst calls for powerful usage and recovery. Minke et al [55] assessed iridium call for related to the growth of proton-exchange-membrane water electrolysis [55]. Their state of affairs evaluation recognized full-size discounts

in catalyst loading and the improvement of powerful recycling infrastructure as important measures for assisting large-scale deployment beneath Neath the assumptions examined. These findings join catalyst engineering without delay to fabric-deliver planning. The suitable layout goal is consequently to lessen fabric intake in keeping with unit of hydrogen added over the working lifetime. Lower preliminary loading is useful most effective if it does now no longer reason a disproportionate lower in sturdiness or boom in strength intake. Recovery yield, substitute frequency, and production losses ought to be blanketed on this assessment. For biomedical nanoplatforms, fabric performance has a specific interpretation. The applicable portions encompass the provider dose required to attain a described exposure, the fraction achieving the remedy site, and the quantity retained after remedy. Increasing hydrogen loading can also additionally lessen provider requirements, however this gain need to be installed along launch conduct and tolerability.

8.3. Life-Cycle Environmental Performance

The environmental overall performance of hydrogen relies on its whole manufacturing and shipping pathway. A suitable evaluation has to specify the strength supply, feedstock requirements, gadget manufacture, purification, compression, transport, and end-of-existence treatment. The practical unit needs to additionally be explicit. Comparing one kilogram of hydrogen on the electrolyze outlet with one kilogram added at a specific stress and purity can produce one-of-a-kind conclusions due to the fact the second one consists of extra processing. Likewise, estimates primarily based totally on one-of-a-kind gadget lifetimes or strength assumptions have to know no longer be dealt with as without delay interchangeable. Hydrogen leakage provides some other environmental consideration. Sand et al. used more than one atmospheric fashion to estimate an oblique 100-12-month international warming capability of 11.6 ± 2. Eight for emitted hydrogen [56]. The impact arises from atmospheric chemistry related to methane, ozone, and stratospheric water vapors. These metric issues hydrogen launched into the atmosphere; it isn't an emission issue for each kilogram of hydrogen produced. Consequently, leakage has to be protected as a measured or scenario-structured amount inside existence-cycle calculations. Environmental comparisons have to file how conclusions extrude with leakage, strength carbon intensity, gadget utilization, and substitute assumptions. For biomedical materials, a complementary evaluation could observe precursor synthesis, solvent use, purification, production yield, packaging, and disposal. The use of hydrogen as an energetic species does now no longer itself set up that the formula has a low environmental burden.

8.4. Manufacturing Reproducibility and Quality Attributes

Reproducibility is the relationship between a promising experimental formula and a reliable product. A synthesis path must produce constant homes throughout impartial batches, which include after adjustments in manufacturing volume. For hydrogen-manufacturing electrodes, applicable attributes encompass catalyst composition, loading uniformity, porosity, adhesion, and electric contact. For hydrogen-shipping nanoparticles, they encompass particle-length distribution, floor chemistry, precursor content, unbound components, and launch kinetics. These attributes must be decided on in line with their confirmed have an effect on performance. A beneficial improvement approach is to outline the intended product feature first and become aware of the fabric homes that manipulate it. For example, a formula meant to generate hydrogen after mobile uptake calls for proof that it keeps its precursor earlier than uptake and releases it beneath the

meant intracellular conditions. A formula meant for sustained nearby remedy calls for a distinctive launch profile. Stability assessment must additionally distinguish chemical balance from useful balance. A pattern might also additionally hold its obvious particle length whilst dropping hydrogen-producing potential or converting its launch rate. Storage research must consequently degree the feature applicable to the intended application.

8.5. Biological Transport and Exposure

The transport of a nanoparticle and the transport of hydrogen are separate delivery problems. A provider ought to attain the applicable organic compartment, even as the hydrogen it releases sooner or later distributes in step with its very own awareness gradients and nearby delivery conditions. Research on nanoparticle access into tumors demonstrates why transport cannot be inferred from particle length alone. Sindhwani et al. discovered that energetic delivery thru endothelial cells accounted for a considerable share of nanoparticle access within the structures they investigated [57]. These locating demanding situations are primarily based totally completely on passage through gaps among endothelial cells. Its utility to a selected hydrogen-transport system though calls for direct experimental evaluation. For hydrogen nanomedicine, publicity evaluation needs to distinguish provider accumulation, precursor conversion, and nearby hydrogen availability. An imaging sign related to a categorized provider does now no longer routinely quantify launched hydrogen. Likewise, measuring a constituent steel in tissue establishes elemental distribution but does now no longer, with the aid of using itself, become aware of the quantity of intact provider or its final activity. These differences endorse a more potent experimental approach: integrate fabric monitoring with hydrogen measurements and organic endpoints at well matched time points. The ensuing proof can set up whether or not a healing reaction follows the supposed publicity profile.

8.6. Economic Evaluation and Appropriate Comparators

Economic evaluation needs to compare the whole feature introduced via means of a technology. For business hydrogen, this consists of capital expenditure, strength and water consumption, maintenance, replacement, fuel Oline conditioning, and shipping requirements. Assumptions regarding working hours and financing need to be said due to the fact they have an effect on the distribution of charges throughout hydrogen output. Deployment studies in addition show that technical upgrades function inside a broader funding environment. The implementation evaluation via the means of Odenweller and Ueckerdt highlights the significance of call for and economic situations along manufacturing capability [5]. Economic projections need to consequently separate verified overall performance from assumed destiny upgrades and policy-based situations. For biomedical platforms, the applicable contrast is the value and medical price of the whole remedy. Manufacturing, pleasant control, administration, activation equipment, and tracking can also additionally contribute. A more complicated formula needs to display a gain that justifies those extra requirements. Comparators need to understand the proposed use. A hydrogen–drug formula needs to be in comparison with the suitable drug regimen, whilst a wound dressing needs to be evaluated towards an applicable dressing or remedy strategy. Comparisons confined to untreated controls cannot set up the realistic price of changing or supplementing present care. Table eight summarizes an assessment framework derived from the manufacturing and shipping issues mentioned on this paper (Table 8). It separates experimental overall performance from the proof had to aid implementation.

Table 8. Proposed criteria for evaluating hydrogen-production technologies and biomedical hydrogen-delivery platforms.

Evaluation dimension	Hydrogen production	Biomedical hydrogen delivery
Intended function	Hydrogen delivered at specified purity, pressure, and output	A defined local exposure associated with a biological outcome
Performance	System energy consumption and sustained productivity	Release profile, tissue exposure, and treatment response
Material efficiency	Material use per unit of lifetime hydrogen output	Carrier and precursor dose required for effective exposure
Durability or stability	Performance under representative operating cycles	Shelf stability and retained function after administration
Transport	Water supply, gas removal, purification, and delivery	Tissue access, carrier distribution, and hydrogen diffusion
Reproducibility	Consistent electrodes, cells, and stacks	Consistent composition, size distribution, loading, and release
Environmental assessment	Life-cycle inputs, emissions, leakage, and recovery	Synthesis, purification, packaging, residual materials, and disposal
Economic comparison	Complete delivered-hydrogen cost	Complete treatment cost relative to an appropriate comparator
Validation	Sustained operation at a relevant scale	Controlled preclinical studies followed by intervention-specific clinical evaluation

9. Conclusions and Future Perspectives

Hydrogen studies connect power conversion, substances engineering, and rising biomedical programs via a shared hobby in controlling hydrogen generation, garage, transport, and release. The literature tested on this bankruptcy demonstrates how nanoscale layout can affect those processes, even as additionally displaying that their realistic price relies upon at the necessities of the very last application. Efficient hydrogen manufacturing, environmentally sustainable operation, and powerful healing transport constitute wonderful results that need to every be mounted via suitable proof. The transition closer to inexperienced hydrogen calls for coordinated enhancements in strength supply, conversion technology, and device integration. Renewable-powered electrolysis affords a pathway for coupling hydrogen manufacturing to low-carbon strength; however, its environmental overall performance relies upon at the strength source, device utilization, production inputs, and downstream processing. Accordingly, the evaluation of hydrogen-manufacturing routes has to increase past conversion performance to encompass life-cycle emissions, fabric consumption, water necessities, and introduced-hydrogen cost [1,31,32]. Nanostructured catalysts provide possibilities to enhance active-web website online utilization, response kinetics, and interfacial transport. Their contribution will become technologically significant while those enhancements persist in whole electrodes and gadgets beneath Neath consultant running conditions. Future catalyst improvement has to consequently combine hobby, durability, manufacturability, and useful resource availability from the outset. For technology counting on scarce metals, decreasing fabric call for need to be observed through sustained overall performance and powerful healing strategies [1 ,55]. Photocatalytic, photoelectrochemical, thermochemical, and organic processes develop the technological foundation of hydrogen manufacturing. Their improvement has to join advances in response chemistry with reactor layout, product separation, and sustained operation. Demonstrations of usual water splitting and operation

at an elevated scale offer especially precious proof due to the fact they cope with necessities past fabric hobby alone [6,16,22]. The maximum appropriate pathway will rely on the to be had power resources, running environment, manufacturing scale, and supposed hydrogen use. Biomedical hydrogen studies introduce the opportunity of the usage of engineered substances to govern publicity at a specific tissue or mobile compartment. Hydrogen-garage substances, precursor-loaded nanocarriers, and regionally activated mills offer specific processes to this objective. Representative research exhibit how those capabilities may be blended with chemotherapy, photothermal treatment, or wound-care substances [3,50–53]. The subsequent strengthen have to set up quantitative relationships among components properties, hydrogen publicity, and organic reaction. Carrier accumulation, precursor conversion, and hydrogen availability have to be measured as separate however related processes. This difference is vital due to the fact the place of a nanoparticle does now no longer always pick out the place or length of the hydrogen publicity it produces. Mechanistic research has to likewise solve the contributions of character components. Heat generation, metal-ion release, modifications in nearby chemistry, and co-introduced pills might also additionally affect the reaction along hydrogen. Carefully matched comparisons can decide whether or not hydrogen produces an impartial effect, modifies an accompanying treatment, or contributes via a components-particular interaction. Clinical improvement needs to continue to be intervention-particular. Evidence received with inhaled hydrogen can tell the wider research of molecular hydrogen; however, it can't set up the efficacy or protection of a nanoparticle component. Each platform calls for assessment of its very own composition, management route, publicity profile, and organic fate [9]. The most powerful possibility for collaboration among electricity and biomedical studies lies in moving techniques and mechanistic understanding. Catalytic-web web page engineering, interfacial characterization, hydrogen quantification, and reaction–delivery evaluation can tell each field. Their implementation must nonetheless mirror extraordinary objectives: business structures searching for dependable hydrogen output over prolonged operation, while biomedical structures searching for the proper neighborhood publicity inside a described remedy period. Three priorities comply with this distinction: First, fabric improvement must start with a certainly distinctive utility and measurable overall performance requirements. Second, experimental research must join fabric homes to complete-gadget conduct through mass balances, time-resolved measurements, and suitable controls. Third, production and end-of-lifestyle concerns must be integrated early sufficient to steer layout choices. For inexperienced hydrogen, this method directs interest closer to sustained productivity, decreased aid demand, and demonstrated environmental benefits. For hydrogen-shipping platforms, it prioritizes reproducible publicity, confirmed healing contribution, and characterized clearance. Across each field, development could be described via means of the capacity to transform nanoscale manage into dependable overall performance beneath the situations wherein the era is meant to operate.

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

Data Availability Statement: Available pre request.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Authors Contribution:

Ehsan kianfar, Hasan Koten, Behnaz Chaharbashi, Mahdiyeh Nosratabadi, Hamidreza Sayadi: writing – original draft, formal analysis, methodology, writing – review and editing, supervision.

Consent to Publish declaration: Not applicable.

Ethics and Consent to Participate declarations: Not applicable.

Clinical trial number: Not applicable.

References

1. de Kleijne, K., Huijbregts, M. A. J., Knobloch, F., van Zelm, R., Hilbers, J. P., de Coninck, H., & Hanssen, S. V. (2024). Worldwide greenhouse gas emissions of green hydrogen production and transport. Nature Energy, 9, 1139–1152. https://doi.org/10.1038/s41560-024-01563-1.

2. Lejeune, M., Kara, S., Hauschild, M. Z., Shahrabifarahani, S., & Daiyan, R. (2026). Pathways to global hydrogen production within planetary boundaries. Nature Communications, 17, 3521. https://doi.org/10.1038/s41467-026-70168-x .

3. Zhao, P., Jin, Z., Chen, Q., Yang, T., Chen, D., Meng, J., Lu, X., Gu, Z., & He, Q. (2018). Local generation of hydrogen for enhanced photothermal therapy. Nature Communications, 9, 4241. https://doi.org/10.1038/s41467-018-06630-2.

4. Zhao, B., Wang, Y., Yao, X., Chen, D., Fan, M., Jin, Z., & He, Q. (2021). Photocatalysis-mediated drug-free sustainable cancer therapy using nanocatalyst. Nature Communications, 12, 1345. https://doi.org/10.1038/s41467-021-21618-1.

5. Johnson, N. J. J., et al. (2019). Facets and vertices regulate hydrogen uptake and release in palladium nanocrystals. Nature Materials, 18, 454–458. https://doi.org/10.1038/s41563-019-0308-5.

6. Nishiyama, H., et al. (2021). Photocatalytic solar hydrogen production from water on a 100-m² scale. Nature, 598, 304–307. https://doi.org/10.1038/s41586-021-03907-3.

7. Zhou, P., Navid, I. A., Ma, Y., Xiao, Y., Wang, P., Ye, Z., Zhou, B., Sun, K., & Mi, Z. (2023). Solar-to-hydrogen efficiency of more than 9% in photocatalytic water splitting. Nature, 613, 66–70. https://doi.org/10.1038/s41586-022-05399-1.

8. National Institute of Standards and Technology. Hydrogen. NIST Chemistry WebBook, Standard Reference Database 69. https://webbook.nist.gov/cgi/cbook.cgi?ID=C1333740&Units=SI. Accessed October 1, 2026.

9. U.S. Department of Energy. Hydrogen Storage. https://www.energy.gov/cmei/fuels/hydrogen-storage. Accessed October 1, 2026.

10. Hubert, M., Esposito, A. M., Peterson, D., Miller, E., & Stanford, J. (2024). Hydrogen Shot: Water Electrolysis Technology Assessment. U.S. Department of Energy. Report.

11. Bauer, C., et al. (2022). On the climate impacts of blue hydrogen production. Sustainable Energy & Fuels, 6, 66–75. https://doi.org/10.1039/D1SE01508G.

12. Upham, D. C., Agarwal, V., Khechfe, A., Snodgrass, Z. R., Gordon, M. J., Metiu, H., & McFarland, E. W. (2017). Catalytic molten metals for the direct conversion of methane to hydrogen and separable carbon. Science, 358(6365), 917–921. https://doi.org/10.1126/science.aao5023.

13. Pascuzzi, S., Anifantis, A. S., Blanco, I., & Scarascia Mugnozza, G. (2016). Electrolyzer performance analysis of an integrated hydrogen power system for greenhouse heating. A case study. Sustainability, 8(7), 629. https://doi.org/10.3390/su8070629.

14. McCrory, C. C. L., Jung, S., Ferrer, I. M., Chatman, S. M., Peters, J. C., & Jaramillo, T. F. (2015). Benchmarking hydrogen evolving reaction and oxygen evolving reaction electrocatalysts for solar water splitting devices. Journal of the American Chemical Society, 137(13), 4347–4357. https://doi.org/10.1021/ja510442p.

15. Slobodkin, I., Davydova, E., Sananis, M., Breytus, A., & Rothschild, A. (2024). Electrochemical and chemical cycle for high-efficiency decoupled water splitting in a near-neutral electrolyte. Nature Materials, 23, 398–405. https://doi.org/10.1038/s41563-023-01767-y.

16. Takata, T., Jiang, J., Sakata, Y., Nakabayashi, M., Shibata, N., Nandal, V., Seki, K., Hisatomi, T., & Domen, K. (2020). Photocatalytic water splitting with a quantum efficiency of almost unity. Nature, 581, 411–414. https://doi.org/10.1038/s41586-020-2278-9.

17. Antonini, C., Treyer, K., Streb, A., van der Spek, M., Bauer, C., & Mazzotti, M. (2020). Hydrogen production from natural gas and biomethane with carbon capture and storage—A techno-environmental analysis. Sustainable Energy & Fuels, 4, 2967–2986. https://doi.org/10.1039/D0SE00222D. See also the published correction.

18. Antonini, C., et al. (2021). Hydrogen from wood gasification with CCS—A techno-environmental analysis of production and use as transport fuel. Sustainable Energy & Fuels, 5, 2602–2621. https://doi.org/10.1039/D0SE01637C.

19. Jia, J., Seitz, L. C., Benck, J. D., Huo, Y., Chen, Y., Ng, J. W. D., Bilir, T., Harris, J. S., & Jaramillo, T. F. (2016). Solar water splitting by photovoltaic-electrolysis with a solar-to-hydrogen efficiency over 30%. Nature Communications, 7, 13237. https://doi.org/10.1038/ncomms13237.

20. Kim, H. R., et al. (2026). Integrated catalyst–transport nickel-iron porous electrode for anion exchange membrane water electrolysis. Nature Communications, 17, 6403. https://doi.org/10.1038/s41467-026-72976-7.

21. Landman, A., Dotan, H., Shter, G. E., Wullenkord, M., Houaijia, A., Maljusch, A., Grader, G. S., & Rothschild, A. (2017). Photoelectrochemical water splitting in separate oxygen and hydrogen cells. Nature Materials, 16, 646–651. https://doi.org/10.1038/nmat4876.

22. Chueh, W. C., Falter, C., Abbott, M., Scipio, D., Furler, P., Haile, S. M., & Steinfeld, A. (2010). High-flux solar-driven thermochemical dissociation of CO_2 and H_2O using

nonstoichiometric ceria. Science, 330(6012), 1797–1801. https://doi.org/10.1126/science.1197834.

23. Chueh, W. C., & Haile, S. M. (2010). A thermochemical study of ceria: Exploiting an old material for new modes of energy conversion and CO_2 mitigation. Philosophical Transactions of the Royal Society A, 368(1923), 3269–3294. https://doi.org/10.1098/rsta.2010.0114.

24. Ozmihci, S., & Kargi, F. (2010). Bio-hydrogen production by photo-fermentation of dark fermentation effluent with intermittent feeding and effluent removal. International Journal of Hydrogen Energy, 35(13), 6674–6680. https://doi.org/10.1016/j.ijhydene.2010.04.090.

25. Lo, Y. C., Chen, C. Y., Lee, C. M., & Chang, J. S. (2010). Sequential dark–photo fermentation and autotrophic microalgal growth for high-yield and CO_2-free biohydrogen production. International Journal of Hydrogen Energy, 35(20), 10944–10953. https://doi.org/10.1016/j.ijhydene.2010.07.090.

26. Xu, Z., et al. (2020). Photosynthetic hydrogen production by droplet-based microbial micro-reactors under aerobic conditions. Nature Communications, 11, 5985. https://doi.org/10.1038/s41467-020-19823-5.

27. *Oriented intergrowth of the catalyst layer in membrane electrode assembly for alkaline water electrolysis.* (2022). *Nature Communications, 13*, 7956. https://doi.org/10.1038/s41467-022-35603-9.

28. Rakousky, C., Reimer, U., Wippermann, K., Kuhri, S., Carmo, M., Lüke, W., & Stolten, D. (2017). Polymer electrolyte membrane water electrolysis: Restraining degradation in the presence of fluctuating power. *Journal of Power Sources, 342*, 38–47. https://doi.org/10.1016/j.jpowsour.2016.11.118.

29. Zheng, Y., Serban, A., Zhang, H., Chen, N., Song, F., & Hu, X. (2023). Anion exchange ionomers enable sustained pure-water electrolysis using platinum-group-metal-free electrocatalysts. *ACS Energy Letters*. https://doi.org/10.1021/acsenergylett.3c01866.

30. Zhu, Z., Hu, B., & Tucker, M. C. (2024). Dynamic operation of metal-supported solid oxide electrolysis cells. *International Journal of Hydrogen Energy, 59*, 316–321. https://doi.org/10.1016/j.ijhydene.2024.01.345.

31. Terlouw, T., Bauer, C., McKenna, R., & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: A techno-economic and environmental assessment. *Energy & Environmental Science, 15*, 3583–3602. https://doi.org/10.1039/D2EE01023B.

32. Ricks, W., Xu, Q., & Jenkins, J. D. (2023). Minimizing emissions from grid-based hydrogen production in the United States. *Environmental Research Letters, 18*, 014025. https://doi.org/10.1088/1748-9326/acacb5.

33. Xie, H., et al. (2022). A membrane-based seawater electrolyser for hydrogen generation. *Nature, 612*, 673–678. https://doi.org/10.1038/s41586-022-05379-5.

34. Subbaraman, R., Tripkovic, D., Strmcnik, D., Chang, K.-C., Uchimura, M., Paulikas, A. P., Stamenkovic, V., & Markovic, N. M. (2011). Enhancing hydrogen evolution activity in water splitting by tailoring Li^+–$Ni(OH)_2$–Pt interfaces. *Science, 334*(6060), 1256–1260. https://doi.org/10.1126/science.1211934.

35. Popczun, E. J., McKone, J. R., Read, C. G., Biacchi, A. J., Wiltrout, A. M., Lewis, N. S., & Schaak, R. E. (2013). Nanostructured nickel phosphide as an electrocatalyst for the hydrogen evolution reaction. *Journal of the American Chemical Society, 135*(25), 9267–9270. https://doi.org/10.1021/ja403440e.

36. Xu, X., Song, F., & Hu, X. (2016). A nickel iron diselenide-derived efficient oxygen-evolution catalyst. *Nature Communications, 7*, 12324. https://doi.org/10.1038/ncomms12324.

37. Chen, W.-F., Sasaki, K., Ma, C., Frenkel, A. I., Marinkovic, N., Muckerman, J. T., Zhu, Y., & Adzic, R. R. (2012). Hydrogen-evolution catalysts based on non-noble metal nickel–molybdenum nitride nanosheets. *Angewandte Chemie International Edition, 51*(25), 6131–6135. https://doi.org/10.1002/anie.201200699.

38. Chen, W.-F., et al. (2013). Highly active and durable nanostructured molybdenum carbide electrocatalysts for hydrogen production. *Energy & Environmental Science, 6*, 943–951. https://doi.org/10.1039/C2EE23891H.

39. Li, Y., Wang, H., Xie, L., Liang, Y., Hong, G., & Dai, H. (2011). MoS_2 nanoparticles grown on graphene: An advanced catalyst for the hydrogen evolution reaction. *Journal of the American Chemical Society, 133*(19), 7296–7299. https://doi.org/10.1021/ja201269b.

40. Hod, I., et al. (2015). A porous proton-relaying metal-organic framework material that accelerates electrochemical hydrogen evolution. *Nature Communications, 6*, 8304. https://doi.org/10.1038/ncomms9304.

41. Stegbauer, L., Schwinghammer, K., & Lotsch, B. V. (2014). A hydrazone-based covalent organic framework for photocatalytic hydrogen production. *Chemical Science, 5*, 2789–2793. https://doi.org/10.1039/C4SC00016A.

42. Zhao, D., Wang, Y., Dong, C.-L., Huang, Y.-C., Chen, J., Xue, F., Shen, S., & Guo, L. (2021). Boron-doped nitrogen-deficient carbon nitride-based Z-scheme heterostructures for photocatalytic overall water splitting. *Nature Energy, 6*, 388–397. https://doi.org/10.1038/s41560-021-00795-9.

43. Chen, Z., Li, P., Anderson, R., Wang, X., Zhang, X., Robison, L., Redfern, L. R., Moribe, S., Islamoglu, T., Gómez-Gualdrón, D. A., Yildirim, T., Stoddart, J. F., & Farha, O. K. (2020). Balancing volumetric and gravimetric uptake in highly porous materials for clean energy. *Science, 368*(6488), 297–303. https://doi.org/10.1126/science.aaz8881.

44. Zhang, R., et al. (2024). Balancing volumetric and gravimetric capacity for hydrogen in supramolecular crystals. *Nature Chemistry, 16*, 1982–1988. https://doi.org/10.1038/s41557-024-01622-w.

45. Jeon, K.-J., Moon, H. R., Ruminski, A. M., Jiang, B., Kisielowski, C., Bardhan, R., & Urban, J. J. (2011). Air-stable magnesium nanocomposites provide rapid and high-capacity hydrogen storage without using heavy-metal catalysts. *Nature Materials, 10*, 286–290. https://doi.org/10.1038/nmat2978.

46. Yang, N., et al. (2022). Magnesium galvanic cells produce hydrogen and modulate the tumor microenvironment to inhibit cancer growth. *Nature Communications, 13*, 2336. https://doi.org/10.1038/s41467-022-29938-6.

47. Sander, R. (2023). Compilation of Henry's law constants (version 5.0.0) for water as solvent. *Atmospheric Chemistry and Physics, 23*, 10901–12440. https://doi.org/10.5194/acp-23-10901-2023.

48. Jin, Z., Zhao, P., Gong, W., Ding, W., & He, Q. (2023). Fe-porphyrin: A redox-related biosensor of hydrogen molecule. *Nano Research, 16*, 2020–2025. https://doi.org/10.1007/s12274-022-4860-y
49. Tamura, T., Suzuki, M., Homma, K., Sano, M., & HYBRID II Study Group. (2023). Efficacy of inhaled hydrogen on neurological outcome following brain ischaemia during post-cardiac arrest care (HYBRID II): A multi-centre, randomised, double-blind, placebo-controlled trial. *EClinicalMedicine, 58*, 101907. https://doi.org/10.1016/j.eclinm.2023.101907
50. He, Y., Tian, X., Fan, X., Gong, X., Tan, S., Pan, A., Liang, S., Xu, H., & Zhou, F. (2023). Enzyme-triggered size-switchable nanosystem for deep tumor penetration and hydrogen therapy. *ACS Applied Materials & Interfaces, 15*(1), 552–565. https://doi.org/10.1021/acsami.2c18184
51. Ji, H., Wang, Y., Yao, K., Li, J., Luo, H., Li, W., Gao, Y., Li, W., Xiao, Q., Lai, T. P., Chen, C., Li, X., Peng, Q., Zhang, C., Sun, B., & Zhang, L. (2026). Engineering an anaerobic microenvironment to empower hydrogenase-catalyzed hydrogen therapy for diabetic wound healing. *Aggregate, 7*(2), e70285. https://doi.org/10.1002/agt2.70285
52. Wang, Y., Liu, Y., Zhou, J., Lin, L., Jia, C., Wang, J., Yu, L., Wang, Y., & Yan, Z. (2021). Controllable hydrogen release for gas-assisted chemotherapy and ultrasonic imaging of drug-resistant tumors. *Chemical Engineering Journal, 421*, 129917. https://doi.org/10.1016/j.cej.2021.129917
53. Bi, S., Qi, J., Zhang, W., & Jiang, X. (2023). A liquid metal dressing for anti-inflammatory and anti-infection applications to treat diabetic wounds. *Chemical Communications, 59*, 8420–8423. https://doi.org/10.1039/D3CC01305G
54. Odenweller, A., & Ueckerdt, F. (2025). The green hydrogen ambition and implementation gap. *Nature Energy, 10*, 110–123. https://doi.org/10.1038/s41560-024-01684-7
55. Minke, C., Suermann, M., Bensmann, B., & Hanke-Rauschenbach, R. (2021). Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis? *International Journal of Hydrogen Energy, 46*(46), 23581–23590. https://doi.org/10.1016/j.ijhydene.2021.04.174
56. Sand, M., Skeie, R. B., Sandstad, M., Krishnan, S., Myhre, G., Bryant, H., Derwent, R., Hauglustaine, D., Paulot, F., Prather, M., & Stevenson, D. (2023). A multi-model assessment of the Global Warming Potential of hydrogen. *Communications Earth & Environment, 4*, 203. https://doi.org/10.1038/s43247-023-00857-8
57. Sindhwani, S., Syed, A. M., Ngai, J., Kingston, B. R., Maiorino, L., Rothschild, J., MacMillan, P., Zhang, Y., Rajesh, N. U., Hoang, T., Wu, J. L. Y., Wilhelm, S., Zilman, A., Gadde, S., Sulaiman, A., Ouyang, B., Lin, Z., Wang, L., Egeblad, M., & Chan, W. C. W. (2020). The entry of nanoparticles into solid tumours. *Nature Materials, 19*, 566–575. https://doi.org/10.1038/s41563-019-0566-2

CHAPTER 2

PROCESS SELECTİON AND FLOW OPTİMİZATİON İN MANUFACTURİNG PROCESSES: TRADİTİONAL AND MODERN APPROACHES FROM AN INDUSTRİAL ENGİNEERİNG PERSPECTİVE

GÜLLÜ AKKAŞ[1]

Introduction

When the world is examined with due regard to global systems and supply chains, it is at a critical juncture. Today, manufacturing processes have reached a level where they can no longer be treated merely as an engineering detail. A clear picture emerges when examining the geographical landscape and the trajectory of technology: manufacturing processes directly influence the main contours of international trade and the geopolitical structure. In determining the role of manufacturing methods within global networks, it has become essential to draw on data from both robust scientific foundations and macroeconomic dynamics, and to evaluate this data within this (Delera et al., 2022; Lanza et al., 2019).

[1] Assistant Professor, Kayseri University, Technical Sciences Vocational School Machine and Metal Technologies, Orcid: 0000-0001-7836-9746

In the past, when describing production processes such as casting, machining and sheet metal forming, the definition ‘technical processes that give physical form to materials’ was commonly used. Today, however, given the current state of global manufacturing, the need to update this definition is evident. This is because, when properly structured, manufacturing methods have become a force capable of rapidly propelling a regional economy to new heights. Furthermore, the decision to produce a material using a particular process does not merely affect the unit cost structure. The structure of the production processes used can have a direct impact on a country’s level of technology. Systems can also be shaped according to the supply potential in the field. When viewed through the lens of technological developments and with an analytical eye, it becomes clear that global manufacturing methods are of considerable importance and must be examined along three key axes to be fully understood (Hannibal & Knight, 2018).

The Impact of Process Selection on Network Architecture: When examining the current state of global production chains, one encounters structures that are not tied to a single centre. Today, flexible and intelligently interconnected networks have been established worldwide. In fact, when this transformation is analysed in terms of what determines geographical choice, the fundamental factor lies in the direct selection of manufacturing based on capital or labour intensity. Essentially, high-precision machining processes or forming processes carried out using advanced automation require, directly, a skilled workforce and R&D centres. For this reason, such processes are able to find production opportunities directly in regions where this type of production is concentrated. However, if we consider the situation in terms of standard shaping processes, it becomes apparent that production and manufacturing processes can be relocated to different geographical areas in the interests of cost optimisation (Antonietti et al., 2026).

Resource Efficiency and Sustainability Constraints: Environmental regulations are becoming increasingly stringent, and carbon taxes continue to become more widespread. Against the backdrop of these developments, perceptions regarding manufacturing methods have also changed. Under these circumstances, a production method should not be assessed solely on the basis of technical adequacy. There is now a clear need to prioritise more efficient forming processes , particularly innovative ones that reduce energy consumption , in order to utilise the materials used in manufacturing more effectively. In this way, companies are able to keep costs under control and maintain their global competitiveness. For this reason, current studies do not address manufacturing processes solely in terms of production potential. In these studies, thermodynamic efficiency, energy consumption and life-cycle impacts also feature prominently (Ingarao, 2017).

Technological Competence and Integration Capacity: When examining the very top tiers of the market, the underlying logic of manufacturing becomes much clearer. In leading countries and companies within the manufacturing sector, there is a strong focus on digitalisation in manufacturing, the analytical capabilities of artificial intelligence, and advanced materials. At this stage, the key priority is not to remain stuck with static process parameters, but to shift the focus towards a data-driven management approach. This enables the emergence of manufacturing systems that are resilient to market shocks and capable of weathering supply chain disruptions (Hedayat Zadeh et al., 2026).

When these criteria are assessed, it becomes clear that, under current conditions, the concept of engineering extends beyond the physical capabilities of the factory. Well-analysed manufacturing methods do not remain confined to the realm of academic research. On the one hand, they provide the means to compete globally. On

the other hand, they confer technological dominance. They also enhance the impact of national strategic plans. This means that supporting manufacturing processes with scientific updates constitutes a strategic decision-making mechanism that determines the direction of global networks.

The factors of cost, flexibility, sustainability and quality must be addressed from a multifaceted perspective. Modern production processes have made it necessary to integrate all these concepts. The fundamental criterion of global competition has become the need to integrate these four components. Today, engineers are able to implement numerous applications that bring these criteria together in order to ensure competitiveness (Benjelloun et al., 2025; Lin & Tseng, 2016).

Market expectations regarding cost, flexibility, sustainability and quality are among the most critical factors driving the increasing complexity of production systems in recent days. It is well known that reducing unit costs in high-precision manufacturing poses a challenge for engineers. As precision increases, the need to reduce error rates and optimise scrap management becomes more demanding. The fact that existing systems must also maintain sustainability is another factor that disrupts the balance of the process. When all these criteria are taken into account, the necessity for manufacturing processes that tolerate no errors becomes apparent. Within this overall equation, the significant increase in the investor's financial liability is an undeniable reality (Farooq et al., 2017; Hallmann et al., 2020).

The ability to be flexible is one of the major challenges facing manufacturing processes within this balance. The shorter lifespan of end products and today's consumers' expectation of personalised products are the most common production input parameters. The need for manufacturing organisations to respond to these demands very quickly is also a widespread challenge. These challenges bring

with them a number of disadvantages. High flexibility is a concept that undermines the need for economies of scale in mass production. The ability to design production and assembly lines to accommodate products with different variants is an issue that directly affects tool changeover times, machine set-up costs and the increasing complexity of processes. It requires great precision and involves solving a significant analytical optimisation equation (Beach et al., 2000; Koren et al., 2018; Weckenborg et al., 2024).

Sustainability, however, is not merely a romantic notion of social responsibility. It is a key production parameter that must be assessed within the framework of a very serious legal responsibility. The sub-concepts of sustainability are: a low carbon footprint, energy efficiency and raw material efficiency. Measures relating to these concepts fall within the scope of sustainability. For this reason, cost and speed alone are insufficient when viewed through the lens of sustainability. Under current conditions, it is essential to approach engineering decisions by optimising the triad of economic feasibility, operational flexibility and even ecological balance (Saad et al., 2019; Zarte et al., 2019).

In this study, manufacturing methods are systematically examined from the perspectives of industrial engineering and mechanical manufacturing, centered on the aforementioned concepts. The challenges in question can only be overcome through a thorough understanding of the processes and the making of correct choices.

Multi-Criteria Decision Making in Process Selection

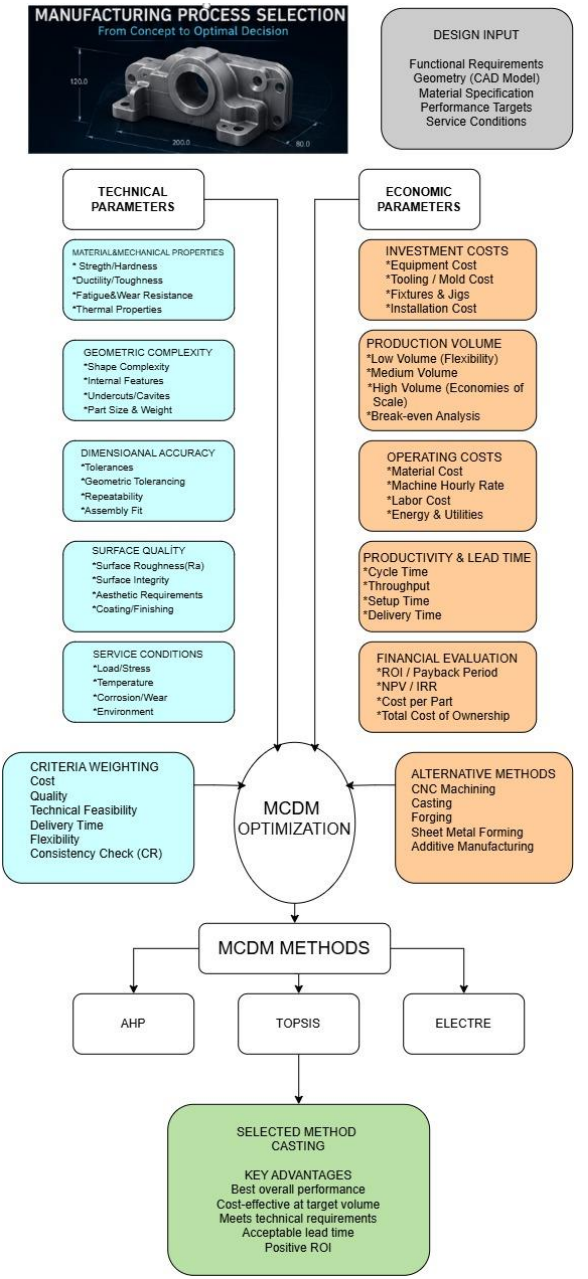
Multi-Criteria Decision Making (MCDM): When transforming an industrial product from an idea into tangible reality, the most critical decision is selecting the most suitable manufacturing method to shape the raw material. This choice is not merely a manufacturing preference at the workshop level; it is a

strategic milestone that determines the performance of the entire system. The axes of technical parameters and economic parameters—these two concepts define the process selection procedure through a scientific and analytical approach (Figure 1) (Sherif & Salonitis, 2025; Zaman et al., 2018).

Technical Parameters Axis: The material's mechanical properties, targeted geometric complexity, dimensional tolerances, surface quality requirements, and the service conditions to which the part will be subjected constitute the initial filter for determining the technical suitability of candidate manufacturing methods. For instance, regarding a component requiring high strength and complex internal geometry, the choice between casting and bulk forming can be analytically assessed by considering material flow behavior and microstructural expectations (Marini & Corney, 2020; Shercliff & Lovatt, 2001).

Economic Parameters Axis: The deciding factor among multiple technically viable alternatives is the balance between investment and operational costs. Annual production volume, investments in molds and fixtures, machine-hour rates, raw material utilization efficiency, and labor costs per unit are the key components of economic feasibility. For instance, while machining offers advantages for low-volume production due to flexibility and low setup costs, pressure die casting or sheet metal forming becomes a rational choice for high-volume mass production, as mold costs are effectively amortized (Esawi & Ashby, 2003; Sherif & Salonitis, 2025).

Figure 1: Multi-Criteria Decision Making in Process Selection



Analytical approaches regarding unit cost, production volume, and investment cost (ROI): When delving deeper into the Multi-Criteria Decision Making (MCDM) methodology for process selection, it is essential to systematically address analytical approaches centred on unit cost, production volume and return on investment, which form the basis of economic sustainability, in addition to technical parameters. The feasibility of an industrial design must ultimately be assessed through the lens of numerical data and financial equations. For engineers and designers, the question of which manufacturing method to select is based directly on the mathematical modelling of this three-way economic balance (Lovatt & Shercliff, 1998; Parenti et al., 2024).

Investment costs and the amortisation of fixed costs, production volume and cost break-even points, and unit cost optimisation; when viewed analytically, these three concepts constitute the three fundamental components of the decision-making process.

Investment costs and the amortisation of fixed costs: Each manufacturing method requires a different level of initial capital investment. For example, investments in custom moulds, casting patterns, sheet metal press dies or specialised tooling incur high initial costs, whilst machining methods using universal CNC machines require a lower initial investment. The analytical approach directly factors in how this initial investment cost will be amortised over the total production life and calculates the return on investment (ROI) (Almaghariz et al., 2016; Parenti et al., 2024).

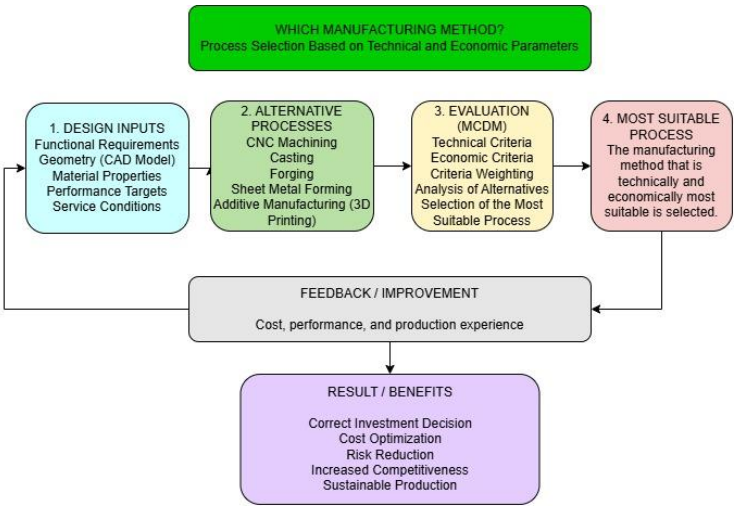
Production volume and cost break-even points: The relationship between volume and cost is the clearest mathematical

indicator for process selection. At low production volumes, methods requiring mould investment increase the cost per unit. In contrast, flexible methods such as machining offer economic advantages. As production volumes increase, the unit cost of mass production methods—such as sheet metal forming or die-casting—falls rapidly as mould costs are spread across the units. Analytical modelling aims precisely to identify these cost-intersection break-even points (Farooq et al., 2018; Moruzzi et al., 2026) .

Unit cost optimisation: Raw material utilisation efficiency, energy consumption during the production cycle and labour costs constitute the variable components of the unit cost. Net shaping or near-net-shape technologies are strategic choices that optimise unit cost by minimising raw material wastage. The inverse relationship between investment cost and unit cost must be balanced using MCDM algorithms or cost-benefit analyses (Balogun et al., 2018; Marini & Corney, 2021).

Establishing this analytical framework will ensure that engineering decisions are underpinned not only by technical expertise but also by sound financial forecasts (Figure 2).

Figure 2: Process selection based on technical and economic parameters



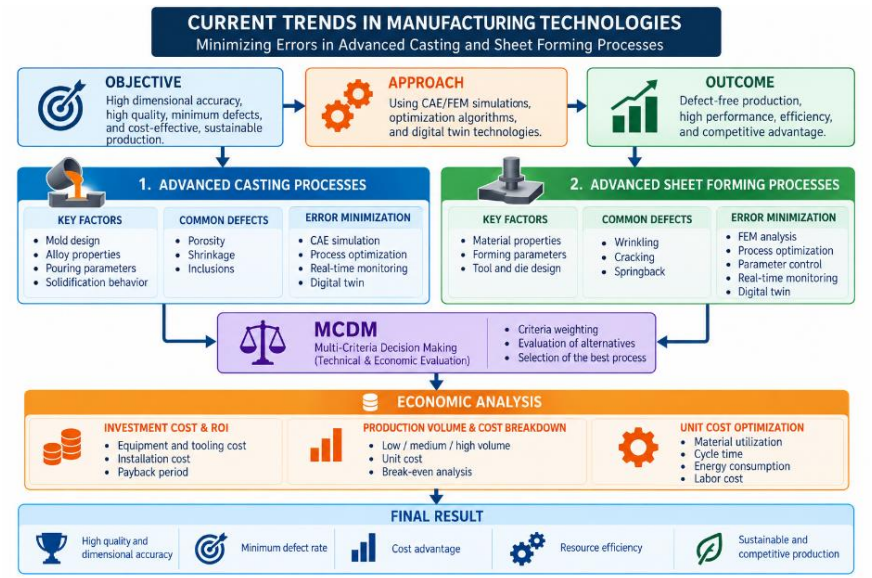
Current trends in forming technologies

Casting is the oldest and most critical primary forming process, based on the principle of shaping molten metal by pouring it into a pre-prepared mould cavity, where it solidifies. In today's advanced casting technologies (precision casting, die casting, vacuum casting, etc.), the primary focus is on improving dimensional accuracy and ensuring microstructural homogeneity (Figure 3) (Pattnaik et al., 2012; Piwonka et al., 2000).

As with all manufacturing processes, there are various potential defects in casting processes. Porosity and voids, cold shuts and shrinkage defects are the three main types of defects that may occur. Porosity refers to air voids that may form within the internal structure due to gas release during the solidification of the molten metal or due to insufficient feed of raw material. In the case of a cold shut defect, the molten metal is unable to completely fill the mould cavity and solidification occurs prematurely; as a result of this solidification, fusion lines appear on the surface. Deformation

defects are also referred to as shrinkage defects, which occur in specific areas of the component when solidification shrinkage is not managed correctly (Bharambe et al., 2023; Pradhan et al., 2019)..

Figure 3. Minimising errors in advanced casting and sheet metal forming processes (Figure 3. A simplified schematic representation of the production process selection framework. The original figure was generated using OpenAI ChatGPT; it was subsequently reviewed by the authors for technical accuracy, amended and verified.)



References: (*ChatGPT*, n.d.; Pattnaik et al., 2012; Piwonka et al., 2000)

To minimise these errors, experimental trial-and-error processes have taken a back seat. The identification of errors has become more cost-effective through CAE (Computer-Aided Engineering)-based solidification simulations. The prior optimisation of mould filling rates, runner system design and casting temperatures using numerical models reduces critical defects such as porosity and shrinkage, whilst maximising mechanical properties (Kwon & Kwon, 2019; Sun et al., 2008).

In sheet metal forming processes, plastic deformation is generally applied to sheet metal at room temperature (cold forming) using dies. This enables three-dimensional shaping operations (cutting, bending, deep drawing, etc.) to be carried out. It is a manufacturing process of significant importance in the production of lightweight structures, particularly in the defence and automotive industries (Hattalli & Srivatsa, 2018).

Fractures and tears, buckling and waviness, and springback defects are among the greatest risks in sheet metal forming processes. Fractures and tears occur when sheet metal breaks due to excessive stresses exceeding its limits during forming. Undesirable folds on the surfaces of thin sheets under compressive stress, on the other hand, are buckling defects. Occasionally, situations arise where, following plastic deformation, the material attempts to return elastically to its original shape to some extent due to internal stresses. In such cases, dimensional tolerance deviations may occur. This type of defect is also referred to in the industry as a springback defect (Neto et al., 2017) .

Forming limit diagrams are utilised to minimise errors in sheet metal forming processes. At the same time, finite element analyses are among the current approaches used to tackle such errors. Optimising pressing forces, controlling friction between the sheet metal and the die (using appropriate lubrication technologies) and mathematically compensating for springback allowances during the die design stage form the fundamental strategies for error-free production (Jadhav et al., 2018).

The concept of volumetric forming, however, is not merely a traditional manufacturing method. In the current situations, it must be addressed through a holistic approach in the context of energy efficiency and raw material conservation, the most critical industrial constraints. The sub-categories of volumetric forming include processes such as forging, rolling and extrusion. The examination

and analysis of these processes are crucial for gaining a clearer understanding of their transformative power within modern production networks (Dixit, 2020; Mehtedi et al., 2021).

The most significant feature of volumetric forming methods is that they offer an unrivalled advantage in terms of raw material savings. These processes can eliminate waste associated with cutting and discarding material, as occurs in machining methods. Instead, the final shape is achieved by utilising the material's plastic flow behaviour. Consequently, the industry's most sought-after objectives in recent years ,precision forming or forming to the closest possible dimensions, can be successfully achieved. These processes are particularly valuable because they reduce scrap rates to virtually zero and ensure that every gram of specialised alloys, which are extremely costly per kilogram, is retained in the final product. Furthermore, in such processes, the grain flow lines that form within the part's internal structure are aligned parallel to the part's outer contour without cutting, thereby achieving higher mechanical strengths with less material (Kitayama, 2024).

The concept of energy efficiency also comes to the fore in these processes. Hot forming operations, which in the past were carried out at very high temperatures with significant energy consumption, are now performed using far more innovative and optimised technologies. In cold forming processes, heat losses in heating furnaces have been eliminated. Localised induction heating can be integrated into the process. Consequently, energy is expended solely on heating the areas to be deformed. Warm forming technologies, carried out at room temperature or moderate temperatures, have rendered the need for the material to melt completely or for temperatures to reach excessively high levels a thing of the past. All these measures are reducing the total energy consumption and carbon footprint of production lines (Ingarao, 2017; Park & Dang, 2013).

Machining Dynamics, Tool Wear, and Process Monitoring

To better understand this heading, we must first define the concept of machining. Machining is the process of removing unwanted material from a raw material in the form of chips, using a cutting tool, in order to achieve the desired shape, dimensions and surface quality. In this process, the physical limits of the material are mechanically strained whilst it is being shaped. A significant amount of thermomechanical energy is released in the cutting zone (Abukhshim et al., 2006; Rodríguez et al., 2020).

The most critical aspect of this demanding process is the wear dynamics of the cutting tools. Due to the high temperatures and friction generated at the interface between the tool and the workpiece during machining, mechanical, thermal and chemical wear inevitably occurs on the tools. Forms of wear such as the delamination of special coating layers (e.g. TiN) on the tool surface, cutting edge fractures and free-surface wear are being studied in detail by researchers. Recently, these wear dynamics have moved beyond being observed solely through conventional methods and are now also being addressed in terms of their algorithmic aspects. Consequently, the progression of wear is no longer a random process but has become data that can be mathematically modelled, tracked and predicted in advance (Lim et al., 1995; Pimenov et al., 2024).

The dynamics of wear are being studied in detail by many researchers because there is a direct and decisive relationship between tool wear and the final surface quality of the product. As the tool geometry deteriorates and the cutting edge becomes dull, the surface roughness on the workpiece also increases rapidly. When a worn tool begins to crush and tear the material rather than cutting it optimally, micro-cracks, dimensional deviations and unwanted burrs are formed on the surface. This situation directly reduces the fatigue life and functional performance of the produced part. Therefore, it is essential to keep this complex relationship under control, determine

the wear limits, and optimise the machining parameters to ensure the surface quality meets the required standards (Figure 4) (Akhavan Niaki & Mears, 2017; Liang et al., 2019).

Process monitoring and optimisation algorithms for smart manufacturing systems are shifting machining systems away from traditional workshop logic and towards fully data-driven, self-decision-making autonomous systems. With this technology, machine tools on the production floor can no longer be regarded merely as mechanical processors. These machines serve as endpoints within cyber-physical systems. To facilitate this transformation, real-time data collected from the physical environment via sensors can be processed using high-performance algorithms, enabling processes to be optimised in real time (Napoleone et al., 2020; Rojas & Rauch, 2019).

When setting up process monitoring infrastructure, hardware and software compatibility is of paramount importance. For example, in machining operations, high-frequency data acquisition networks are installed on machine tools via piezoelectric dynamometers and accelerometers to measure in real time the dynamic cutting forces, temperature fluctuations and vibrations occurring at the interface between the cutting tool and the workpiece. The process is not completed merely by the physical installation and connection of sensors; these raw signals are also processed in real time using software capable of data processing, such as MATLAB, to create exact ‘digital twins’ of the cutting process. Consequently, during machining, even the slightest dynamic deviation—such as an asymmetric increase in cutting forces indicating tool wear or a vibration that triggers chatter—can be detected instantly in the virtual environment. Before the error affects the surface quality of the workpiece or causes tool breakage, autonomous adjustments can be made to the feed rate or cutting speed (Qiu et al., 2025; Zhang et al., 2024).

Figure 4: Machining (Figure 4. A simplified schematic representation of the production process selection framework. The original figure was generated using OpenAI ChatGPT; it was subsequently reviewed by the authors for technical accuracy, amended and verified)



References: (Akhavan Niaki & Mears, 2017; *ChatGPT*, n.d.; Liang et al., 2019)

The Integration of Hybrid and Modern Production Paradigms

Additive manufacturing systems represent the opposite of the ‘subtractive’ principle, which has been the norm for many years, of removing material by cutting or carving it away from a block. Developed 3D CAD models are divided into thin cross-sections (layers) in a digital environment. The system builds the object layer by layer with micron-level precision, starting from the base and using various types of material, ranging from metal to laser-melted wires. Using technologies such as Selective Laser Melting (SLM) or Directed Energy Deposition (DED), it is possible to produce, in a single operation, topologically optimised, lightweight bionic geometries with complex internal cooling channels, something that

would be physically impossible to achieve using traditional casting, forging or machining methods. Furthermore, in doing so, it reduces moulding costs to zero and minimises raw material waste (Kokare et al., 2023; Sefene, 2022).

However, the design freedom offered by additive manufacturing is not always sufficient on its own when it comes to production speed, surface roughness and sub-micron dimensional tolerances. The stepped surface effect created by the metal layers deposited by the laser often fails to meet the standards required for precision components intended for assembly. This is where the hybrid manufacturing approach comes into play. By making additive manufacturing systems compatible with conventional machining systems, an integrated manufacturing process is created (Lalegani Dezaki et al., 2022; Pragana et al., 2021).

This integration enables the strengths of two different processes to be combined within a single machine body (in hybrid CNC machines) or in sequential production cells. When manufacturing a mould component or an aerospace component as part of the process, the rough body of the material can first be produced using an additive manufacturing head. Whilst the part is still on the machine, the CNC milling spindle can be brought into operation. Assembly surfaces, critical bores and profiles requiring sealing on the complex shape produced by additive manufacturing are machined by removing material with high-precision cutting tools. In other words, whilst geometric freedom and material savings are achieved through additive manufacturing, the final precision and ideal surface quality demanded by the industry are attained through machining (Smith et al., 2024).

This integration is actively utilised not only in the production of new parts but also in the repair of high-cost moulds. A worn or damaged surface is first scanned in three dimensions, after which a new layer of metal can be deposited onto the damaged area using

additive manufacturing. The area is then machined using CNC until it meets its original tolerances, allowing the part to be returned to service (Flynn et al., 2016) .

In traditional computer-aided process planning (CAPP) approaches, the machine tools on which a part is to be machined, the sequence of operations, and the parameters to be used are determined statically before production begins. However, with the Industry 4.0 vision, this structure has been completely opened up to change. CNC machines, presses, robotic arms and casting units in the workshop are connected to one another and to a central cloud system via an Internet of Things (IoT) infrastructure. By simply instructing the machines on what to do, they are enabled to communicate instantly with one another and with central decision-making mechanisms. Data is continuously collected from all nodes of the system to build the factory's digital neural network (Besharati-Foumani et al., 2019).

By incorporating artificial intelligence at the process planning stage, large datasets derived from past production runs are processed using machine learning and deep learning algorithms. Algorithms are being trained to analyse hundreds of different variables simultaneously, such as material type, geometric complexity, the machine's current condition, tool wear history and the dynamic workload in the workshop. This removes the need for planning to rely on operators' intuition or fixed guidelines. Production routes offering the lowest cost, the shortest lead times and the highest energy efficiency are generated entirely autonomously (Marzia et al., 2023).

The direct impact of this planning on manufacturing processes is realised in real time during production. For example, if an unexpected fluctuation in hardness originating from the raw material is detected whilst a milling operation—for which a process plan has been drawn up—is in progress, the machine learning algorithm can analyse this deviation in as little as one-tenth of a

second. Without waiting for the operator to intervene, it can instantly replan the cutting speed or feed parameters according to the current conditions and make the necessary adjustments. In other words, process planning is transformed from an office task completed before production begins into a closed-loop optimisation cycle that operates in tandem with the machine until the part comes off the workbench (Bergmann & Reimer, 2021).

Results

When planning the production networks of the future, the traditional multi-criteria decision-making (MCDM) matrices used must be updated. In conventional production methods, decision-making mechanisms relied solely on unit cost, return on investment (ROI) and quality. In light of current developments, the carbon footprint of products, specific energy consumption and resource efficiency have begun to take on greater significance. Today's decision-making algorithms are concerned not so much with the question of which method is less costly, but rather with which process ensures economic sustainability by minimising global carbon taxes.

In line with this vision, practices in process selection are undergoing a fundamental transformation. For example, in machining, tonnes of emulsion-based coolants—which are harmful to both the environment and human health—can be phased out. Instead, minimum quantity lubrication (MQL), cryogenic processing and completely dry cutting strategies can be directly integrated into process planning. In casting and forming processes, thermal losses from furnaces are monitored digitally, and closed-loop energy cycles can be designed to recover waste heat and return it to the system.

When determining future research directions, life-cycle assessment will evolve from being a static reporting tool to one that can be integrated with artificial intelligence and digital twin

technologies. Even whilst a component is still at the design stage, it is possible to simulate in real time which of the casting, forging or additive manufacturing routes will result in the lowest emissions over its entire life cycle. Furthermore, production strategies are shifting from the ‘take-make-dispose’ (linear economy) model to the ‘circular economy’ model. The primary manufacturing method can be determined by calculating not only how a product will be manufactured, but also how it can be easily dismantled at the end of its life and through which processes its materials can be reintroduced into the manufacturing cycle. Consequently, it is clear that engineers, who are at the forefront of future decision-making, are not merely cost-reducers; they are also key players in managing the world’s scarce resources and striking a delicate balance between ecological limits and industrial objectives.

The manufacturing paradigm of the future is being built upon the seamless integration of the principles of digitalisation, autonomy and ecological sustainability. With the widespread adoption of cyber-physical systems and AI-enabled process planning architectures, manufacturing methods are evolving from static workshop operations into smart ecosystems that optimise themselves using real-time data. In this context, the combination of traditional machining and forming manufacturing methods with additive manufacturing technologies on hybrid platforms is redefining the boundaries of industrial capabilities by bringing design freedom and micron-level precision together on the same platform. Digital twins and real-time monitoring algorithms provide a proactive mechanism that prevents potential deviations in the production process before errors occur.

On the other hand, global climate crises and increasingly stringent environmental regulations are placing ‘green production’ and circular economy models at the heart of the vision for the future. Ecological criteria such as carbon footprint, energy efficiency and

raw material conservation are no longer merely elements of social responsibility; they are binding engineering constraints managed through MCDM and life cycle assessment (LCA) algorithms. The industrial engineers and researchers of the future will be the architects of a new generation of production paradigms that blend technological advancement with ecological balance, spanning a broad spectrum from the autonomous optimisation of hybrid systems to circular supply chains.

References

Abukhshim, N. A., Mativenga, P. T., & Sheikh, M. A. (2006). Heat generation and temperature prediction in metal cutting: A review and implications for high speed machining. International Journal of Machine Tools and Manufacture, 46(7), 782–800. https://doi.org/https://doi.org/10.1016/j.ijmachtools.2005.07.024

Akhavan Niaki, F., & Mears, L. (2017). A comprehensive study on the effects of tool wear on surface roughness, dimensional integrity and residual stress in turning IN718 hard-to-machine alloy. Journal of Manufacturing Processes, 30, 268–280. https://doi.org/https://doi.org/10.1016/j.jmapro.2017.09.016

Almaghariz, E. S., Conner, B. P., Lenner, L., Gullapalli, R., Manogharan, G. P., Lamoncha, B., & Fang, M. (2016). Quantifying the Role of Part Design Complexity in Using 3D Sand Printing for Molds and Cores. International Journal of Metalcasting, 10(3), 240–252. https://doi.org/10.1007/s40962-016-0027-5

Antonietti, R., Burlina, C., & Franco, C. (2026). Robots and the regionalization of global value chains. Research Policy, 55(2), 105373.
https://doi.org/https://doi.org/10.1016/j.respol.2025.105373

Balogun, V. A., Edem, I. F., Gu, H., & Mativenga, P. T. (2018). Energy centric selection of machining conditions for minimum cost. Energy, 164, 655–663. https://doi.org/https://doi.org/10.1016/j.energy.2018.09.020

Beach, R., Muhlemann, A. P., Price, D. H. R., Paterson, A., & Sharp, J. A. (2000). A review of manufacturing flexibility. European Journal of Operational Research, 122(1), 41–57. https://doi.org/https://doi.org/10.1016/S0377-2217(99)00062-4

Benjelloun, M., Rzine, B., Dadda, A., & Hmamed, H. (2025). A scoping review to bridge lean six sigma and industry 5.0 for sustainable manufacturing and SDGs alignment. Discover Sustainability, 6(1), 1340. https://doi.org/10.1007/s43621-025-02107-7

Bergmann, B., & Reimer, S. (2021). Online adaption of milling parameters for a stable and productive process. CIRP Annals, 70(1), 341–344. https://doi.org/https://doi.org/10.1016/j.cirp.2021.04.086

Besharati-Foumani, H., Lohtander, M., & Varis, J. (2019). Intelligent process planning for smart manufacturing systems: a state-of-the-art review. Procedia Manufacturing, 38, 156–162. https://doi.org/https://doi.org/10.1016/j.promfg.2020.01.021

Bharambe, C., Jaybhaye, M. D., Dalmiya, A., Daund, C., & Shinde, D. (2023). Analyzing casting defects in high-pressure die casting industrial case study. Materials Today: Proceedings, 72, 1079–1083. https://doi.org/https://doi.org/10.1016/j.matpr.2022.09.166

ChatGPT. (2026). https://chatgpt.com/ Date:19.09.2026

Delera, M., Pietrobelli, C., Calza, E., & Lavopa, A. (2022). Does value chain participation facilitate the adoption of Industry 4.0 technologies in developing countries? World Development, 152,

105788.
https://doi.org/https://doi.org/10.1016/j.worlddev.2021.105788

Dixit, U. S. (2020). 1 - Modeling of metal forming: a review. In V. V. B. T.-M. of M. in M. M. M. and P. T. Silberschmidt (Ed.), Elsevier Series in Mechanics of Advanced Materials (pp. 1–30). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-818232-1.00001-1

Esawi, A. M. K., & Ashby, M. F. (2003). Cost estimates to guide pre-selection of processes. Materials & Design, 24(8), 605–616. https://doi.org/https://doi.org/10.1016/S0261-3069(03)00136-5

Farooq, M. A., Kirchain, R., Novoa, H., & Araujo, A. (2017). Cost of quality: Evaluating cost-quality trade-offs for inspection strategies of manufacturing processes. International Journal of Production Economics, 188, 156–166. https://doi.org/https://doi.org/10.1016/j.ijpe.2017.03.019

Farooq, M. A., Roth, R., & Kirchain, R. (2018). Lightweighting technologies: Analyzing strategic and economic implications of advanced manufacturing processes. International Journal of Production Economics, 206, 268–279. https://doi.org/https://doi.org/10.1016/j.ijpe.2018.10.003

Flynn, J. M., Shokrani, A., Newman, S. T., & Dhokia, V. (2016). Hybrid additive and subtractive machine tools – Research and industrial developments. International Journal of Machine Tools and Manufacture, 101, 79–101. https://doi.org/https://doi.org/10.1016/j.ijmachtools.2015.11.007

Hallmann, M., Schleich, B., & Wartzack, S. (2020). From tolerance allocation to tolerance-cost optimization: a comprehensive literature review. The International Journal of Advanced Manufacturing Technology, 107(11), 4859–4912. https://doi.org/10.1007/s00170-020-05254-5

Hannibal, M., & Knight, G. (2018). Additive manufacturing and the global factory: Disruptive technologies and the location of international business. International Business Review, 27(6), 1116–1127. https://doi.org/https://doi.org/10.1016/j.ibusrev.2018.04.003

Hattalli, V. L., & Srivatsa, S. R. (2018). Sheet Metal Forming Processes – Recent Technological Advances. Materials Today: Proceedings, 5(1, Part 3), 2564–2574. https://doi.org/https://doi.org/10.1016/j.matpr.2017.11.040

Hedayat Zadeh, A., Sacco, F., Magnani, G., & Veglio, V. (2026). The impact of industry 4.0 technologies on global value chain geographical configuration, efficiency, and sustainability: a systematic literature review. Review of Managerial Science. https://doi.org/10.1007/s11846-026-01007-y

Ingarao, G. (2017). Manufacturing strategies for efficiency in energy and resources use: The role of metal shaping processes. Journal of Cleaner Production, 142, 2872–2886. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.10.182

Jadhav, S., Schoiswohl, M., & Buchmayr, B. (2018). Applications of Finite Element Simulation in the Development of Advanced Sheet Metal Forming Processes. BHM Berg- Und Hüttenmännische Monatshefte, 163(3), 109–118. https://doi.org/10.1007/s00501-018-0713-0

Kitayama, S. (2024). Technical review on design optimization in forging. The International Journal of Advanced Manufacturing Technology, 132(9), 4161–4189. https://doi.org/10.1007/s00170-024-13593-w

Kokare, S., Oliveira, J. P., & Godina, R. (2023). Life cycle assessment of additive manufacturing processes: A review. Journal of Manufacturing Systems, 68, 536–559. https://doi.org/https://doi.org/10.1016/j.jmsy.2023.05.007

Koren, Y., Gu, X., & Guo, W. (2018). Reconfigurable manufacturing systems: Principles, design, and future trends. Frontiers of Mechanical Engineering, 13(2), 121–136. https://doi.org/10.1007/s11465-018-0483-0

Kwon, H.-J., & Kwon, H.-K. (2019). Computer aided engineering (CAE) simulation for the design optimization of gate system on high pressure die casting (HPDC) process. Robotics and Computer-Integrated Manufacturing, 55, 147–153. https://doi.org/https://doi.org/10.1016/j.rcim.2018.01.003

Lalegani Dezaki, M., Serjouei, A., Zolfagharian, A., Fotouhi, M., Moradi, M., Ariffin, M. K. A., & Bodaghi, M. (2022). A review on additive/subtractive hybrid manufacturing of directed energy deposition (DED) process. Advanced Powder Materials, 1(4), 100054.
https://doi.org/https://doi.org/10.1016/j.apmate.2022.100054

Lanza, G., Ferdows, K., Kara, S., Mourtzis, D., Schuh, G., Váncza, J., Wang, L., & Wiendahl, H.-P. (2019). Global production networks: Design and operation. CIRP Annals, 68(2), 823–841. https://doi.org/https://doi.org/10.1016/j.cirp.2019.05.008

Liang, X., Liu, Z., & Wang, B. (2019). State-of-the-art of surface integrity induced by tool wear effects in machining process of titanium and nickel alloys: A review. Measurement, 132, 150–181. https://doi.org/https://doi.org/10.1016/j.measurement.2018.09.045

Lim, S. C., Lim, C. Y. H., & Lee, K. S. (1995). The effects of machining conditions on the flank wear of tin-coated high speed steel tool inserts. Wear, 181–183, 901–912. https://doi.org/https://doi.org/10.1016/0043-1648(95)90214-7

Lin, Y.-H., & Tseng, M.-L. (2016). Assessing the competitive priorities within sustainable supply chain management under

uncertainty. Journal of Cleaner Production, 112, 2133–2144. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.07.012

Lovatt, A. M., & Shercliff, H. R. (1998). Manufacturing process selection in engineering design. Part 2: a methodology for creating task-based process selection procedures. Materials & Design, 19(5), 217–230. https://doi.org/https://doi.org/10.1016/S0261-3069(98)00039-9

Marini, D., & Corney, J. R. (2020). Process selection methodology for near net shape manufacturing. The International Journal of Advanced Manufacturing Technology, 106(5), 1967–1987. https://doi.org/10.1007/s00170-019-04561-w

Marini, D., & Corney, J. R. (2021). Concurrent optimization of process parameters and product design variables for near net shape manufacturing processes. Journal of Intelligent Manufacturing, 32(2), 611–631. https://doi.org/10.1007/s10845-020-01593-y

Marzia, S., AlejandroVital-Soto, & Azab, A. (2023). Automated process planning and dynamic scheduling for smart manufacturing: A systematic literature review. Manufacturing Letters, 35, 861–872. https://doi.org/https://doi.org/10.1016/j.mfglet.2023.07.013

Mehtedi, M. El, Buonadonna, P., D'Annibale, A., & Ilio, A. Di. (2021). Effects of process parameters on the deformation energy in a sheet-bulk metal forming process for an automotive component. Procedia CIRP, 99, 248–253. https://doi.org/https://doi.org/10.1016/j.procir.2021.03.100

Moruzzi, M. C., Kraleva, V. P., & Bagassi, S. (2026). Additive manufacturing of soluble cores for composite manufacturing. The International Journal of Advanced

Manufacturing Technology. https://doi.org/10.1007/s00170-026-19111-4

Napoleone, A., Macchi, M., & Pozzetti, A. (2020). A review on the characteristics of cyber-physical systems for the future smart factories. Journal of Manufacturing Systems, 54, 305–335. https://doi.org/https://doi.org/10.1016/j.jmsy.2020.01.007

Neto, D. M., Oliveira, M. C., Santos, A. D., Alves, J. L., & Menezes, L. F. (2017). Influence of boundary conditions on the prediction of springback and wrinkling in sheet metal forming. International Journal of Mechanical Sciences, 122, 244–254. https://doi.org/https://doi.org/10.1016/j.ijmecsci.2017.01.037

Parenti, P., Puccio, D., Semeraro, Q., & Colosimo, B. M. (2024). A techno-economic approach for decision-making in metal additive manufacturing: metal extrusion versus single and multiple laser powder bed fusion. Progress in Additive Manufacturing, 9(2), 185–210. https://doi.org/10.1007/s40964-023-00442-7

Park, H.-S., & Dang, X.-P. (2013). A Study on the Heating Process for Forging of an Automotive Crankshaft in Terms of Energy Efficiency. Procedia CIRP, 7, 646–651. https://doi.org/https://doi.org/10.1016/j.procir.2013.06.047

Pattnaik, S., Karunakar, D. B., & Jha, P. K. (2012). Developments in investment casting process—A review. Journal of Materials Processing Technology, 212(11), 2332–2348. https://doi.org/https://doi.org/10.1016/j.jmatprotec.2012.06.003

Pimenov, D. Y., da Silva, L. R. R., Ercetin, A., Der, O., Mikolajczyk, T., & Giasin, K. (2024). State-of-the-art review of applications of image processing techniques for tool condition monitoring on conventional machining processes. The International Journal of Advanced Manufacturing Technology, 130(1), 57–85. https://doi.org/10.1007/s00170-023-12679-1

Piwonka, T. S., Woodbury, K. A., & Wiest, J. M. (2000). Modeling casting dimensions: effect of wax rheology and interfacial heat transfer. Materials & Design, 21(4), 365–372. https://doi.org/https://doi.org/10.1016/S0261-3069(99)00080-1

Pradhan, A. R., Pattnaik, S., & Sutar, M. K. (2019). Improving the Filling System for a Defect Free Casting: A Review. Materials Today: Proceedings, 18, 2887–2892. https://doi.org/https://doi.org/10.1016/j.matpr.2019.07.157

Pragana, J. P. M., Sampaio, R. F. V, Bragança, I. M. F., Silva, C. M. A., & Martins, P. A. F. (2021). Hybrid metal additive manufacturing: A state–of–the-art review. Advances in Industrial and Manufacturing Engineering, 2, 100032. https://doi.org/https://doi.org/10.1016/j.aime.2021.100032

Qiu, Y., Mao, X., Gao, C., Xu, Y., & Liu, H. (2025). Structural dynamics-driven digital twin framework for real-time vibration modelling of machine tools. Mechanical Systems and Signal Processing, 240, 113406. https://doi.org/https://doi.org/10.1016/j.ymssp.2025.113406

Rodríguez, J. M., Carbonell, J. M., & Jonsén, P. (2020). Numerical Methods for the Modelling of Chip Formation. Archives of Computational Methods in Engineering, 27(2), 387–412. https://doi.org/10.1007/s11831-018-09313-9

Rojas, R. A., & Rauch, E. (2019). From a literature review to a conceptual framework of enablers for smart manufacturing control. The International Journal of Advanced Manufacturing Technology, 104(1), 517–533. https://doi.org/10.1007/s00170-019-03854-4

Saad, M. H., Nazzal, M. A., & Darras, B. M. (2019). A general framework for sustainability assessment of manufacturing processes. Ecological Indicators, 97, 211–224. https://doi.org/https://doi.org/10.1016/j.ecolind.2018.09.062

Sefene, E. M. (2022). State-of-the-art of selective laser melting process: A comprehensive review. Journal of Manufacturing Systems, 63, 250–274. https://doi.org/https://doi.org/10.1016/j.jmsy.2022.04.002

Shercliff, H. R., & Lovatt, A. M. (2001). Selection of manufacturing processes in design and the role of process modelling. Progress in Materials Science, 46(3), 429–459. https://doi.org/https://doi.org/10.1016/S0079-6425(00)00013-X

Sherif, Z., & Salonitis, K. (2025). A systematic review of decision tools for process selection and performance improvement in manufacturing. The International Journal of Advanced Manufacturing Technology, 141(3), 1113–1141. https://doi.org/10.1007/s00170-025-16806-y

Smith, S., Schmitz, T., Feldhausen, T., & Sealy, M. (2024). Hybrid metal additive/subtractive machine tools and applications. CIRP Annals, 73(2), 615–638. https://doi.org/https://doi.org/10.1016/j.cirp.2024.05.002

Sun, Z., Hu, H., & Chen, X. (2008). Numerical optimization of gating system parameters for a magnesium alloy casting with multiple performance characteristics. Journal of Materials Processing Technology, 199(1), 256–264. https://doi.org/https://doi.org/10.1016/j.jmatprotec.2007.08.036

Weckenborg, C., Schumacher, P., Thies, C., & Spengler, T. S. (2024). Flexibility in manufacturing system design: A review of recent approaches from Operations Research. European Journal of Operational Research, 315(2), 413–441. https://doi.org/https://doi.org/10.1016/j.ejor.2023.08.050

Zaman, U. K. uz, Rivette, M., Siadat, A., & Mousavi, S. M. (2018). Integrated product-process design: Material and manufacturing process selection for additive manufacturing using

multi-criteria decision making. Robotics and Computer-Integrated Manufacturing, 51, 169–180. https://doi.org/https://doi.org/10.1016/j.rcim.2017.12.005

Zarte, M., Pechmann, A., & Nunes, I. L. (2019). Decision support systems for sustainable manufacturing surrounding the product and production life cycle – A literature review. Journal of Cleaner Production, 219, 336–349. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.02.092

Zhang, L., Liu, J., & Zhuang, C. (2024). Digital Twin Modeling Enabled Machine Tool Intelligence: A Review. Chinese Journal of Mechanical Engineering, 37(1), 47. https://doi.org/10.1186/s10033-024-01036-2

CHAPTER 3

WASTE HEAT RECOVERY IN OIL INJECTED SCREW AIR COMPRESSORS

ARDA ZAİM[1]

Introduction

The increase in gas temperature during compression in an air compressor requires continuous heat removal from the system. The heat removed to maintain the compressor operating temperature constitutes an energy stream that can be reused under suitable conditions. The industrial significance of heat recovery increases with the share of compressed air systems in overall energy consumption. These systems are among the industrial utility systems with high energy consumption and can account for up to 10% of a facility's energy demand in some applications (Benedetti et al., 2018).

A portion of the energy used for compressed air generation is removed from the system as heat during compression and cooling processes. Distribution losses and end use conditions also affect the

[1] Asst. Prof., Ankara Science University, Faculty of Aviation and Space Sciences, Department of Aeronautical Engineering, arda.zaim@ankarabilim.edu.tr, ORCID: 0000-0002-2602-3169

total energy consumption of the system. This system structure requires energy efficiency assessments to consider energy flows throughout the system together with compressor electricity consumption. Recovery of the heat generated during compression is among the energy efficiency measures applicable to compressed air systems (Nehler, 2018).

The design of a heat recovery application is based on the combined evaluation of the amount and temperature level of the heat removed from the compressor and the heat demand of the facility. The system configuration is determined by the fluid from which the heat is recovered, the method used to transfer it to the point of use, and the required temperature level. Operating time, auxiliary equipment consumption, and investment cost affect the economic value of the recovered heat. In compressed air systems, evaluating the production and use sides together improves the assessment of energy performance, while applications requiring investment, such as heat recovery, also require a separate economic feasibility analysis (Cabello Eras et al., 2020).

In oil injected screw air compressors, the heat generated during compression is transferred out of the compressor through different flow paths. The oil circuit and hot cooling air constitute two main heat transfer paths that can be used for heat recovery. This study examines heat generation and transport during compression, recoverable waste heat potential, main system configurations, and application areas. The thermal and hydraulic assessments required for system design are also addressed. The economic evaluation approach is based on annual energy recovery, displaced energy, and payback period.

Heat Generation and Waste Heat Potential

In oil injected screw air compressors, compression occurs as the working volume between the rotors and the casing decreases. The

reduction in volume increases the pressure and temperature of the air. The oil supplied to the compression chamber provides lubrication, sealing, and cooling (Zhang, Cai & Kong, 2009). The air and oil mixture reaches the separator at the compressor outlet. The separated oil passes through filtration and cooling elements before returning to the compression chamber. Continuous oil circulation plays a central role in transferring the heat generated during compression out of the compressor. The main thermal interaction during compression occurs between the air and the injected oil. During the suction stage, hot oil can transfer heat to the air. As compression proceeds, the air temperature increases and heat transfer is directed toward the oil (Fujiwara & Osada, 1995). The oil limits the compression temperature and carries the absorbed thermal energy through the circulation circuit. The energy flow in the oil circuit provides a directly accessible source for heat recovery.

The energy exchange between the gas and the oil is related to the temperature difference, contact area, and heat transfer coefficient (Seshaiah et al., 2007). The oil flow rate and the inlet and outlet oil temperatures are used to determine the thermal balance of the compressor. In the absence of phase change, the instantaneous thermal power transferred by the fluid can be calculated using Equation (1):

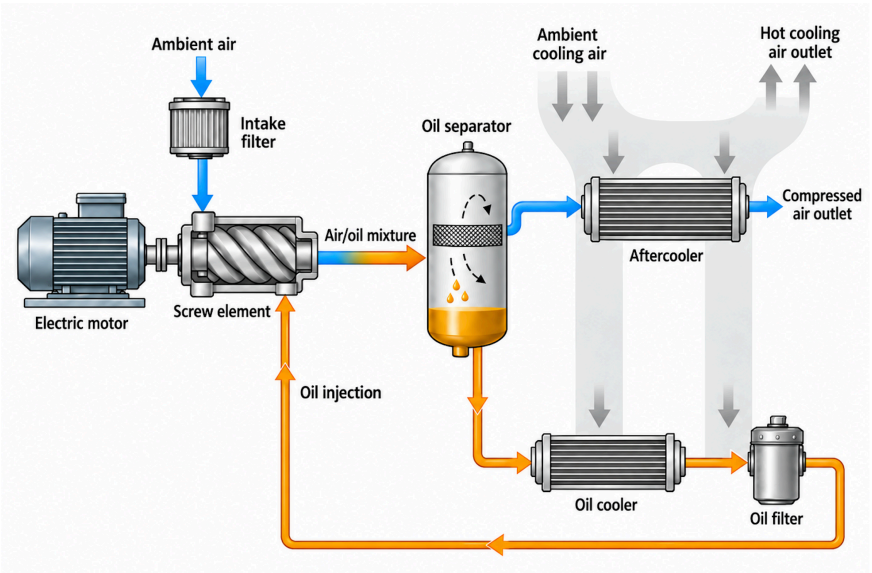
$$\dot{Q} = \dot{m} c_p (T_{out} - T_{in}) \quad (1)$$

Here, $\dot{Q}$ denotes thermal power, $\dot{m}$ the mass flow rate, c_p the specific heat at constant pressure, and T_{in} and T_{out} the inlet and outlet temperatures of the fluid, respectively. The same energy balance can be applied to the oil, cooling air, and heat recovery water circuits.

The rotors, bearings, casing, and compressed air also participate in energy transfer within the compressor. Part of the heat transferred from the discharge side bearings to the rotors is transferred from the rotor surfaces to the compressed air.

Temperature distributions along the rotors indicate that heat transfer varies with position within the compressor (Hsieh et al., 2011). The oil circuit is one of the most accessible thermal transport paths for heat recovery. The overall thermal balance of the compressor also includes energy transfer among the other components. In air cooled screw compressors, ambient air drawn into the enclosure by the fan is heated while cooling the compressor and is discharged through the outlet vent (Sapmaz, Kaya & Eyidoğan, 2016). The hot air at the outlet provides a second source from which heat removed from the compressor can be recovered. The main flow and heat transfer paths are shown in Figure 1.

Figure 1. Main flow and heat transfer paths in an oil injected screw air compressor



Oil injection flow rate is one of the main operating variables that determine the compression temperature and safe operating range. An increase in oil flow rate reduces the discharge temperature within a certain operating range. At low rotational speeds, a high oil flow rate can cause excessive cooling of the discharge air and

condensation of water vapor. At high rotational speeds, a low oil flow rate increases the discharge temperature and limits the thermal stability of the oil (He et al., 2018). The thermal power extracted for heat recovery should be determined while maintaining the required compressor operating temperature. The distribution of oil within the compression volume also affects the local temperature field. Uneven oil distribution over the rotor surfaces can lead to the formation of high temperature regions. Distributing the injected oil across different regions can provide a more uniform temperature distribution over the rotor surfaces (Basha, Kovacevic & Rane, 2021). Injection location, oil distribution, and the contact area between the gas and oil are among the key parameters governing thermal energy transfer.

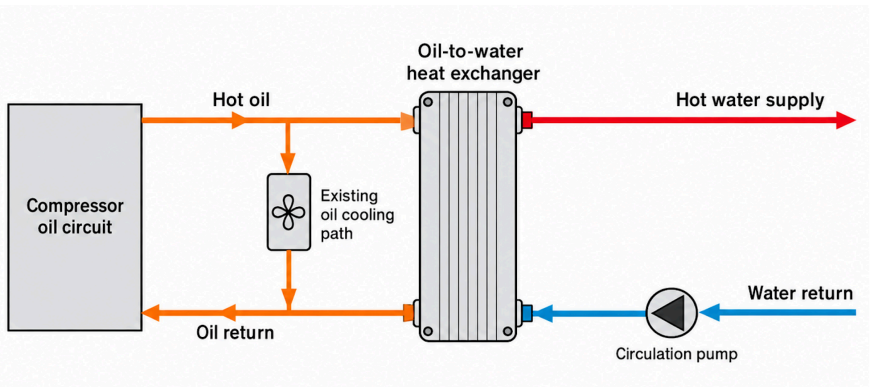
Waste heat potential can be evaluated in theoretical, technical, and economic terms. Theoretical potential refers to the thermal energy available above ambient temperature and carried by a fluid. Technical potential represents the portion that can be utilized considering available recovery technology, temperature level, and heat demand. Economic potential defines the portion of technically usable heat that is feasible under the prevailing investment and operating conditions (Brückner et al., 2015). The usability of thermal energy depends on both its quantity and temperature level. The same amount of energy has different exergy values at different temperature levels. Exergy represents the capacity of a heat flow to be converted into useful work relative to ambient conditions (Petrilean, Tataru & Tataru, 2025). The evaluation of waste heat therefore considers the amount of energy, temperature level, thermal demand at the point of use, and heat transfer losses together.

System Configurations

The transfer of waste heat to a useful application in oil injected screw air compressors can be implemented in different ways

according to the fluid carrying the heat and the connection point of the recovery system to the compressor. The main configurations are heat transfer from the oil circuit to water, direct use of hot cooling air, and heat transfer from hot cooling air to water. In these systems, heat can be carried directly by the existing fluid or transferred to a second fluid. In the oil to water configuration, the hot oil in the compressor oil circuit passes through a heat exchanger. Water circulating on the other side of the exchanger is heated by the heat transferred from the oil. A plate heat exchanger, a three way thermostatic valve, and a water circulation pump are among the main components used in such systems. The heated water can be sent directly to the point of use or stored in a buffer tank. Keeping the existing oil cooler in service allows the normal oil temperature of the compressor to be maintained under operating conditions where the heat recovery system cannot provide sufficient cooling (Broniszewski & Werle, 2018).

Figure 2. Typical heat recovery configuration based on heat transfer from the oil circuit to water

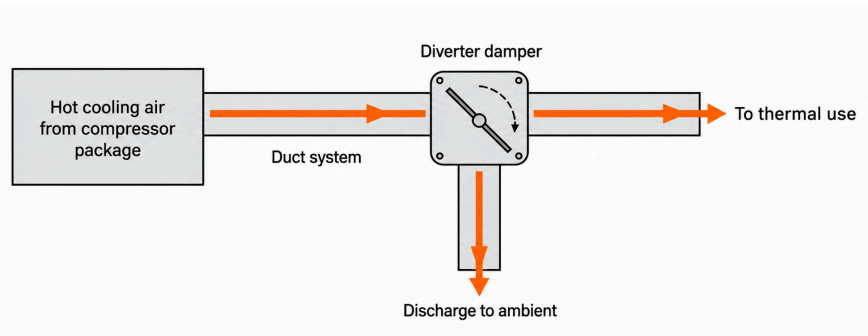


The recovery heat exchanger does not replace the primary oil cooling function of the compressor. The heat transferred from the oil to the water is limited so that the compressor operating temperature is maintained. When heat demand decreases or the recovery circuit

is out of service, the existing oil cooling path continues to operate. The basic heat recovery configuration based on heat transfer from the oil circuit to water is shown in Figure 2.

In the direct hot air configuration, the hot cooling air leaving the compressor package is directed to the point of heat use through a duct system. Since the heat is not transferred to another fluid, a separate water circuit or recovery heat exchanger is not required. The hot air acts as the direct heat carrying medium along the duct between the compressor and the point of use. Air flow direction can be controlled by a damper. Under conditions where heat demand exists, the hot air is directed to the point of use. During periods when the heat is not used, the air is discharged to the ambient environment. The duct connection should be arranged so that it does not interfere with the cooling air flow required by the compressor. The basic recovery arrangement for the direct use of hot cooling air is shown in Figure 3.

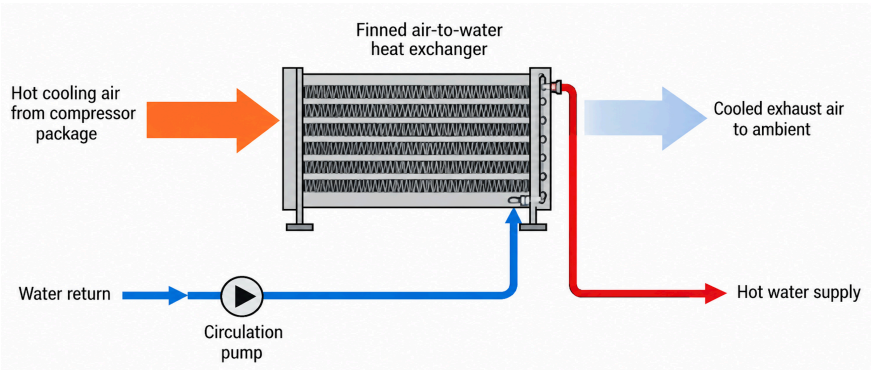
Figure 3. Typical heat recovery arrangement for the direct use of the compressor hot cooling air



In the air to water configuration, the hot cooling air leaving the compressor package passes through an air to water heat exchanger. The thermal energy carried by the air is transferred to the water circuit through the heat exchanger surfaces. In a finned tube cross flow heat exchanger, the hot air passes over the finned outer

surfaces while the water flows inside the tubes (Opoku et al., 2020). After releasing its heat, the air is discharged to the ambient environment, while the heated water is conveyed to the point of use. Water circulation can be provided by a circulation pump. In this configuration, no direct connection is established with the oil circuit. The heat is first carried by the hot cooling air of the compressor and then transferred to the water in the heat exchanger. The heat exchanger added on the air side should not restrict the compressor cooling air flow. The basic recovery arrangement based on heat transfer from hot cooling air to water is shown in Figure 4.

Figure 4. Typical heat recovery arrangement based on heat transfer from the compressor hot cooling air to water



The three configurations differ in terms of access to the heat source and the method used to transfer heat to the point of use. In the oil to water system, thermal energy is transferred directly from the oil circuit to the water. In the direct hot air system, the hot cooling air from the compressor is conveyed to the point of use using the same fluid. In the air to water system, the thermal energy carried by the cooling air is transferred to the water circuit through a heat exchanger. The heat source, heat carrying fluid, and main heat transfer component of the three configurations are compared in Table 1.

Table 1. Basic structural comparison of heat recovery configurations

Configuration	Heat source	Fluid carrying heat to the point of use	Heat transfer component
Oil to water	Hot compressor oil	Water	Oil to water heat exchanger
Direct hot air	Hot cooling air	Air	No additional heat exchanger
Air to water	Hot cooling air	Water	Air to water heat exchanger

Applications

The useful utilization of recovered heat depends on the match between the heat available from the compressor and the heat demand of the facility. The method of use is determined by whether the heat is transported by air or water, the achievable temperature, and the operating periods during which heat demand occurs. Hot cooling air can be used directly in applications where air heating is suitable. Space heating, drying, and process air preheating are included in this group. Proximity between the compressor and the point of use facilitates the direct use of hot air. Air quality should also be considered in applications involving contact with products or hygienically sensitive environments.

Heat transferred to water can be used for heating process and cleaning water, preparing hot water for cleaning in place systems, heating products and processes, and preheating boiler feedwater (Sarode & Vinchurkar, 2023). Using water as the heat carrying fluid allows the recovered heat to be transported from the compressor room to different points and supplied to existing hot water systems. If the temperature of the heated water is sufficient for the intended use, the recovered heat can be utilized directly. In processes requiring a higher temperature, the water can be preheated. The

existing heating system then provides only the remaining temperature increase.

The overlap between heat demand and compressor operating hours directly affects the amount of recovered heat that can be utilized. Continuously operating processes are more favorable in this respect. In seasonal applications such as space heating, heat demand may disappear during certain periods of the year. Short term differences between heat production and use can be balanced through thermal storage. The availability of a suitable heat load at the facility determines the extent to which recoverable energy can be utilized (Eret et al., 2012). System evaluation should therefore focus on the heat that can be used within the facility rather than the total theoretical waste heat potential. Once the application is defined, the annual usable heat, the amount of energy displaced, and its economic value can be calculated.

Design and Economic Evaluation

Sizing of the heat recovery system is based on flow rate, temperature, and operating data for both the heat source and the point of use. Heat losses in the heat exchanger, piping, and ductwork are included in the calculations. Design flow rates are selected to represent the expected operating range of the system. The fluid flow rate at the point of use is determined according to the thermal power to be transferred and the required temperature increase.

The heat exchanger capacity is selected according to the thermal power to be transferred and the inlet and outlet temperatures of the hot and cold fluids. The temperature difference between the fluids and the heat transfer characteristics are considered when determining the required heat transfer area. Pipe diameters and duct cross sections are sized to carry the required flow at an appropriate pressure drop. The flow resistance created by ducts and equipment added on the air side is kept within the operating limits of the

compressor cooling system (Hernandez-Herrera et al., 2020). The annual recovered heat can be calculated by integrating the instantaneous recovered thermal power over time using Equation (2):

$$E_{rec} = \int_0^{t_y} \dot{Q}_{rec}(t)\, dt \tag{2}$$

Here, E_{rec} denotes the annual recovered heat, $\dot{Q}_{rec}$ the instantaneous recovered thermal power, and t_y a one year time interval. For direct simultaneous use, the annual utilized heat can be determined from the recovered thermal power and the instantaneous thermal power demand at the point of use using Equation (3):

$$E_{use} = \int_0^{t_y} min\left[\dot{Q}_{rec}\,(t), \dot{Q}_{dem}\,(t)\right] dt \tag{3}$$

Here, E_{use} denotes the annual utilized heat, and $\dot{Q}_{dem}$ the instantaneous thermal power demand at the point of use. The energy displaced by the recovered heat in a fuel based or electric resistance heating system can be calculated using Equation (4):

$$E_{disp} = \frac{E_{use}}{\eta_{ref}} \tag{4}$$

Here, E_{disp} denotes the amount of energy that would otherwise be purchased, and η_{ref} denotes the efficiency of the reference heating system. When a heat pump is used as the reference system, the equivalent energy is determined according to the coefficient of performance of the system. The type and unit price of the displaced energy source are used to calculate the annual monetary savings. The auxiliary energy required to operate the heat recovery system is included in the economic evaluation. The circulation pump in the water circuit and additional fans used on the air side contribute to electricity consumption. Maintenance costs associated with the

system are added to the annual operating cost. Annual net savings are calculated by subtracting these costs from the monetary value of the displaced energy.

The initial investment cost includes the heat exchanger, piping or ductwork, auxiliary equipment, control components, insulation, and installation costs. Mechanical and electrical modifications required for integration with the existing facility are added to the investment cost. The simple payback period (SPP) is calculated as the ratio of the initial investment cost to the annual net savings using Equation (5):

$$SPP = \frac{I_0}{S_{net}} \tag{5}$$

Here, I_0 denotes the initial investment cost, and S_{net} denotes the annual net savings. The investment decision considers the initial investment cost, energy savings, and payback period together with compatibility with the existing system, implementation complexity, accessibility, and maintenance requirements (Trianni, Accordini & Cagno, 2020).

Conclusion

In oil injected screw air compressors, the technical heat recovery potential is related to the available thermal power and temperature level. The required compressor operating temperature constitutes the main design limit for heat that can be recovered. The heat demand of the facility determines the extent to which the recovered heat can be utilized. The annual usable heat depends on the temporal match between compressor operation and heat demand. Heat transfer and distribution losses reduce the amount of energy delivered to the point of use. The economic value of the recovered heat is calculated based on the energy displaced at the point of use. Energy unit cost, auxiliary energy consumption, and operating expenses affect the annual net savings. The initial investment cost is

a key component of the payback period. Ultimately, the actual value of compressor waste heat to the facility depends on how much of the technically recoverable heat can meet the annual heat demand.

References

Basha, N., Kovacevic, A. & Rane, S. (2021). Numerical investigation of oil injection in screw compressors. Applied Thermal Engineering, 193, 116959. Doi: 10.1016/j.applthermaleng.2021.116959.

Benedetti, M., Bonfà, F., Bertini, I., Introna, V. & Ubertini, S. (2018). Explorative study on compressed air systems' energy efficiency in production and use: First steps towards the creation of a benchmarking system for large and energy-intensive industrial firms. Applied Energy, 227, 436–448. Doi: 10.1016/j.apenergy.2017.07.100.

Broniszewski, M. & Werle, S. (2018). The study on the heat recovery from air compressors. E3S Web of Conferences, 70, 03001. Doi: 10.1051/e3sconf/20187003001.

Brückner, S., Liu, S., Miró, L., Radspieler, M., Cabeza, L. F. & Lävemann, E. (2015). Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. Applied Energy, 151, 157–167. Doi: 10.1016/j.apenergy.2015.01.147.

Cabello Eras, J. J., Sagastume Gutiérrez, A., Sousa Santos, V. & Cabello Ulloa, M. J. (2020). Energy management of compressed air systems. Assessing the production and use of compressed air in industry. Energy, 213, 118662. Doi: 10.1016/j.energy.2020.118662.

Eret, P., Harris, C., O'Donnell, G. & Meskell, C. (2012). A practical approach to investigating energy consumption of industrial compressed air systems. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 226 (1), 28–36. Doi: 10.1177/0957650911423173.

Fujiwara, M. & Osada, Y. (1995). Performance analysis of an oil-injected screw compressor and its application. International

Journal of Refrigeration, 18 (4), 220–227. Doi: 10.1016/0140-7007(95)00008-Y.

He, Z., Wang, T., Wang, X., Peng, X. & Xing, Z. (2018). Experimental investigation into the effect of oil injection on the performance of a variable speed twin-screw compressor. Energies, 11 (6), 1342. Doi: 10.3390/en11061342.

Hernandez-Herrera, H., Silva-Ortega, J. I., Martínez Diaz, V. L., Sanchez, Z. G., García, G. G., Escorcia, S. M. & Zarate, H. E. (2020). Energy savings measures in compressed air systems. International Journal of Energy Economics and Policy, 10 (3), 414–422. Doi: 10.32479/ijeep.9059.

Hsieh, S. H., Shih, Y. C., Hsieh, W. H., Lin, F. Y. & Tsai, M. J. (2011). Calculation of temperature distributions in the rotors of oil-injected screw compressors. International Journal of Thermal Sciences, 50 (7), 1271–1284. Doi: 10.1016/j.ijthermalsci.2011.02.006.

Nehler, T. (2018). Linking energy efficiency measures in industrial compressed air systems with non-energy benefits – A review. Renewable and Sustainable Energy Reviews, 89, 72–87. Doi: 10.1016/j.rser.2018.02.018.

Opoku, R., Sekyere, C. K. K., Ackumey, S., Abotsi, O. Y. W. & Kizito, J. P. (2020). Exergoeconomic analysis of staggered tube cross-flow heat recovery unit incorporated into industrial air-compressor for process water heating. Energy Conversion and Management: X, 7, 100055. Doi: 10.1016/j.ecmx.2020.100055.

Petrilean, D. C., Tataru, A. C. & Tataru, D. (2025). Reduction of energy consumption and greenhouse gas emissions in oil injected helicalscrew compressors. Revista Minelor – Mining Revue, 31 (1), 100–106. Doi: 10.2478/minrv-2025-0009.

Sapmaz, S., Kaya, D. & Eyidoğan, M. (2016). Energy conservation and emission reduction through waste heat recovery on compressed air systems. International Journal of Ecosystems and Ecology Sciences, 6 (4), 509–514.

Sarode, R. P. & Vinchurkar, S. M. (2023). An approach to recovering heat from the compressed air system based on waste heat recovery: A review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 45 (3), 9465–9484. Doi: 10.1080/15567036.2023.2238647.

Seshaiah, N., Ghosh, S. K., Sahoo, R. K. & Sarangi, S. K. (2007). Mathematical modeling of the working cycle of oil injected rotary twin screw compressor. Applied Thermal Engineering, 27 (1), 145–155. Doi: 10.1016/j.applthermaleng.2006.05.007.

Trianni, A., Accordini, D. & Cagno, E. (2020). Identification and categorization of factors affecting the adoption of energy efficiency measures within compressed air systems. Energies, 13 (19), 5116. Doi: 10.3390/en13195116.

Zhang, Y., Cai, M. & Kong, D. (2009). Overall energy efficiency of lubricant-injected rotary screw compressors and aftercoolers. 2009 Asia-Pacific Power and Energy Engineering Conference (APPEEC), 28–31 March 2009, Wuhan, China, (pp. 1–5). Doi: 10.1109/APPEEC.2009.4918581.


BİDGE