



TECHNOLOGY DEVELOPMENT FOUNDATION OF TÜRKİYE



TTGV PIONEER PROJECT PROGRAM

NEXT GENERATION FUEL TECHNOLOGIES IN HARD-TO-DECARBONIZE SECTORS

DEEP DIVE ANALYSIS REPORT **SUMMARY**

May 2025



TTGV
**PIONEER PROJECT
PROGRAM**
#ClimatePioneer



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1.

Introduction

Technology Development Foundation of Türkiye (TTGV), since 2023, has focused on climate technologies to comply with international requirements arising from climate change and to enhance the global competitiveness of the Turkish industry. Accordingly, the “Pioneer Project Program” has been launched with a three-phase support model to develop and implement scalable and high-impact innovative climate technologies in the field. The program consists of comprehensive phases: Pioneer Seed, Pioneer Demo, and Pioneer Investment support stages.

In the Pioneer Seed and Pioneer Demo programs, original acceleration methodologies focusing on technology valuation and market entry are applied for early-stage technology owners and ventures; whereas in the Pioneer Investment program, it aims to demonstrate feasibility and accelerate scaling processes by investing in climate technology solutions, which are the first of their kind and differ from known practices in Türkiye.

Within this scope, an in-depth analysis study is conducted first under the Pioneer Investment program for the prioritized climate technology identified by TTGV. This process involves a comprehensive literature review as well as engagement with domestic and international stakeholders to evaluate the current status of the technology and address sectoral needs in detail. As a result of the in-depth analysis study, an information report is prepared that includes fundamental details about the technology, stakeholder perspectives, and assessments regarding investability. Within the scope of the in-depth analysis report, researchers conducting studies with early-stage technology potential and ventures

capable of developing product/service demos are also identified, and these researchers/ventures are supported under the “Pioneer Seed and Demo” phases of the Pioneer Project Program. In the “Pioneer Investment” phase of the program, it is aimed to increase capacity by implementing the relevant climate technology studied in the in-depth analysis in the field — either at commercial scale or pre-commercial scale — as the first of its kind, to contribute to the development of the sector, and to trigger opportunities for localization and industrialization.

Within the scope of the TTGV Pioneer Project Investment Program, “Next Generation Fuel Technologies in Hard-to-Decarbonize Sectors” has been selected as the VI. In-Depth Analysis topic. In this context, a TTGV expert working group examined the emission reduction potential of biofuel and synthetic fuel technologies in sectors with high dependence on fossil fuels, such as aviation, maritime, heavy freight transportation, and energy-intensive industries like iron and steel and chemical-petrochemical. During the in-depth analysis study, more than 120 experts, academics, and sector representatives operating both domestically and internationally were interviewed in person or online. In these meetings, the technical, economic, legal, and environmental dimensions of next generation fuel technologies were discussed.

The in-depth analysis focuses on three key elements when evaluating the feasibility of next generation fuel technologies in the global and local context. First, it aims to analyze the critical needs in hard-to-decarbonize sectors in line with global energy transition targets. Second, it aims to examine new generation biofuels and synthetic fuel technologies from technical, economic, legal, and environmental perspectives, and then to analyze the current situation in Türkiye to identify potential opportunities and areas that can provide a competitive advantage in these sectors. Finally, it seeks to create potential scenarios for the integration of these technologies into business models and to engage with ecosystem stakeholders.

Conducted from a techno-economic perspective, this study addresses developments in biofuel and synthetic fuel technologies, policy and regulatory frameworks, investment ecosystems, and market dynamics with a multi-dimensional approach. In this way, it demonstrates how these technologies can be integrated into existing infrastructure, what investment opportunities they may offer, and which scalable business models can be developed. This summary report, derived from the comprehensive version, serves as a

strategic guide to inform investments in this field by providing an in-depth examination of the potential, feasibility conditions, and possible business models of biofuels and synthetic fuels in the energy transition processes of hard-to-decarbonize sectors.

Below are summary findings and evaluations regarding the results obtained in this study.

1. In the selection of biofuel production technologies, the feedstock (biomass) factor, which directly affects production efficiency and fuel quality, plays a highly critical role. The moisture content of the feedstock used, its chemical composition (cellulose, hemicellulose, and lignin content), and its oil, sugar, and starch content determine the preferred biochemical or thermochemical conversion technology. For example, a high moisture content in the feedstock increases the costs of traditional thermochemical technologies (pyrolysis and gasification) due to extra drying requirements and decreases efficiency. Such feedstocks, referred to as wet biomass, need to be processed with technologies based on hydrothermal carbonization (HTC), hydrothermal liquefaction (HTL), and hydrothermal gasification (HTG), which convert biomass into solid, liquid, and gaseous products under different temperature and pressure conditions in water. In addition, for FAME (Fatty Acid Methyl Esters), also known as first-generation biodiesel or conventional biodiesel, the oil content of the feedstock is very important. While biodiesel production can be carried out using the transesterification method for biomass with high oil content such as canola, soybean, sunflower, and palm oil, lignocellulosic fermentation/fermentation or thermochemical conversion technologies are more suitable for low-oil feedstocks and biomass such as forest/agricultural residues. Compared to more conventional technologies such as pyrolysis, which have been used for many years, conversion technologies such as hydrothermal gasification/liquefaction and biomass-based Fischer-Tropsch (FT) process stand out as technologies with greater development potential. In the conversion of next-generation biomass such as microalgae and seaweed into biofuels, methods such as lipid extraction or algal fermentation are used to produce biodiesel and biomethane. Although still a very early-stage technology, biofuel is also produced from genetically modified microorganisms through methods such as synthetic biology techniques or artificial photosynthesis. In general, each biofuel production technology selected according to the types of biomass used has its own technical and economic advantages or disadvantages. At this point, the feedstock and technology selection should be made by determining the quality parameters (cetane number, aromatic content, etc.) and areas of use of the biofuel to be obtained.

2. In the selection of synthetic fuel production technologies, the choice of carbon source to be used (CO₂ captured from a point source/direct air capture, biogenic CO₂, waste, etc.) and the hydrogen production method (electrolysis and steam reforming) is important. By evaluating the energy consumption of the electrolysis and synthesis processes, the ratio of fuel obtained to the energy input should be optimized. In addition, a life cycle analysis (LCA) of the produced synthetic fuel should be carried out, and technologies with the highest carbon reduction potential and energy efficiency should be preferred. Furthermore, in the production of synthetic fuels such as electrofuels, which already have high investment costs under current conditions, it may be necessary to avoid unscaled technologies that would further increase initial investment and operational costs (such as Direct Air Capture “DAC” or solid oxide “SOEC” electrolyzers for hydrogen production). In addition, in the production of e-fuels to be generated using technologies such as PtL, the capacity factors of infrastructures that will provide renewable energy, such as solar power plants (GES) and wind power plants (RES), and the efficiencies of energy storage systems are also factors that will directly or indirectly affect synthetic fuel production. In this context, it is critically important to identify the right locations for establishing PtL facilities in our country by considering solar and wind potentials, carbon sources, and proximity to water resources.
3. As stated in the “Carbon Capture, Utilization, and Storage (CCUS) and Carbon Dioxide Removal (CDR) Solutions with Economic Value Creation Potential” report previously prepared by TTGV, CO₂ storage solutions are considered the most critical stage of CCUS projects in line with climate goals. However, the lack of sufficient available capacity for suitable storage sites in our country and the fact that the potential capacity has not yet been identified bring on-site utilisation scenarios for at least a portion of the CO₂ captured from point sources to the forefront as the most rapidly implementable option. Especially for some sectors that want to valorize their carbon emissions and convert them into value-added products, converting the captured CO₂ into high value-added chemicals such as SAF, methanol, and ethanol would be economically meaningful, as it would subsidize part of the private sector’s transition costs to carbon capture, utilization, and storage (CCUS) technologies. Although such an investment plan falls outside the core business area of many Turkish companies with emissions, for some emission-intensive industries such as petrochemicals, cement, glass-ceramics, and iron-steel, it can be considered a meaningful investment opportunity in the medium to long term.

4. Biomass-based HVO (Hydrotreated Vegetable Oil) and HEFA (Hydroprocessed Esters and Fatty Acids), which currently dominate the market, are expected to dominate the global renewable diesel and global SAF markets by 2035. In particular, the cultivation of unique and lesser-known oilseed plant species such as pelemir (*Cephalaria syriaca*) as alternatives to traditional crops used in biodiesel production (canola, sunflower, soybean, and palm oil) — preferably on non-arable lands — is of critical importance for HVO and HEFA production, as it will contribute to the search for scalable feedstock. In addition, the broader use of animal fats known as “HVO Class III” and forest residues, which are difficult to collect, should also be explored. At this point, it is essential that national databases such as the Biomass Energy Potential Atlas (BEPA) are regularly updated. Despite its high potential, it is strongly anticipated that bio-feedstock and biomass supply used for fuel production may face bottlenecks in the near future due to food supply security concerns. Moreover, practices such as adulteration and fraud involving critical feedstocks like used cooking oil (UCO) and palm oil mill effluent (POME) including attempts to introduce uncertified raw materials (lacking international ISCC certification) into global markets and the gradual encroachment of solar panels onto arable farmland are chronic challenges. If such issues remain unresolved, an accelerated shift to synthetic fuels may occur even before 2035.
5. Although today the production of jet fuel from various biologically derived feedstocks through options such as co-processing integrated into petroleum refineries is accepted as SAF, in the near future there is a significant risk that this production method may no longer be recognized as SAF due to its integration with petrochemical processes. The fact that there are investment plans for only 4 Co-Processing SAF production facilities (while there are currently 13 operational co-processing plants) compared to 32 planned Power-to-Liquid (PtL) synthetic SAF plant investments in the Europe-Middle East and Africa region supports this observation. In Türkiye, Tüpraş and DB Tarımsal Enerji have announced that they will produce SAF. However, there is currently no announced production or investment plan in our country for synthetic fuel production technologies such as Power-to-Liquid (PtL) or Alcohol-to-Jet (AtJ). Therefore, pioneering initiatives in this field could be a critical investment as the first of their kind to be implemented in Türkiye. Medium-haul flights with a capacity of 100–250 passengers and under 2.5 hours, together with long-haul flights with capacities over 250 passengers and more than 2.5 hours, account for 75% of total sectoral emissions from civil aviation. The global

PtL market is projected to grow by 51.1% between 2023 and 2031¹, while the AtJ market is expected to grow by 18.2% between 2025 and 2034². There is no alternative other than the use of Sustainable Aviation Fuels (SAF) for the decarbonization of the civil aviation sector by 2050. Considering that as of 2035, at least 5% of SAF to be used in aircraft must come from synthetic fuels, PtL or AtJ technologies are expected to scale up rapidly compared to other existing technologies.

6. Türkiye, thanks to its geopolitical position, is positioned as a strategic energy bridge in energy transfer between the East and the West through projects such as TANAP and the Baku-Tbilisi-Ceyhan pipeline. In addition, our country, which has good potential in renewable energy sources such as solar and wind, has significant potential for the transport of various fuels and energy carriers (SAF, hydrogen, methanol, ammonia, biomethane, DME, etc.), especially due to its proximity to European energy corridors. This situation has become even more noteworthy in recent years with the increasing concerns in Europe regarding energy independence. While the European Union, aiming to diversify its energy supply, currently relies on the wind energy and carbon storage capacities of the northern EU countries and invests in countries such as Morocco, Egypt, and Algeria in the south, it is considered that it may also evaluate Türkiye's potential for access to niche fuels such as SAF. Estimates suggest that with increasing demand, global SAF supply is expected to exceed 20 million tons by 2035³. The ARA (Antwerp-Rotterdam-Amsterdam) port network, which is of critical importance for Europe, manages Europe's SAF market. Considering the high cost and additional emissions that would arise from transporting SAF from distant markets such as North America and Asia (Singapore, Japan), which will become the largest SAF production hubs by 2030, the potential SAF supply that Türkiye can provide is considered to be highly critical for buyers in Europe.
7. Türkiye's energy supply still depends on largely fossil fuels (82%) such as coal, natural gas, and oil, and coal accounts for a significant portion (27%) of the fossil fuels used. It is known, however, that the majority of coal reserves in our country consist largely of lignite-type coal. Unlike hard coal, a large portion of our lignite reserves has low calorific value and is generally used for electricity generation in thermal power plants. Although studies aimed at converting low-calorific-value domestic lignite into value-added chemicals and fuels are of strategic importance for our country, it should be noted that global investment trends have shifted away from Coal-to-Liquid (CtL) technology, indicating

the need to work on new thematic areas in this field. In this context, the integration of Carbon Capture and Storage (CCS) systems, co-gasification with biomass, and modular CtL facilities are among the current research topics that should be considered. Studies of this nature have been carried out in our country to investigate the more efficient use of our coal reserves. Under the coordination of the TÜBİTAK Marmara Research Center (MAM) Energy Institute, the TRIJEN project (Production of Liquid Fuel from Biomass and Coal Blends), which was actively conducted between 2009 and 2016, is an example of CBtL (Coal & Biomass-to-Liquid) technology, aiming to produce liquid fuels such as gasoline and diesel and valuable chemicals such as naphtha using domestic lignite coal and biomass resources. The synthesis gas (a mixture of carbon monoxide and hydrogen) obtained by gasifying coal was converted into liquid fuels and other chemical products using special catalysts. It is important that the results of this project, which was launched with a major investment, be rapidly scaled up for industrial use without delay and that the developed catalysts be commercialized by enabling their use in different areas.

8. With the expiration of mechanisms such as YEKDEM (Renewable Energy Sources Support Mechanism) after its 10-year support period, it has been observed that especially the first biogas plants established around 2015 have not been able to sell the electricity they produce to the grid with sufficient profitability. Compared to the years when these plants benefited from YEKDEM support, profitability has significantly declined post-support. At this point, with advancing technology, biogas can be upgraded to biomethane, which becomes a much more value-added product due to its higher efficiency. One of the main reasons for this is that the initial investment, maintenance, and operating costs of gas engines used in biogas plants are quite high. Therefore, in order to ensure the continuity of biogas plants, they need to gradually transition to next-generation technologies such as Membrane/PSA technologies or biomethanization and be able to sell the biomethane they produce directly to the natural gas grid. For example, a biogas plant that received YEKDEM support before 2021 and had a biogas conversion efficiency of approximately 2 kWh electricity/m³ could generate about TRY 16/m³ in electricity sales revenue for each cubic meter of biogas produced. Without YEKDEM support, however, this figure can drop to approximately 4.5 TRY/m³, based on market clearing prices as of March 2025. On the other hand, if such a plant could sell the biomethane it produces directly to the system as gas, it could generate approximately 12 TRY/m³ in biomethane revenue based on April

2025 prices. However, as of today, our current legislation and administrative regulations do not permit biogas plants to sell biomethane to the natural gas grid. Considering that there are a total of 116 biogas plants in our country and the new investment potential in this area, it is foreseen that making the necessary legal arrangements to allow injection into the natural gas grid would make a significant contribution to the sustainability of the biogas and biomass sector.

9. Due to high investment costs, electro-fuel (e-fuel) investments are most directly influenced by long-term off-take guarantees and the market share of the final product to be produced (methanol, ethanol, ammonia, kerosene, e-SAF, etc.). At this point, a multilateral off-take structure established with the right stakeholders in our country could enable a potential investment to mature faster and more healthily. It has been observed that investments necessary for electrolyzer installations for green hydrogen production and costly carbon capture units cannot be made when supply and demand are uncertain or when multiple demand-side parties do not exist. Therefore, it is critical for synthetic fuel-using airlines and international airports in our country to create demand by making SAF projections and determining SAF roadmaps, which will accelerate e-SAF investments domestically. The Twelfth Development Plan states that studies supporting the production and use of sustainable aviation fuels in the aviation sector will be supported in line with net zero emission targets. At this point, public supports and guidance from pioneer platforms also accelerate the process. For example, the draft SAF regulation prepared by the General Directorate of Civil Aviation (SHGM) entering into force as soon as possible will play a role in accelerating market formation and attracting investors' interest. Similarly, the roadmap study prepared by the "Türkiye Sustainable Aviation Platform" to encourage SAF adoption is also an important work for coordinated progress of all relevant stakeholders. Additionally, under CORSIA, the mandatory carbon offsetting and reduction system for international civil aviation, sustainable aviation fuel use is expected to increase especially for long-haul flights, and investment demand for these fuels is expected to accelerate further. Furthermore, developing a domestic certification and monitoring system compatible with international certifications (e.g., ISCC, RSB) for the traceability of sustainable fuels in our country is important for accelerating investment processes. In this transformation process, the establishment of national MRV (Monitoring-Reporting-Verification) systems that will verify the carbon benefits of such alternative fuels is also necessary for the development of a reliable carbon market.

10. The use of alternative fuels in the maritime sector has accelerated in recent years in line with the IMO's (International Maritime Organization) target to reduce carbon emissions by 50% by 2050. However, a similar committed sustainability movement as seen in the aviation sector has not occurred in this sector, and the transition to alternative fuels and electrification is progressing more slowly than expected. The primary reason for this is the absence of strict regulations and sanctions in the maritime sector comparable to those in civil aviation. In the short term, renewable diesel fuels such as biodiesel and HVO are preferred solutions, while methanol is gaining popularity as an emerging technology. As a long-term solution, the use of green ammonia is being considered in the sector, alongside some safety concerns, and motor/infrastructure technologies are still under development. Hydrogen or electric marine vessels are also considered a smaller group mainly for short-distance routes and niche applications (tugboats, ferries, etc.). Some global shipping companies offer scope 3 emission reduction opportunities to their customers in various sectors through a reservation model based on the "Book&Claim" system. Sustainable fuels can be sold by documenting their environmental benefits (ISCC, RSB, GLEC) and reserving the amounts requested by customers receiving logistics services from shipping companies without the need for physical transportation in the supply chain. With the expected increase in scope 3 emission tracking mechanisms in the future, many companies receiving logistics services are anticipated to prefer this system to reduce emissions from transportation. This commercial method, which will be a driving force for the use of sustainable fuels in the maritime sector, can be further encouraged and expanded.

11. While the transformation to electric vehicles in passenger cars and light commercial vehicles continues at full speed, the electrification of heavy-duty vehicles used in long-haul freight transport is becoming quite challenging with today's battery and charging technologies. Currently, the additional costs of high-capacity batteries expected to provide long ranges, the lack of charging infrastructure in long-distance logistics leading to extended routes, and the time losses caused by waiting for long charging durations result in inefficiencies in commercial operations. Moreover, as the weight of batteries used in heavy-duty vehicles increases, the vehicle's payload capacity decreases and economic efficiency in logistics operations diminishes. At this point, renewable diesel fuels such as HVO (Hydrotreated Vegetable Oil), unlike conventional biodiesel (FAME),

can be used in diesel engines with minor or no modifications (drop-in fuel) and thus will continue to be a good alternative for passenger cars, light commercial vehicles, and heavy-duty vehicles with 100% HVO-compatible diesel engines during the transition to electrification. In this context, in our country, to support sustainable HVO production, new business models facilitating the collection of waste oils, which are the primary feedstock for HVO, as well as initiatives to raise social awareness, need to be enhanced. Additionally, legal regulations must prevent unregistered collection and usage.

- 12.** Türkiye's potential in the field of new generation fuels is closely monitored by international investors. The involvement of international firms such as TTCL and Honeywell in SAF facility projects in Türkiye,⁴ and large producers like Neste and TotalEnergies⁵ evaluating collaboration opportunities with Turkish Airlines, concretize this interest. Furthermore, the Japan-based Mitsubishi Corporation's identification of Türkiye as a potential market indicates that the country is considered a regional player, particularly in e-fuels. Sources such as Argus, ICF, and the IEA World Energy Outlook also recognize Türkiye among emerging markets with growing demand and production potential for low-carbon fuels.

As a result, although interest in biofuels is expected to increase over the next 10 years, due to potential issues in the supply of biologically sourced feedstock and logistical challenges related to inputs used (such as waste oil), biofuels are anticipated to share their market share with synthetic fuels in the medium to long term. While any form of energy farming that does not negatively impact food security and biodiversity will ensure the sustainability of biofuel production, with increasing solar and wind energy capacity and advancing technologies, it is expected that price advantages will eventually shift towards synthetic fuels. Regulations such as the European Union's Refuel EU support this expectation by encouraging the transition to synthetic fuels. However, both the high costs of CCUS technologies and difficulties in accessing green hydrogen currently stand as the biggest obstacles to synthetic fuel plant investments. Therefore, it is critical to quickly understand the mechanisms that will facilitate the transition to alternative fuels, such as synthetic sustainable aviation fuels (SAF), which are expected to see high demand in the coming years, and to validate production concepts.

2.

Hard-to-Abate Sectors

Energy transition requires the decarbonization of sectors such as electricity generation, transportation, and heating and cooling; however, some sectors face a much more challenging and costly transformation process due to technological limitations, high costs, infrastructure requirements, and geopolitical sensitivities. Within the scope of this study, the so-called Hard-to-Abate Sectors are considered as heavy freight transport, shipping (maritime transport), aviation, iron and steel, and chemical–petrochemical industries.

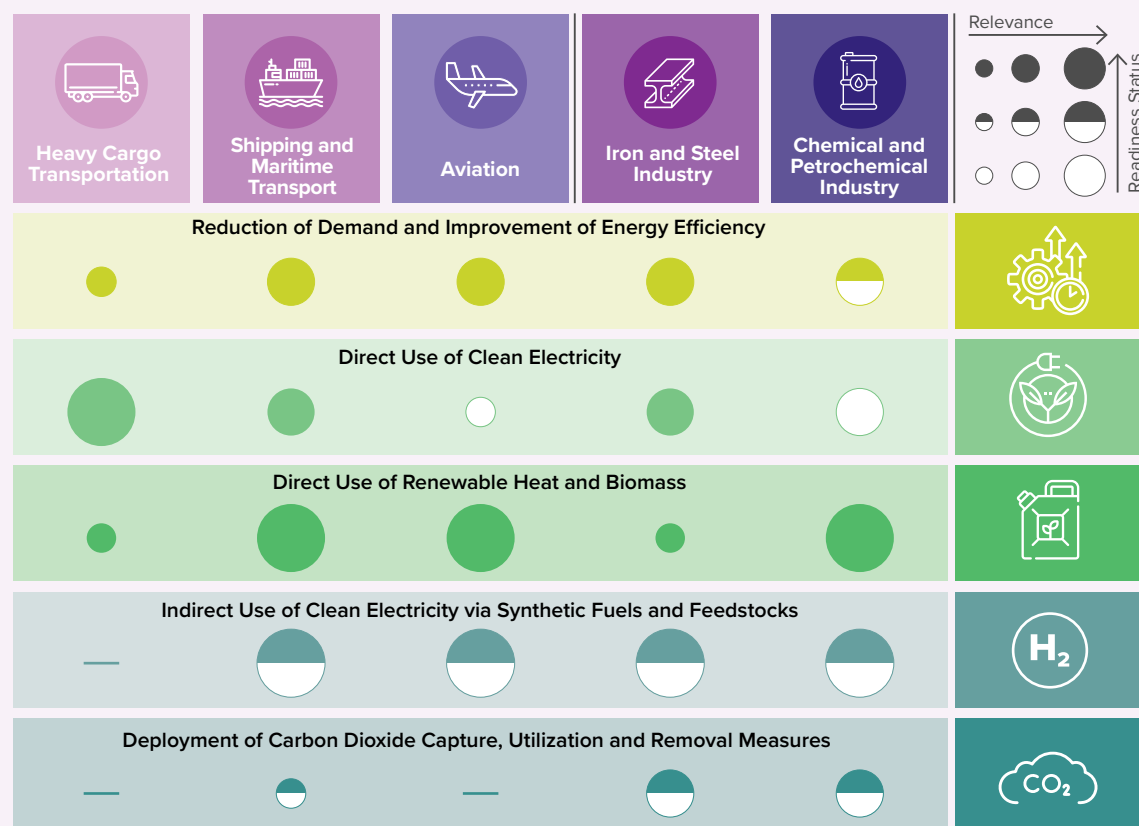


Figure 1. Key Technology Pathways and Readiness Level in Hard-to-Abate Sectors [7]

In recent years, significant progress has been made in the technologies developed for the transformation of hard-to-abate sectors. Figure 1 illustrates which technology pathways stand out for these sectors in terms of both impact potential and readiness level. In heavy-duty transport, direct electrification demonstrates the highest level of interest and commercialization speed, while in maritime and aviation, the main solution technologies are biofuels and e-fuels. In the iron and steel and chemical-petrochemical sectors, hydrogen-based processes and CCUS technologies are at the forefront. The rapid advancement of hydrogen-based direct reduction (DRI) towards commercial-scale plants in the iron and steel sector⁶ and the pilot-stage development of pioneer electric steam cracking (e-cracking)

projects in the chemical sector can be cited among these developments.⁷ However, the necessary infrastructure investments, economies of scale, and policy incentives required for the rapid deployment of these technologies have not yet been fully implemented.

Direct electrification covers various applications such as the widespread use of electric arc furnaces in steel production, the commercialization of electric heavy-duty trucks, and the use of heat pumps in low- to medium-temperature industrial processes. Indirect electrification, on the other hand, involves the production of hydrogen and its derivatives (green hydrogen, e-fuels, etc.) from renewable sources and contributes to emission reductions particularly in the iron and steel, maritime, aviation, and chemical sectors.⁸ In this context, Figure 2 schematically summarizes the production and distribution flows of e-fuels (a subcategory of synthetic fuels) and biofuels, starting from renewable sources and extending to various end-use areas.

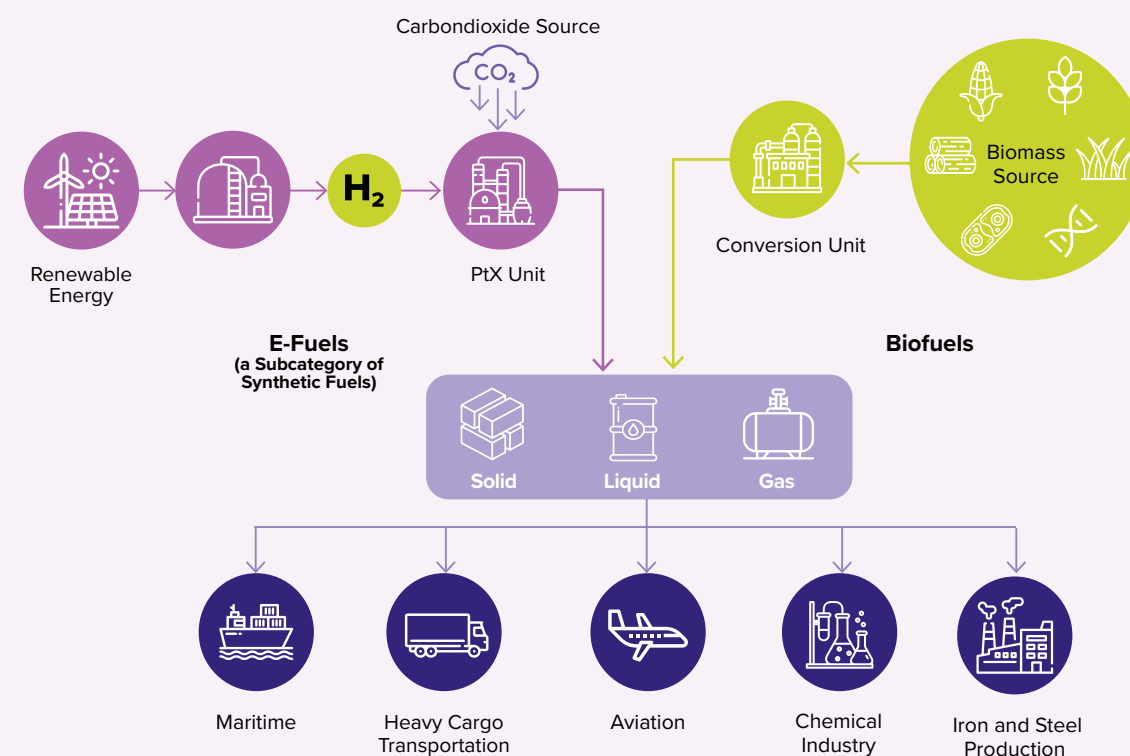


Figure 2. Flow Diagram of E-Fuels and Biofuels from Production to End-Use in Hard-to-Abate Sectors

Biofuels and synthetic fuels stand out as complementary solutions in segments of these sectors where electrification cannot be implemented. Biofuels, in particular, have significant potential to replace conventional fossil fuels and substantially reduce emissions in the short and medium term, especially in long-haul or high energy density applications such as aviation and maritime. This potential is detailed in Figure 3 based on the years 2030–2040–2050. With the acceleration of the electric vehicle transition in the automotive sector, it is anticipated that the biofuels used in this field will shift towards the aviation and maritime sectors in the long term.⁹ In the chemical and petrochemical sectors, the use of sustainable bio-feedstocks and synthetic carbon sources reduces dependence on fossil-based feedstocks and shrinks the overall carbon footprint.

Fuel Type	Fuel	Aviation Demand (EJ)				Maritime Demand (EJ)			
		2023	2030	2040	2050	2022	2030	2040	2050
Biofuels	Maritime Biofuels	-	-	-	-	0.0	0.6	1.3	1.7
	Biokerosene	0.0	1.2	3.9	6.1	-	-	-	-
Synthetic Fuels	Ammonia/Methanol	-	-	-	-	0.0	1.2	3.9	8.9
	Sentetik kerosene	0.0	0.4	3.3	6.8	-	-	-	-
Fossil Fuels	Kerosene	13.1	13.2	9.1	3.7	-	-	-	-
	Marine Fuel Oil	-	-	-	-	9.4	9.1	5.7	0.5

Figure 3. Havacılık ve denizcilik sektörlerinde düşük karbonlu yakıtlara oluşacak talep (Deloitte)

In addition to these transition pathways, energy efficiency, adoption of circular economy principles, behavioral and process changes, as well as carbon capture, utilization, and storage (CCUS) technologies can accelerate the approach of hard-to-decarbonize sectors to their net-zero targets. However, for technologies like CCUS to achieve economies of scale, both technical and economic conditions must be improved.

Increased awareness at the political and societal levels has mobilized government and private sector initiatives. Initiatives such as the Breakthrough Agenda, Mission Innovation, and the Climate Club, along with policies like the United States’ Inflation Reduction Act and the European Union’s Fit for 55 Package—specifically the RefuelEU Aviation and FuelEU Maritime regulations—represent efforts to accelerate the transition in hard-to-

decarbonize sectors. However, despite the growth in current initiatives and projects, stronger policy instruments, appropriate financing models, and enhanced international cooperation are needed in the medium term to enable these sectors to meet their net-zero emission targets.

Within this framework, the energy supply, infrastructure, and technology integration in hard-to-decarbonize sectors must be addressed in a multidimensional manner. While each sector has its unique requirements and potential solutions, the common ground lies in the rapid rise of renewable energy sources and the increasing competitiveness of next-generation fuel technologies. However, the cost gap with fossil-based systems must be bridged through policies and incentive mechanisms to achieve a comprehensive and sustainable transition. The speed and success of this transformation largely depend on the restructuring of global supply chains, infrastructure investments, and the realization of economies of scale.



A Comprehensive Look at Next-Generation Fuel Technologies

Advanced fuels can be defined as a specific group of fuels targeting low or zero carbon emissions, produced from renewable sources using advanced production technologies, and compatible with existing fuel infrastructures (drop-in fuels) or usable with minor adaptations to current infrastructure. According to the IEA NZE Scenario, the supply of these fuels is expected to increase rapidly by 2050. As illustrated in Figure 4, demand for low-emission hydrogen and hydrogen-based fuels, which started at a low level in the 2010s, is projected to grow exponentially, with an average annual growth rate of approximately 80% until 2030, followed by around 9% growth annually between 2030 and 2050. Meanwhile, demand for modern solid bioenergy, predominantly used in industry, is expected to expand gradually until 2050, thereby increasing its share in the supply portfolio.¹⁰

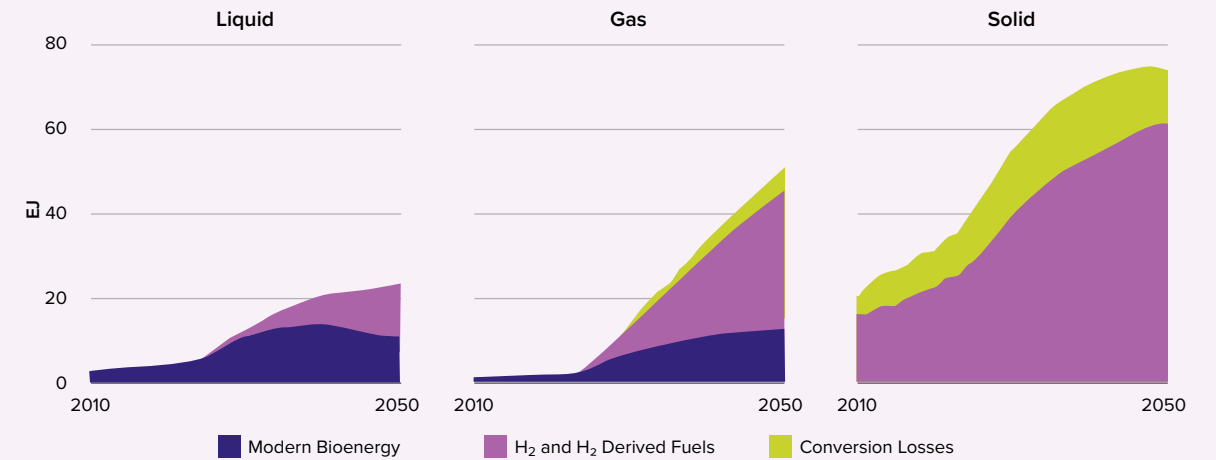


Figure 4. Demand for Low-Emission Fuels in the IEA NZE Scenario, 2010–2050 [10]

The demand for modern liquid biofuels is projected to increase by 200% by 2040. In the coming years, as internal combustion engine vehicles are gradually phased out, the blending requirements in road transport are expected to decline, which will be balanced by continuing demand growth in maritime and aviation sectors. For gaseous fuel forms such as biogas and biomethane, 2030 is anticipated to mark their emergence as a valuable component of the energy system, especially in the power sector. This development holds strategic importance due to biogas and biomethane offering a cost-effective alternative to natural gas following the Russia-Ukraine conflict. By 2050, biogas produced through new generation technologies is expected to play various roles in flexible power generation, industrial heat and hydrogen production, and low-cost clean gas demand in maritime fuels.

In light of these global projections, within the scope of this study and under the framework of next-generation fuel technologies, twelve (12) different production methods with high potential for both commercial success and decarbonization capacity in the short, medium, and long term have been examined in detail and are presented in Figure 5. The production methods addressed in the study were evaluated based on multifaceted criteria including current technological advancements, economic feasibility, scalability, and policy support mechanisms.

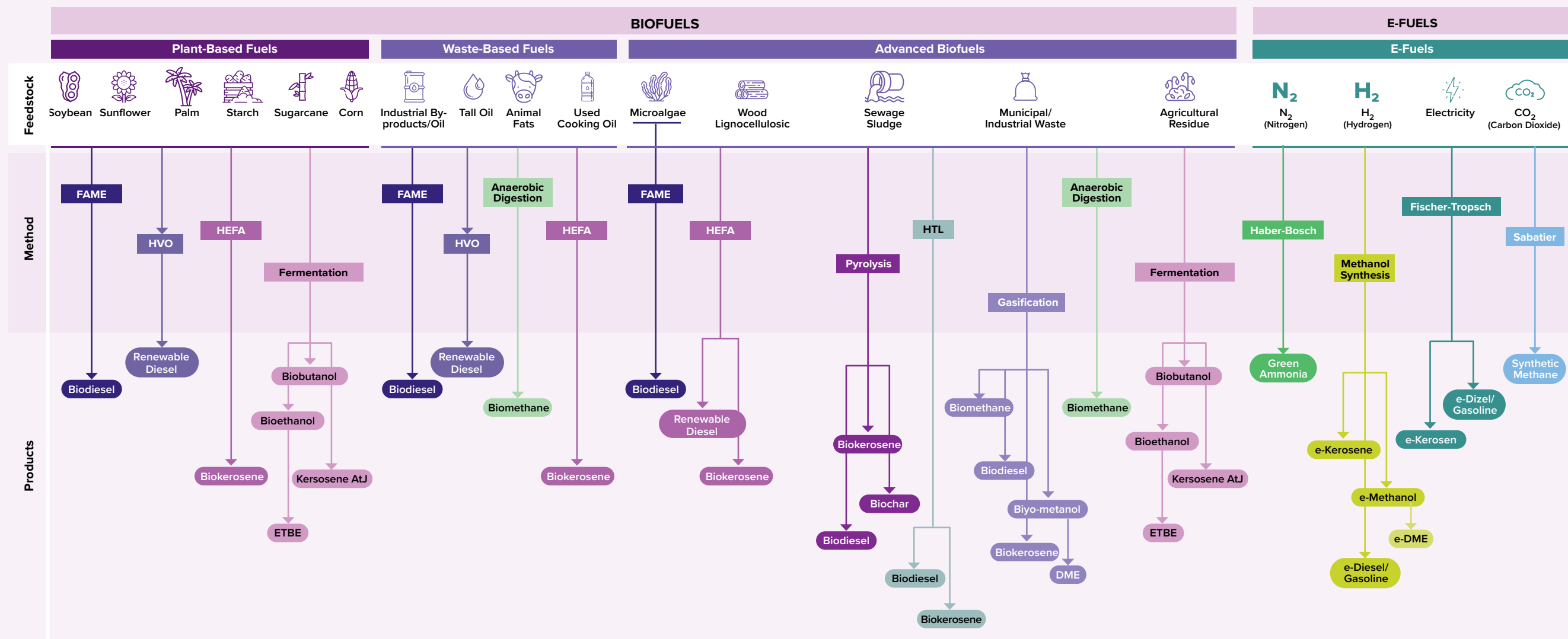


Figure 5. Next-Generation Fuel Technologies: Feedstock, Method, and Product

3.1. Biofuel Technologies

Biofuels are defined as fuels produced from organic materials derived from living organisms. In other words, combustible materials in solid, liquid, or gaseous form obtained through physical, chemical, or biological processes from biomass sources such as wood, agricultural residues, oilseeds, or organic waste are called biofuels.¹¹ For centuries, humans have used biomass like wood and dried animal manure as fuel for heating and cooking. Over time, these traditional biomass methods have gradually been replaced by more efficient and environmentally friendly modern biofuels. Today, biofuels constitute one of the largest renewable energy sources, supplying more than 6% of the world's energy demand. The figure below (Figure 6) illustrates the share of biomass energy within the total energy supply.

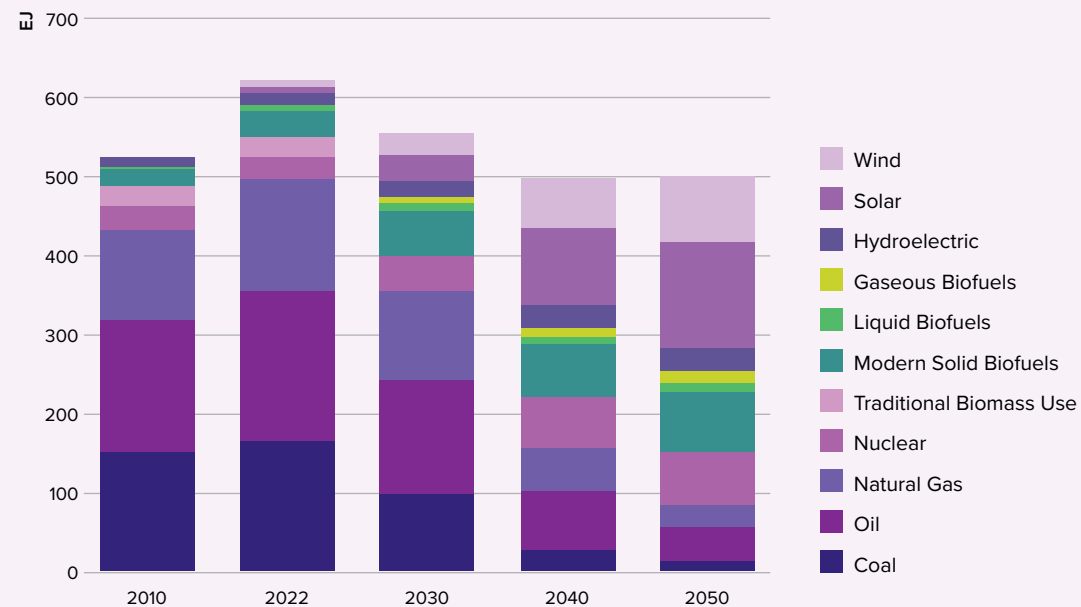


Figure 6. Changes in Global Total Energy Supply by Source (2010 – 2050, EJ) [10]

The concept of modern biomass, as outlined above, encompasses more advanced technological applications beyond the traditional use of biomass, such as producing diesel engine fuel from vegetable oils or generating biogas from organic waste. Within this context, biofuels produced under appropriate conditions can be considered carbon neutral because they are part of the carbon cycle. In other words, the CO₂ released into the atmosphere during fuel combustion is effectively the reuse of CO₂ absorbed by plants during their growth. Additionally, when BECCS (Bioenergy with Carbon Capture and Storage) techniques are employed, biofuels can become carbon negative. Naturally, this balance depends on emissions from agriculture, land use, and processing stages, so not all biofuels are fully carbon neutral. Given these definitions and balances within the carbon cycle, it is crucial to closely examine both the current share of biofuels and the growth expectations for the future.

Currently, biofuel usage holds a significant place in road transportation, electricity generation, and heating sectors, and it is expected to grow exponentially by 2050. The root causes behind this expectation include global efforts to diversify energy supply, mitigating the impacts of crude oil price fluctuations, reductions in biofuel production costs, and increasing environmental awareness. Additionally, development policies implemented in some regions serve as an extra factor supporting interest in biofuels. Currently, approximately 80% of global biofuel production is carried out by Brazil and the United States.

In this context, as indicated in Figure 7, approximately 10% of bioenergy in 2020 was allocated to road transportation through liquid biofuels, and 6% to power and heat generation in the form of biogas/biomethane. According to the International Energy Agency's Net Zero Emissions scenario, liquid biofuel production is projected to increase about fourfold, while biogas/biomethane production is expected to increase sixfold by 2050.¹²

Global Distribution of Biofuel Production in NZE by Type and Technology



Liquid biofuel production is projected to increase fourfold between 2020 and 2050, driven by the development of sustainable biomass supply chains, while biogas production is expected to increase sixfold during the same period.

Notes: EJ = exajoule; CCUS = carbon capture, utilization, and storage. Conventional ethanol refers to production using food-based energy crops. Advanced ethanol refers to production obtained from waste and residues as well as non-food energy crops grown on marginal or non-arable lands. Conventional biodiesel encompasses biodiesel produced by the FAME method using food-based energy crops. Advanced biodiesel includes biodiesel produced from biomass using Fischer-Tropsch and HEFA methods, utilizing wastes, residues, and non-food energy crops grown on marginal or non-arable lands. Biomethane refers to methane obtained through upgrading (refining) biogas and techniques based on biomass gasification.

Figure 7. Net Zero Emission Scenario (NZE) Biofuel Distribution and 2050 Projection [12]

3.1.1. Fundamental Technological Pathways within Biofuels

Biofuel production is highly diverse in terms of feedstocks used and conversion technologies. Biofuels can exist in physical forms as solid, liquid, or gas. This classification is made based on the mode of biofuel usage and the degree of processing. Fuels obtained through the direct use or mild processing of solid biomass are referred to as solid biofuels. Fuels in liquid form, generally used in vehicle engines, are classified as liquid biofuels. Major examples of gaseous biofuels include biogas and its derivative, biomethane.¹³

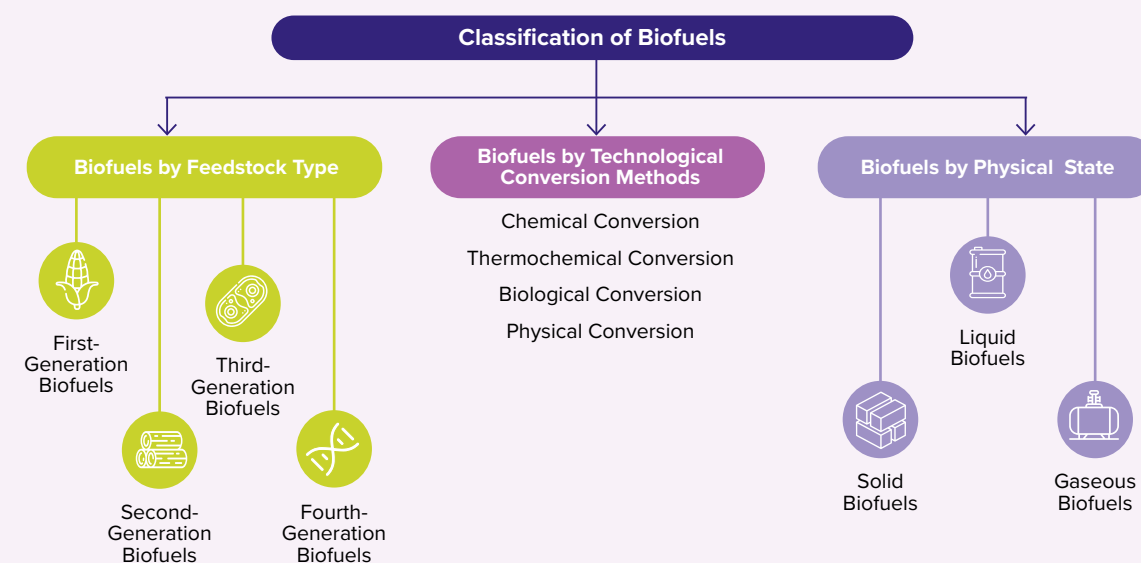


Figure 8. Classification of Biofuels

Another classification divides biofuels into first, second, third, and fourth generations based on feedstock types and sustainability levels.¹⁴ Within this framework, the classification of biofuels is schematically summarized in Figure 8.

- **First-generation biofuels**, refer to the earliest developed and widely adopted types of biofuels. They use agricultural products grown for food purposes as feedstock and are therefore also known as “food-based biofuels.”
- **Second-generation biofuels** are fuels produced from non-food feedstocks known as lignocellulosic biomass. Lignocellulosic biomass includes materials with high cellulose, hemicellulose, and lignin content such as wood, agricultural plant stalks and straw, forest residues, grasses, energy crops, urban waste, and industrial cellulose residues. The primary goal of second-generation biofuels is to produce fuel using waste and residue materials that do not enter the food chain or specially cultivated cellulosic plants.
- **Third-generation biofuels** generally refer to algae-based fuels. Microalgae and some macroalgae are organisms that grow through photosynthesis and produce biomass

rich in oils, carbohydrates, or other high-energy components. The third-generation biofuel approach aims to produce fuel using fast-growing organisms such as algae, which have low agricultural land requirements. The newest and most advanced biofuel concepts are grouped under the fourth generation in the literature.

- Fourth-generation biofuels**, Fourth-generation biofuels aim to achieve net negative carbon emissions during production or utilize innovative biotechnological methods. There are two main approaches within this concept. The first approach involves carbon capture and storage (CCS) during biofuel production to retain CO₂ emissions released into the atmosphere. The second approach focuses on developing biofuel production systems that use genetically engineered and synthetic biology-designed organisms to directly consume CO₂ as a carbon source. The first approach includes integrating CCS into a biomass power plant to achieve net carbon-negative energy (BECCS). The second approach involves converting CO₂ directly into fuel components in open-atmosphere systems using laboratory-designed microorganisms or algae.¹⁵ Below, different biomass feedstock examples classified under various biofuel generations are provided.



Figure 9. Examples of Feedstock Sources from Different Generations of Biofuels

Within the framework of the above classification, it is also important to emphasize that the development of biofuel technologies may not be linear. For example, while some sources categorize biodiesel produced from waste cooking oils as second-generation, technically the process resembles first-generation biodiesel technology. Therefore, the concept of “generation” should be seen more as a guide rather than an absolute technical classification. What matters is the sustainability of the feedstock used in biofuel production and the technology readiness level. In this context, it is necessary to evaluate how these different types of biofuels are produced, specifically focusing on their conversion technologies.

Biofuel production requires different technological conversion pathways depending on the chemical composition of the feedstock used and the type of fuel desired. In general, there are four fundamental technological pathways for obtaining fuel from biomass. These are, as shown in Figure 10, chemical conversion, thermochemical conversion, biological conversion, and physical conversion methods.¹⁶

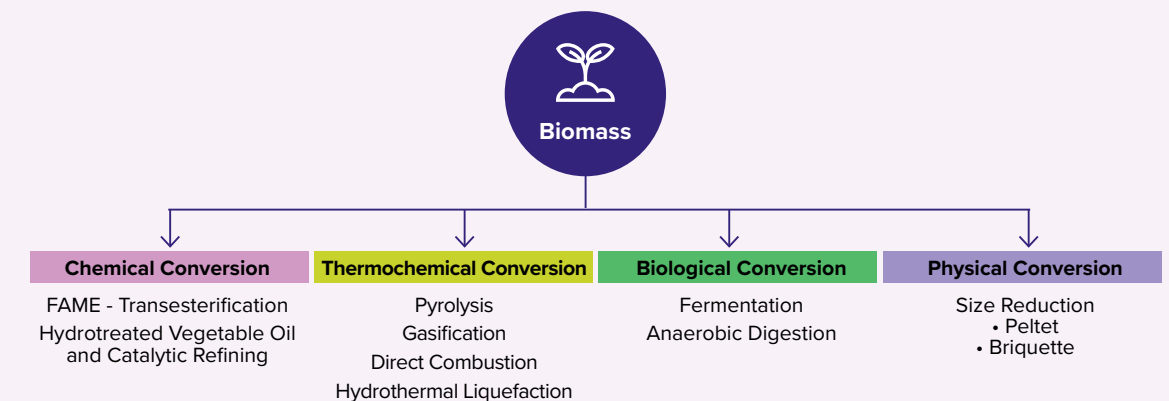


Figure 10. Examples of Conversion Pathways for Fuel and Energy Production from Biomass

Chemical conversion, is the transformation of biomass or biomass-derived intermediates into targeted fuels through chemical reactions and catalysts. This method typically involves selective conversions in a chemical reaction environment without the need for high temperatures. Among chemical biofuel production methods are Transesterification (Ester Exchange) Reaction, the primary chemical pathway for producing biodiesel (FAME)

from vegetable and animal oils, and Hydrotreated Vegetable Oil (HVO) and Catalytic Refining. These chemical conversion pathways have a Technology Readiness Level (TRL) of 9. Although the HVO process, whose production flowchart is shown in Figure 11, is more expensive and technologically demanding than transesterification, the fuel quality of the resulting product is very high. HVO diesel fuel is a drop-in fuel that can fully replace petrodiesel and can be used in existing diesel infrastructure without blend limits.

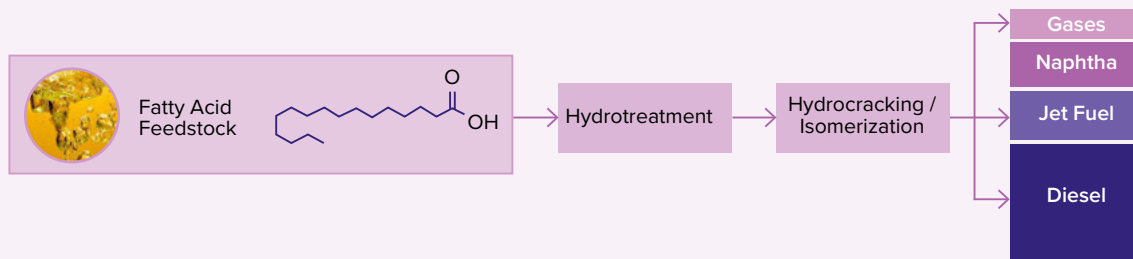


Figure 11. Production Process of HVO and Renewable Diesel/Jet Fuel Production Flowchart

Global production of HVO has rapidly increased in recent years; especially in Europe, some oil refineries (such as ENI in Italy and Total in France) have converted their facilities into biofuel refineries. The Finnish company Neste is among the world's largest HVO diesel producers, with an annual capacity of approximately 3 million tons.¹⁷ In the 2020s, renewable diesel also gained significant momentum in the USA thanks to California's Low Carbon Fuel Standard. According to IEA data, the global HVO production capacity, which was approximately 9 million tons in 2020, is expected to triple by the end of this year (2025).¹⁸ This upward trend demonstrates the growing importance of HVO as a chemical conversion technology. Currently, there is no commercial-scale HVO production facility in Türkiye. In biofuels, the concept of chemical conversion includes some specific processes in addition to the aforementioned methods. The Fischer-Tropsch (FT) synthesis is a catalytic chemical synthesis that produces long-chain hydrocarbon fuels from synthesis gas (a mixture of CO and H₂). The FT synthesis used in the biomass-to-liquid (BtL) fuel production process can be classified as a chemical conversion because its key step involves the polymerization of CO and H₂ over a chemical catalyst (based on iron or cobalt) into hydrocarbon chains ranging from C₅ to C₁₅. Currently, there is no fully commercial-

scale FT-BtL facility. In Türkiye, there is not yet any commercial-scale production facility in this field. Chemical conversion pathways are an important part of liquid biofuel production and currently have a market volume of millions of tons through fuels such as biodiesel and HVO. Although biodiesel production is the first to come to mind when discussing chemical conversion in Türkiye, it is likely that HVO and advanced chemical catalytic processes will also be implemented in the near future. The success of these methods will depend on the development of suitable catalysts, utilization of by-products, and cost optimization based on economies of scale.

Thermochemical conversion is based on the principle of chemically breaking down biomass into simpler fuels or intermediates with the help of heat energy. In these methods, high temperatures and sometimes high pressures are applied to convert the large molecules in biomass (cellulose, lignin, oils, etc.) into smaller hydrocarbons, gas, or coal. The main thermochemical methods include direct combustion, pyrolysis, gasification, hydrothermal liquefaction, and carbonization.¹⁹ Within the scope of this report, the pyrolysis method is considered, which involves the thermal decomposition of biomass exposed to high temperatures in an oxygen-free environment. Pyrolysis technology has been studied for many years and its Technology Readiness Level (TRL) varies between pilot and demonstration stages. In Finland, Fortum company has produced and sold fast pyrolysis oil from sawdust at one facility. In the USA, Ensyn and in Spain, BTG have undertaken similar pyrolysis oil production initiatives. Although not yet commercially widespread, pyrolysis could become part of the biorefinery concept in the future. In Türkiye, pyrolysis-related work exists at the academic and technology startup levels.

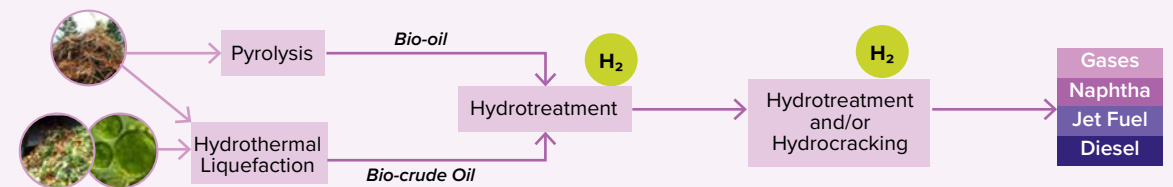


Figure 12. Flowchart of Liquid Fuel Production from Biomass Based on Pyrolysis and HTL (Hydrothermal Liquefaction)

Within the scope of this report, another thermochemical method examined is Hydrothermal Liquefaction (HTL) technology, developed especially for wet biomass (such as moist waste, sewage sludge, and algal biomass). In HTL, biomass is processed together with water under high pressure and temperature, directly converting it into a bio-oil phase. A key advantage of this technology is that the feedstock does not require drying. Therefore, biomass with 80-90% moisture content, like algae or food waste, can be converted directly. The Pacific Northwest National Laboratory (PNNL) in the USA and its corporate partners have tested a pilot HTL system producing petroleum-like oil from sewage treatment sludge. Denmark-based Steeper Energy plans to produce HTL oil from forest residues at a facility in Norway. Shell's IH² technology is a catalytic hydrothermal liquefaction variant, with a demo-scale plant established in India.²⁰ HTL is also a topic of interest in Türkiye. Although no industrial-scale facility currently exists, it holds potential for future energy recovery from municipal waste sludge. The production flowchart of the pyrolysis process is presented in Figure 12.

Another thermochemical conversion method is gasification, a process in which biomass is subjected to partial combustion in a controlled oxygen or air environment, without complete combustion, to produce synthesis gas. The advantage of the gasification method is that it converts solid fuel into synthesis gas, allowing versatile applications. Synthesis gas can be used to generate electricity in internal combustion gas engines or gas turbines. Alternatively, liquid biofuels can be produced via the Fischer-Tropsch process (detailed in Figure 13), or synthetic renewable methane (SNG) can be produced through catalytic methanation. Additionally, synthesis gas can be used to produce methanol, DME, or even hydrogen.

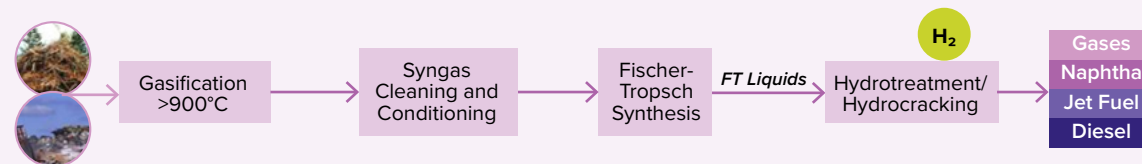


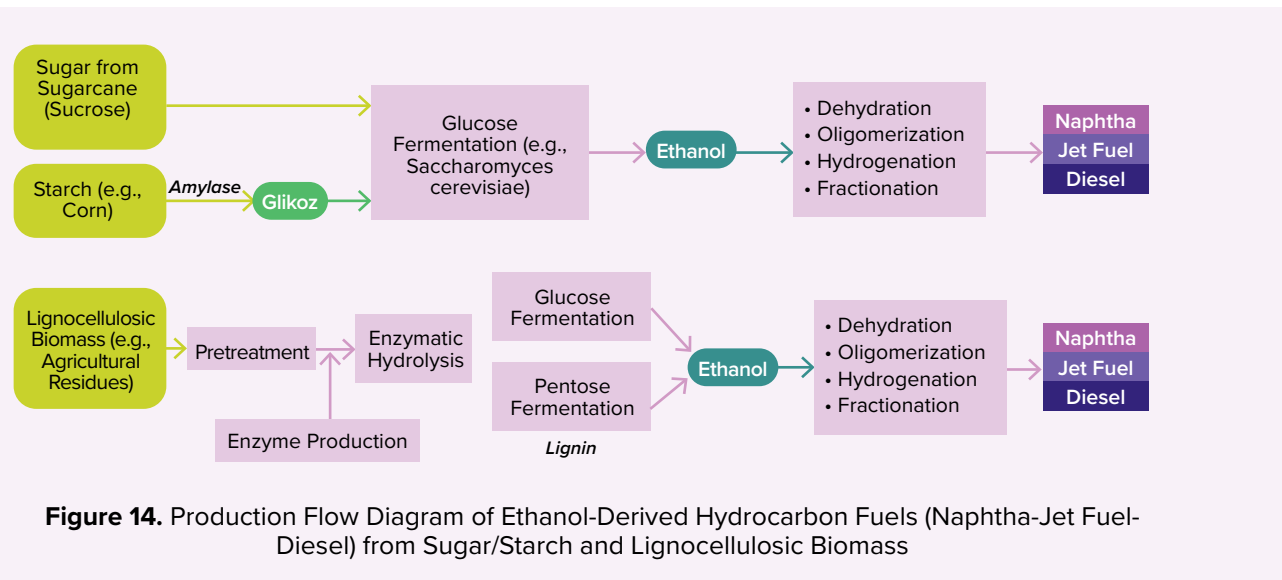
Figure 13. Flow Diagram of Gasification/Fischer-Tropsch Based “Biomass-to-Liquid” (BtL) Process

However, high-temperature processes, material and design challenges, and synthesis gas cleaning steps increase investment and operational costs. Therefore, only a limited number of full-scale biomass gasification plants have been established worldwide. In the past, an integrated gasification-diesel synthesis pilot plant named Värnamo operated in Sweden. Currently, some plants in South Africa (Sasol) and China convert synthesis gas derived from coal gasification into fuel via Fischer-Tropsch; however, the biomass share is very low. The TRL (Technology Readiness Level) of biomass gasification is considered to be around 6-8.²¹ There are no industrial-scale examples in our country. Since scale and continuity are important for the economic viability of the thermochemical methods mentioned above, supply chain and investment costs must be well analyzed. Table 1 presents the readiness levels and first-of-its-kind plant costs of the thermochemical conversion methods analyzed in detail within this report.

Table 1. Some Thermochemical Conversion Methods: Readiness Levels and Capital Costs²²

Technology	Technology Readiness Level	Cost
Pyrolysis	Depending on the process and design, TRL 6-9.	The investment cost for a pyrolysis plant with an annual production capacity of 20 million liters of oil is approximately €25 million.
HTL (Hydrothermal Liquefaction)	Depending on the process and design, TRL 6-8.	The investment cost for a facility with a daily production capacity of 110 tons (based on waste sludge) is approximately \$93.3 million.²³
Biomass-to-Liquid - Gasification (BtL)	Demonstration-pilot scale, TRL 6-8.	- The production cost of synthetic fuels via gasification ranges from €0.6 to €1.7 per kilogram, with the variation due to feedstock differences. - CAPEX for biomethane and methanol production is approximately €2,000–3,000 per kW of product output. - CAPEX for Fischer-Tropsch (FT) fuels ranges from €2,600 to €4,500 per kW of product output. The capital cost for hydrogen production using the same technology, for a 50 MW capacity plant, is approximately €65 million.²⁴

In agricultural countries like Türkiye, thermochemical methods are particularly attractive for converting abundant agricultural residues into energy. For these methods to be economically viable, scale and continuity are important; therefore, supply chain and investment costs must be thoroughly analyzed. The final conversion method to be addressed in this report involves biological conversion, which includes the transformation of biomass into desired fuels with the help of microorganisms or enzymes. This method generally occurs at lower temperatures and relies on biochemical reactions. The most common biological conversion methods are fermentation and anaerobic digestion. Fermentation is the process of converting biomass containing sugars or starches into ethanol or other alcohols via microorganisms. An example flow diagram is presented in the following figure.



The most common method in the context of biofuels is ethanol fermentation. Fermentation is a fully commercialized process (TRL 9) in first-generation bioethanol production. In second-generation bioethanol, the process becomes more complex due to the addition of pre-fermentation steps; however, the fermentation step itself remains fundamentally the same. In Türkiye, ethanol production through fermentation typically refers to molasses-based ethanol produced in sugar factories. There are facilities in agricultural regions such as Konya, Eskişehir, and Ankara that produce ethanol for the fuel industry. Within fermentation, genetic engineering studies have been conducted to develop more efficient microorganisms,

such as bacteria like *Zymomonas mobilis* or genetically modified yeasts, which can even ferment pentose sugars. This approach aims to convert the hemicellulose sugars present in lignocellulosic feedstocks into fuel. Another method is anaerobic digestion. In this process, organic wastes are broken down by microorganisms in an oxygen-free environment to produce biogas. High-organic-content and wet wastes such as animal manure, food waste, sewage sludge, and agricultural residues are used as feedstock. The produced biogas can be immediately used for electricity generation by burning it in generators or stored and utilized as fuel wherever needed. Additionally, in global applications, biogas can be purified with appropriate equipment and upgraded to biomethane containing up to 96% CH₄. Biomethane can be compressed and filled into CNG cylinders to be used as vehicle fuel or injected into the natural gas grid. An important by-product of biogas production is the nutrient-rich semi-solid digestate. This material can be dried or processed and used as organic fertilizer in agriculture, thereby ensuring a circular process.

Biogas technology in Türkiye has made significant advances over the past decade. Biogas production is a technology at TRL 9 maturity level. Innovations in the technology focus mainly on improving efficiency, such as through two-stage reactors and dry fermentation techniques, as well as biogas upgrading methods like membrane separation systems and PSA (Pressure Swing Adsorption). The European Union's REPowerEU plan, which aims to increase biomethane production tenfold by 2030, highlights the strategic importance of biogas technology.²⁵ As observed, fermentation and anaerobic digestion are already mature and widespread technologies, while enzyme-based and synthetic biology methods are emerging on the horizon. Biological conversion methods are particularly valuable for Türkiye in terms of utilizing agricultural and livestock waste. Biogas plants in regions with widespread cattle farms provide both environmental protection and energy production. Existing industries such as sugar factories create added value by converting by-product molasses into ethanol. In the future, when technologies like lignocellulosic ethanol or biobutanol reach commercial maturity, countries with extensive agricultural lands like Türkiye could find new opportunities in this field. However, R&D investments and pilot projects are critically important to build knowledge. Finally, physical/mechanical conversion methods that focus on improving only the physical properties (size, density, moisture) of biomass without altering its chemical composition are also widely used in the sector. Pelletizing and briquetting applied after grinding and drying fall under this category (see Figure 15).



Figure 15. Examples of Physical Conversion Methods

On the other hand, patent applications, as indicators of technological innovations and commercialization efforts, reveal which biofuel production pathways and feedstock sources have attracted significant attention in both industry and academia. Table 2 summarizes the biofuel technology pathways and feedstock sources with the highest number of patent applications between 2000 and 2025. This data has been compiled from reliable sources such as WIPO, Espacenet, and PATSTAT.

Table 2. Technology Pathways and Feedstock Sources with the Highest Number of Patent Applications in the Biofuel Sector During the Period 2000–2025

Technology Pathway	Raw Material	Approximate No. of Patent Applications
Biodiesel from Microalgae	Microalgae	315
Bioethanol from Corn Stover	Corn stover	280
Biodiesel from Waste Cooking Oil	Waste cooking oil	240
Cellulosic Ethanol from Agricultural Residues	Agricultural residues	300
Fischer-Tropsch Gasification from Lignocellulosic Biomass	Lignocellulosic biomass	350
Biogas/Biomethane from Municipal Solid Waste	Municipal solid waste	210

This table highlights the prominent areas in biofuel technologies in terms of patent applications, ranging from biodiesel production from microalgae, cellulosic ethanol production from agricultural residues, to Fischer-Tropsch gasification technologies from lignocellulosic biomass. The data provides valuable insights for investors, researchers, and policymakers as the technological development potential and commercial application scales increase. Furthermore, the rise in patent applications can be interpreted as a positive indicator of the commercialization potential and global adoption of the related technologies.

3.2. Synthetic Fuel Technologies

The concept of “synthetic fuels” has emerged as a result of artificially synthesizing hydrocarbon-derived fuels or valuable chemicals such as ammonia, methanol, and dimethyl ether (DME) through various chemical reactions instead of refining crude oil. The primary goal of synthetic fuel production is not to completely eliminate the use of fossil fuels but to complement these unsustainable conventional fuels with sustainable alternatives or, in the long term, to offer the most ideal alternative fuel option necessary for minimal fossil fuel usage. Moreover, the limited availability of fossil fuel resources and global concerns regarding energy supply security have triggered the search for alternative fuels like synthetic fuels to reduce dependence on oil throughout different historical periods. The synthetic fuel development race, which began before World War II, accelerated further during the oil crises of the 1970s. Unlike first and second-generation biofuels, new-generation synthetic fuel production does not require extensive agricultural land or excessive water consumption²⁶ associated with intensive agricultural irrigation needed for biomass production.²⁷ Therefore, synthetic fuels do not pose a threat to food supply security or land use. In this respect, synthetic fuels offer a sustainable alternative to meet global energy demand while also reducing the threats that biofuels may create regarding sustainable food supply and land competition.

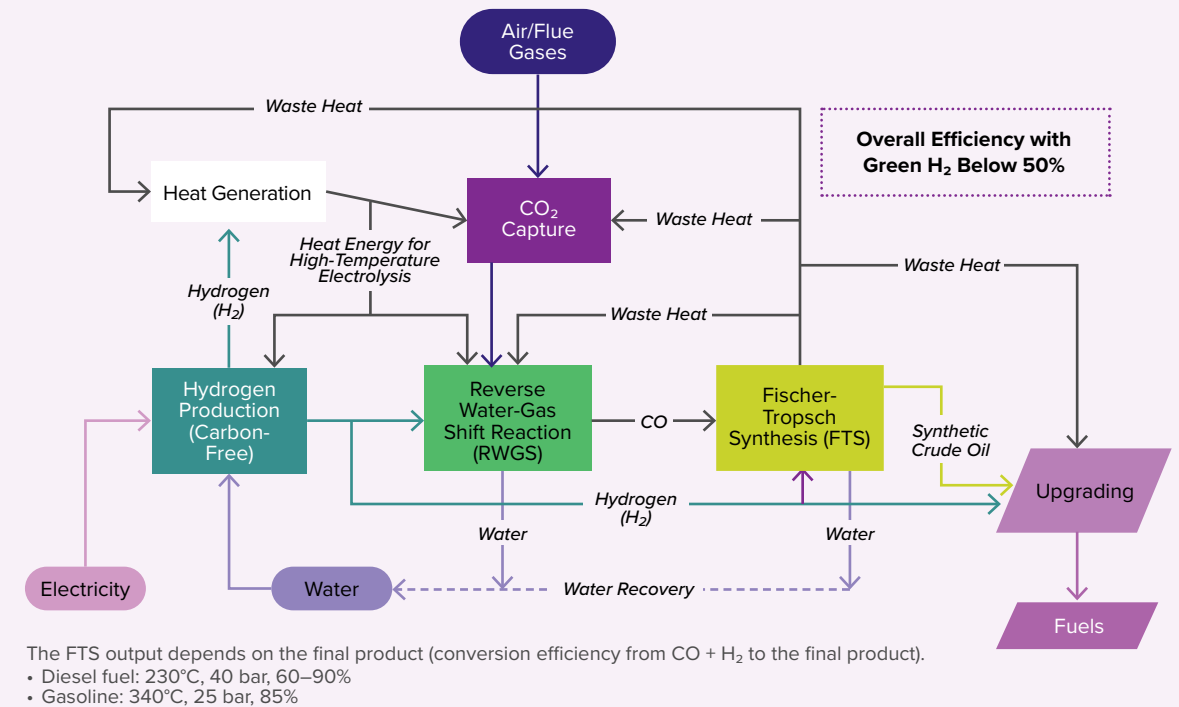
The diversity in production processes and the differing nature of the inputs/raw materials used have led to various classifications of synthetic fuels in the international literature. This classification is presented in Table 3. When examining synthetic fuels from the perspectives of technological development and sustainability, it can be said that classifications based on resource type and production process are more commonly used. This approach allows better tracking of synthetic fuels’ carbon footprint, energy efficiencies, and scalability. Therefore, to be more comprehensive, the concept of synthetic fuels can be classified in two different ways, as shown in the table below: according to the “type of input/raw material” or the “type of production process.” Biogenic carbon-containing biomass-based synthetic fuel production technologies (such as gasification and pyrolysis) are not included in the “Classification by Input/Raw Material Type” in the table below, as they are covered under Section 3.1 “Biofuels” in this report.*

Table 3: Classification of Synthetic Fuels

SYNTHETIC STRUCTURES	
By Input/Feedstock Type*	By Type of Production Processes
1. Renewable Carbon-Based Obtained via Carbon Capture (DAC or point source)	1. Indirect Conversion Processes
2. Natural Gas-Based (Gas-to-Liquids) / GtL	2. Direct Conversion Processes
3. Coal-Based (Coal-to-Liquids) / CtL	3. Conversion Processes to Carbon-Free Fuels (RFNBO such as Ammonia and Hydrogen production)

In recent years, with the impact of renewable energy use, carbon-neutral solutions such as Power-to-Liquid (PtL) or electrofuel (e-fuel) production concepts have begun to replace Coal-to-Liquids (CtL) and Gas-to-Liquids (GtL) technologies, and new investments are shifting toward this technology. According to the “SAF Capacity Map” published by Argus in February 2025, there are currently 4 operational PtL facilities worldwide, and investment plans have been made for 47 new PtL plants to be established.²⁸

In classification based on the type of production processes, a general distinction can be made between carbon-containing and carbon-free synthetic fuel conversion processes. For carbon-containing synthetic fuels, two different pathways can be followed: direct or indirect conversion. In indirect conversion methods, synthesis gas (a mixture of CO and H₂) is typically produced first from carbon dioxide (CO₂), followed by catalytic methods such as Fischer-Tropsch (FT) synthesis to obtain the targeted synthetic fuels. For example, PtL technology is an indirect conversion process involving sequential reaction steps. As shown in Figure 16, PtL technology includes stages of electrolysis, carbon capture, reverse water-gas shift (RWGS) reaction, and Fischer-Tropsch (FT) process to convert into liquid synthetic fuel (electrofuel & e-fuel). The RWGS reaction is required to convert into synthesis gas.

**Figure 16.** Flow Diagram of E-Fuel Production Process Integrating CO₂ Capture, RWGS, and Fischer-Tropsch

Traditional synthetic fuels can be produced from various fossil sources such as coal and natural gas, whereas e-fuels produced via PtL technology are a type of synthetic fuel synthesized solely using green hydrogen generated from renewable electricity and carbon dioxide captured from the atmosphere or industrial facilities. A general representation of the value chain for e-fuel production processes is shown in Figure 17.

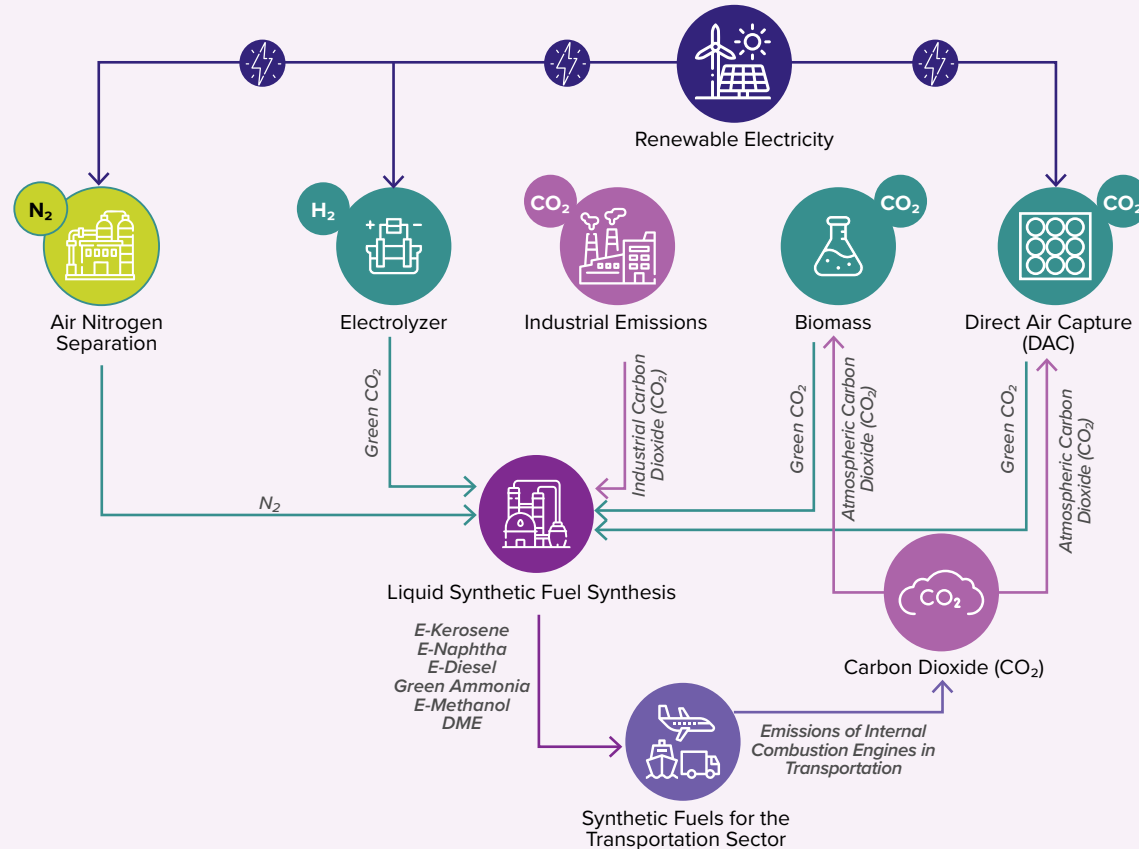


Figure 17. E-Fuel Value Chain from Raw Material to Final Product

In direct conversion methods, final products such as methanol, dimethyl ether (DME), and synthetic methane are produced by directly subjecting CO₂ captured from the air or other carbon sources to catalytic reaction with hydrogen, without the need for a synthesis gas formation stage. Power-to-Gas (PtG) technology is one of the most well-known examples of direct conversion. The Sabatier process, which forms the basis of this technology, converts CO₂ directly into synthetic methane (e-methane)

Regardless of classification type, all synthetic fuel production processes fundamentally rely on hydrogen, and the method of hydrogen production is a crucial factor defining the identity of the synthetic fuel. Therefore, strict monitoring of whether the hydrogen used in

synthetic fuel production is truly produced from renewable energy sources has become increasingly critical alongside rising hydrogen demand. For example, the European Union (EU) has set a target to use 10 million tons of domestically produced hydrogen and 10 million tons of imported renewable hydrogen by 2030, and launched the “European Hydrogen Bank” at the end of 2023 to strengthen market formation.²⁹ Approximately 9% of this large hydrogen demand of 20 million tons (about 1.8 million tons) is allocated for e-fuels produced via PtL technology.³⁰ At this point, the EU has introduced the concept of “RFNBO” (Renewable Fuels of Non-Biological Origin) to clearly define the boundaries of synthetic fuels and to exclude solutions that appear “green” but are actually derived from fossil-based electricity-produced hydrogen and unwanted fuels derived from such hydrogen. The RFNBO concept, first defined under the EU’s Renewable Energy Directive II (RED II) in 2018 and clarified with enforcement in 2021, broadly covers renewable liquid and gaseous fuels produced from non-biological sources. Since RFNBOs generally use green hydrogen produced via electrolysis as the primary feedstock, they are often confused with e-fuels, but they have some fundamental technical and regulatory differences from e-fuels.

3.2.1. Fundamental Technological Pathways within Synthetic Fuels

Efforts to obtain carbon and hydrogen, the building blocks of synthetic fuel production, through more sustainable means beyond fossil fuel sources have led to the emergence of “next-generation” synthetic fuels. Within this context, foundational chemical processes such as Fischer-Tropsch, the Sabatier Process, Haber-Bosch, and Reverse Water-Gas Shift (RWGS)—whose roots trace back to the early twentieth century—have been reshaped and adapted to contemporary needs, driven by the goals of reducing carbon emissions and the widespread adoption of renewable energy sources.

Recent advances in catalyst technology, the conversion of green hydrogen produced from solar and wind energy into synthetic fuels for transport and storage, large-scale carbon capture applications, and more efficient reactor designs have significantly impacted the transformation of these four fundamental chemical processes used in synthetic fuel production. For example, although the Reverse Water-Gas Shift (RWGS) process has been known for many years, it was initially rarely used industrially. However, with the increasing adoption of carbon capture technologies, RWGS has gained importance recently as a

key step in converting captured carbon dioxide into synthesis gas ($\text{CO} + \text{H}_2$). A similar transformation applies to the traditional Fischer-Tropsch (FT) synthesis, which converts synthesis gas into synthetic fuels (see Figure 18). For many years, coal and natural gas served as fossil carbon sources for the FT process. Over time, these carbon sources have been gradually replaced by biomass and industrial carbon emissions (flue gas). The utilization of these new carbon sources has led to new engineering solutions, such as “modular FT reactors,” which enable smaller-scale synthetic fuel production closer to biomass sources or integrated with industrial facilities, replacing traditional large-scale FT plants.

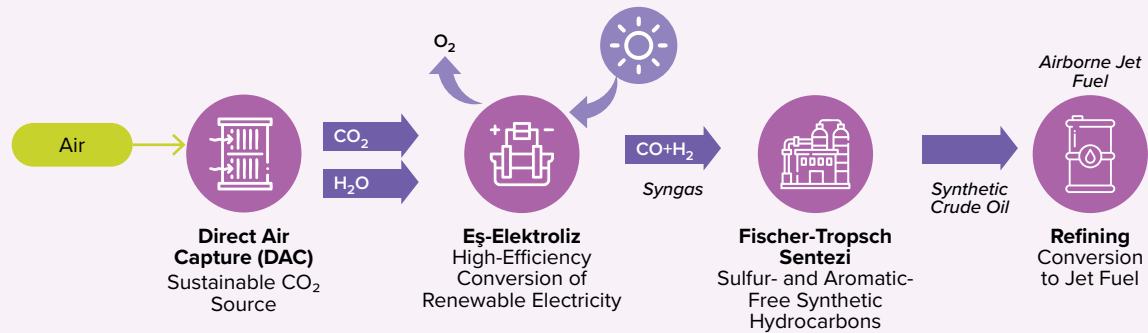


Figure 18. E-Fuel Production Flowchart Using the Fischer-Tropsch Method

Another example illustrating this transformation is the Haber-Bosch process (Figure 19), which for many years has produced ammonia (NH_3) using grey hydrogen derived from natural gas reforming. When green hydrogen is fed into the process, the resulting product is called “green ammonia.” Therefore, considering all these examples, it can be stated that in synthetic fuel production, radical changes—such as how conversion to carbon-based fuels occurs (direct, indirect, etc.), the shift to new carbon sources, and the method of hydrogen production—not only affect production concepts but also determine the preferred technologies.

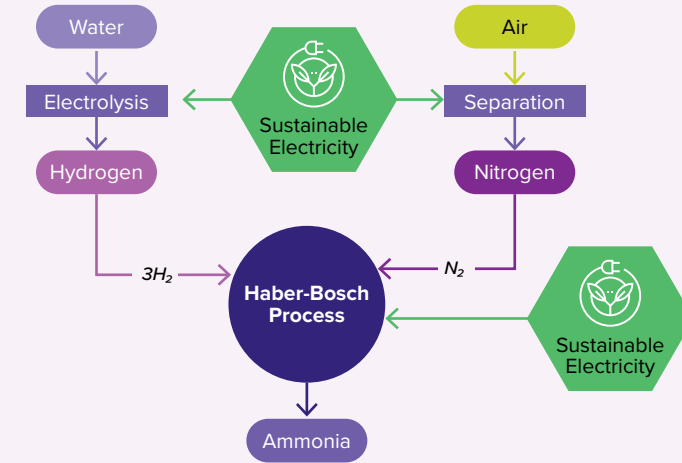


Figure 19. Production Flowchart of Ammonia Manufactured via the Haber-Bosch Process

Table 4 lists synthetic fuel production concepts along with the core technologies/chemical processes and the final synthetic fuels obtained, arranged vertically. Synthetic fuel production concepts comprise a combination of sub-technologies and chemical processes with varying technology readiness levels (TRLs). Due to this modular structure, the TRL levels of production concepts may vary within a certain range. For example, the PtG process, which falls within the TRL 5-8 range, consists of subsystems with different technological maturity levels, such as electrolysis, methanation, and gas grid integration. At this point, the TRL level of the process can be determined based on the type of electrolyzer used (Alkali, PEM, AEM, SOEC) and the methanation type (catalytic or biological). Although there are pioneering projects like the George Olah facility in Iceland for direct conversion processes such as thermocatalytic hydrogenation and methanol production, this technology is not yet mature enough for scalable deployment due to some technical limitations (TRL 6-7).³¹ The selectivity, efficiency, and lifespan of catalysts used in this process, such as $\text{Cu/ZnO/Al}_2\text{O}_3$ or Cu/ZnO/ZrO_2 , need to be improved.

Table 4. Different Synthetic Fuels and Their Technological Pathways

	1. Synthetic Fuel Consumption by Input/ Feedstock Type (Carbon Source)			2. Synthetic Fuel Production by Type of Manufacturing Process		
Production Concept	Coal-to-Liquids (CtL) fossil carbon-based	Gas-to-Liquids (GtL) fossil carbon-based	Renewable carbon sourced from Carbon Capture (DAC or BECCS)***	Indirect Conversion Processes (Two-step conversion requiring CO ₂ to synthesis gas conversion)	Direct Conversion Processes** (Direct conversion from CO ₂ to fuel)	Carbon-Free Fuel Conversion Processes (RFNBO Production)
Technological Pathways and Chemical Processes	↓	↓	↓	↓	↓	↓
	Gasification	Steam/ATR Reforming	Power-to-Liquid (PtL)* Synthesis gas production via Reverse Water-Gas Shift (RWGS) reaction + Fischer-Tropsch synthesis		Direct Methanol Synthesis*	Power-to-Gas (PtG)* Sabatier Process
Obtained Synthetic Fuels	Fischer-Tropsch Synthesis					Green Ammonia Synthesis* Haber-Bosch Process
	Synthetic Paraffinic Kerosene (FT-SPK) Synthetic Gasoline Synthetic Naphtha Methanol/DME		e-Kerosene e-Naphtha e-Diesel e-DME (Dimethyl Ether) e-OME (Oxymethylene Ether)		e-methanol	Synthetic Methane (SNG) or e-Methane Green Ammonia Green Hydrogen

* This production concept entirely utilizes Green Hydrogen produced from renewable electricity.
** Direct conversion processes such as coal hydrogenation and coal carbonization/pyrolysis, which are no longer commercially used, are not included in the table.
*** Fossil carbon from flue gases obtained from installations covered by the EU Emissions Trading System can be used until 2041.

The Power-to-Liquid (PtL) technology, operational in four different facilities worldwide and positioned within TRL 6-8, consists of multiple sequential subsystems and technologies, including electrolysis, carbon capture, synthesis gas conversion, and Fischer-Tropsch synthesis. At this point, the selected type of electrolyzer (Alkaline, PEM, AEM, SOEC), the carbon capture method (pre-combustion, post-combustion, oxy-fuel combustion), and the FT reactor system directly determine the TRL level of the PtL process. Traditional technologies such as Coal-to-Liquid (CtL) and Gas-to-Liquid (GtL), which include technologically mature processes like gasification and steam/autothermal reforming,

have been operated industrially for many years and have demonstrated large-scale applicability, thus are classified at TRL 8-9. However, new integrations based on CCUS for the decarbonization of these two mature technologies lower their TRL levels. Lastly, the Haber-Bosch process, which forms the foundation for green ammonia synthesis and is used in numerous ammonia plants globally, is commercially proven and also classified at TRL 8-9. Nevertheless, recent R&D efforts focus on addressing energy inefficiencies in this process (net energy efficiencies between 30–40%) and facilitating the direct use of ammonia as fuel. Concurrently, emerging next-generation ammonia production technologies, such as Direct Electrochemical Nitrogen Reduction, remain in the developmental stage.³²

4.

Analysis of Strategic and Economic Aspects of Next-Generation Fuel Technologies

Next-generation fuels, despite having different motivations and challenges across various regions of the world regarding their production and use, consistently secure a place in global markets due to their contributions to energy supply security, environmental benefits, and the fuel diversity they offer. Oil-exporting and oil-importing countries are affected differently by the transformation caused by these fuels. For oil-exporting countries, next-generation fuels are generally perceived as a demand-side risk factor, whereas for oil-importing countries, they are viewed as an opportunity to enhance energy security. Nevertheless, under current economic and technological conditions, all next-generation fuels are more expensive than conventional fossil fuels and are produced at volumes insufficient to fully replace traditional fossil fuels.

There are several key factors that determine the circulation of next-generation fuels in the global trade network and their place within supply chains, influencing both supply and demand. For biofuels, these factors primarily include access to and proximity of raw materials, the carbon footprint of the final product, and biofuel quality. For synthetic fuels, critical

production infrastructures such as electrolyzers, the availability of renewable energy sources, and regional biogenic CO₂ potential are essential. Especially in regions like Türkiye and the EU, which meet a large portion of their oil demand through imports, biofuels produced from domestic agricultural resources and waste provide strategic benefits. Similarly, depending on the efficient utilization of renewable energy sources, mid-to-long term e-fuel production holds significant potential for energy-import-dependent countries, a development that also reflects on international trade dynamics.

Global Map of Hydrogen-Derived Fuel Trade by Final Use Molecule in 2050

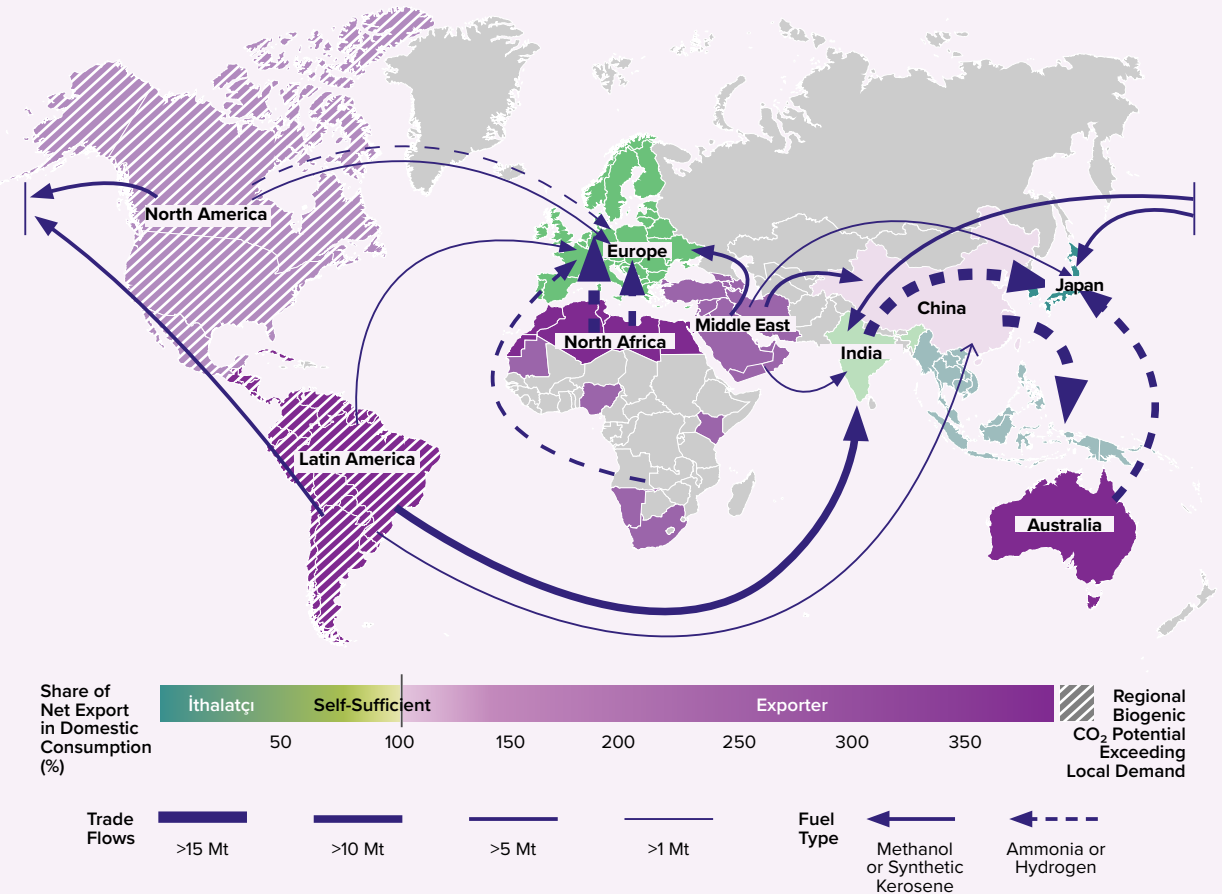


Figure 20. Global Map of Hydrogen-Derived Fuel Trade by Final Use Molecule in 2050³³

For example, the global situation regarding the trade of hydrogen-derived synthetic fuels such as methanol, synthetic kerosene, and ammonia by 2050 is summarized in Figure 20. Despite lacking significant biogenic CO₂ potential, the Middle East emerges as a strong candidate for methanol export due to its existing export infrastructure, low-carbon hydrogen production potential, and Direct Air Capture (DAC) investments. Benefiting from its geographic proximity to critical demand centers such as Europe, the Middle East is well-positioned to export methanol, which is economically favorable over short distances. Unlike regions with high e-fuel demand such as Europe, Japan, and South Korea, China and India possess substantial renewable energy potential. However, due to insufficient biogenic CO₂, these countries are likely to both import large quantities of methanol and synthetic diesel while exporting ammonia and hydrogen. This dynamic enables them to achieve a balanced and nearly self-sufficient energy economy. This complex trade network not only reduces regional imbalances but also optimizes resource allocation, thereby enhancing overall economic efficiency. Since the most suitable production locations for synthetic fuels are not expected to be near demand centers and shipping costs are generally lower compared to production costs, global trade can reduce costs and alleviate regional disparities. Regions rich in renewable energy and biogenic CO₂, such as North and South America, are well-positioned to become leading producers of synthetic fuels, especially synthetic diesel, which has a higher final product value but lower transportation costs. Their significant biogenic CO₂ potential provides a competitive advantage in fuel production. Meanwhile, regions with strong renewable potential but limited biogenic CO₂, such as North Africa and Sub-Saharan Africa, are best suited to focus on ammonia production and export. However, the lack of biogenic CO₂ restricts their ability to export carbon-based synthetic fuels. All these commercial dynamics directly influence the global market prices of next-generation fuels.

As shown in Figure 21, between January 2023 and October 2024, the price per ton of HEFA-SPK SAF decreased by approximately 43%, Class II renewable diesel HVO by about 40%, and conventional jet fuel by roughly 21%. Since the beginning of 2023, the price gap between HEFA/SPK and HVO compared to conventional jet fuel has started to narrow. The primary reasons for this include increased capacity and improved operational efficiency of HEFA and HVO plants, which have lowered unit costs. From the perspective of synthetic fuels, the most fundamental factor determining costs under

current conditions is the expense of obtaining carbon or, alternatively, the preference for carbon-free fuels by avoiding this cost.

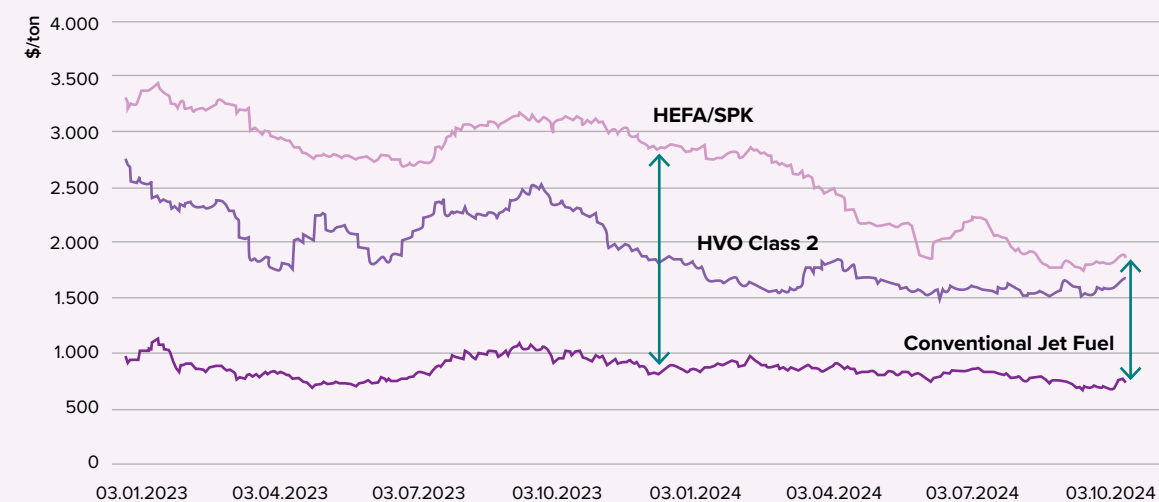
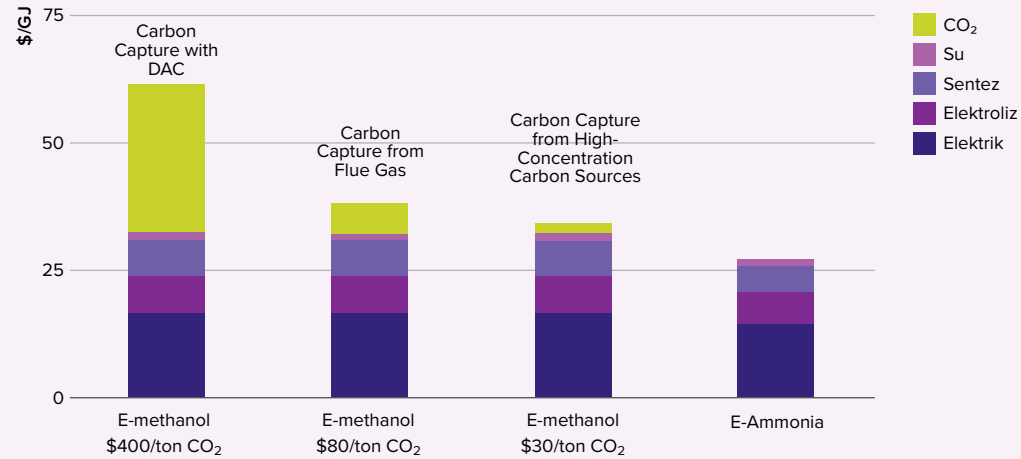


Figure 21. Periodic Price Comparison for HEFA-SPK, Class 2 HVO, and Conventional Jet Fuel³⁴

The cost of capturing carbon dioxide largely depends on the initial concentration levels. For example, Figure 22 compares the levelized costs of e-methanols produced using carbon captured from various sources and e-ammonia, where green hydrogen is the determining component in production. The presence of CO₂ at lower concentrations (by volume 10-20%) in industrial plant flue gases compared to fermentation processes increases carbon capture costs to approximately 60-80 USD/ton CO₂. If biogenic point carbon sources are not available at the production site, e-fuel plants can supply CO₂ raw material from the atmosphere via Direct Air Capture (DAC). When DAC-based CO₂ capture technology is preferred for large-scale e-fuel plants, capture costs of 400-670 USD/ton CO₂ are expected by 2030. Thus, e-methanol production relying on a high-concentration CO₂ source is about 25% more expensive than e-ammonia production; when based on post-combustion capture from biogenic flue gases, it is about 40% more expensive than e-ammonia. Finally, if CO₂ must be sourced directly from the air (DAC), the production of low-emission e-methanol becomes twice as expensive as e-ammonia. In conclusion,

the absence of additional carbon capture costs for e-ammonia production and its lower synthesis costs compared to e-methanol directly influence the competition between these two fuels, especially regarding their use in the maritime sector.



Note: A WACC of 5% and an economic lifetime of 25 years have been assumed. All assumptions are made for the year 2030. Performance parameters (all based on LHV) are considered as follows: electrolyzer efficiency at 69%, H₂-to-ammonia conversion at 88%, and H₂-to-methanol conversion at 80%.

Figure 22. Levelized Cost Comparison of E-Methanol and E-Ammonia Produced Using Captured Carbon from Different Carbon Sources³⁵

5.

Recommendations for Türkiye

The European Union's efforts to reduce its gas dependency on Russia through new generation fuels and energy carriers, the importance given to fuels in the incentives such as the IRA in the United States, the investments made by oil-rich countries to prepare for a post-oil economy, and the attempts of countries such as Chile, New Zealand, Morocco, Algeria, Egypt, and Singapore—candidates to become the clean energy exporters of the future—to turn their solar and wind potential into value-added chemicals and fuels, all demonstrate that a profound paradigm shift has taken place in the last decade regarding new generation fuels. Considering the size of our country's foreign trade volume and its vulnerabilities in energy supply security, it is inevitable that Türkiye will be among the countries most affected by this global paradigm shift in new generation fuel technologies. Therefore, it is highly critical for Türkiye to be prepared for this change both technologically and in terms of legislation and human resources. Taking into account the country's needs, existing infrastructures, and technological capabilities, the following recommendations are presented for Türkiye in the field of new generation fuel technologies to ensure the

continued international competitiveness of our private sector:

1. Off-take mechanisms and financing models for the sustainability of investments:

For investments in new generation fuel technologies to succeed, it is necessary to ensure a long-term demand guarantee for the products resulting from these investments and to provide appropriate financing conditions. Purchase guarantee agreements, known as off-take agreements, are key tools that reduce the risks of the private sector in this field. Especially in sectors such as aviation and maritime fuels, which have high initial investment costs and global supply-demand imbalances, the future of investments in new generation fuel technologies depends more on long-term purchase guarantees (off-take) rather than the formation of voluntary markets. For example, while airline companies currently consider HEFA—a biomass-based fuel—and fuels obtained through co-processing to meet their SAF needs, they will also have to include e-SAF fuels such as PtL and AtJ in their product portfolios in the coming years to meet the increasing SAF demand. At this point, a multi-party “off-take” structure to be established with the right stakeholders in our country may enable a potential investment to mature faster and more soundly. It is known that in cases where supply and demand are uncertain or where there is not more than one demand side, it is not possible to make the necessary investments for installing electrolyzers required for green hydrogen production and high-cost carbon capture units. For this reason, it is extremely critical for airline companies that could be potential synthetic fuel users in our country and our international airports with high numbers of flights to create demand by making SAF and e-SAF projections to accelerate investments in our country. In this context, it should also be considered that the public sector, if necessary, could step in as a buyer to provide assurance to the market. Additionally, by establishing a climate finance fund, revenues from mechanisms such as carbon pricing or the EU Carbon Border Adjustment Mechanism can be transferred to this fund and provided as subsidies for innovative projects

2. R&D investments and supports for new generation fuel technologies in aviation and maritime sectors:

Although interest in biofuels is expected to increase over the next 10 years, it is anticipated that biofuels will share market share with synthetic fuels in the medium to long term due to possible problems in ensuring sufficient supply of biologically sourced

raw materials, concerns about food security, and potential difficulties in the logistics of the inputs used (such as waste oil). The mandatory requirements introduced by regulations such as the European Union’s Refuel EU also support this expectation and promote the transition to synthetic fuels. At this point, the two fuel types expected to see the highest demand in the future will be sustainable aviation fuels produced synthetically (e-SAF) and sustainable maritime fuels (e-SMF). Today, while options such as integrating intermediate products obtained from various bio-feedstocks into petroleum refineries for jet fuel production (co-processing) are accepted as the fastest SAF production solutions, there is a significant risk that this production method will not be considered “sustainable” in the near future due to its integration into petrochemical processes. For this reason, the trend of global investments toward synthetic fuel production is increasing day by day. The fact that there are investment plans for only 4 Co-Processing SAF production facilities compared to 32 Power-to-Liquid synthetic e-SAF plant investments planned in the Europe-Middle East and Africa region supports this observation. At this point, there is currently no announced production and investment plan in our country for PtL technology, which is one of the e-SAF production methods. However, both the high costs of CCUS technologies and the global challenges in accessing green hydrogen currently stand out as the biggest obstacles to such synthetic fuel plant investments. Therefore, it is essential that efficient production concepts, high benefit/cost ratio business model examples, and climate technologies that will facilitate the transition to alternative fuels such as e-SAF, which are expected to see high demand in the coming years, are rapidly scaled up and implemented. In this context, it is recommended that feasibility studies be conducted for e-fuel projects and that know-how be developed accordingly.

3. Biomass-based limitations and PtL-based investments:

More than 99% of the aviation fuel used today is fossil-based, and reducing the carbon emissions of the aviation sector is critically important to achieving global climate targets. The civil aviation sector accounts for approximately 2% of global emissions.³⁶ Although this ratio appears relatively low compared to other emission source sectors, the impact of aviation on the climate will increase disproportionately in the coming years, as it is a rapidly growing sector. Moreover, the long service life of aircraft (20–30 years) and the challenges that will be experienced in the near term in implementing alternative technologies such as batteries or fuel cells in large passenger aircraft bring sustainable

aviation fuels to the forefront in the “carbon-neutral” transformation of aviation. In its 2050 vision for the sector, IATA foresees that 65% of the required emission reductions will be achieved through the use of SAF.³⁷ Therefore, especially with the projection studies carried out by aviation authorities after 2016, SAF is considered one of the fundamental elements of the carbon-neutral future of aviation. The aviation sector also has a highly strategic importance in Türkiye. Our country, which has a global airport such as Istanbul Airport, is a regional leader in passenger and cargo transportation. Since Türkiye has adopted a net-zero emission target for 2053, emissions from aviation must also be reduced within this scope. The implementation of sustainable aviation fuel within our country’s borders is critical both for fulfilling international commitments and for maintaining the competitiveness of the Turkish aviation sector. For example, Türkiye participated in the pilot phase of the CORSIA program initiated by ICAO and monitors the emissions of international flights and reports them to the relevant authorities.³⁸ Global policies are also shaping in a way that supports SAFs in the carbon-neutral transformation of aviation. Countries like the USA are introducing support programs (e.g., tax credits) to promote SAF production. Additionally, with the “ReFuelEU” regulation to be implemented by the European Union as of 2025, it has become mandatory for aircraft departing from EU airports to contain a certain proportion of SAF and for fuel suppliers to blend SAF.³⁹ In this context, at least 2% of the jet fuel supplied to EU airports must be SAF, and this ratio will gradually increase to reach 70% by 2050. As of 2035, a certain portion of the blending will also be required to be synthetic SAF (e-SAF). Furthermore, it is planned that the share of renewable electricity-based synthetic kerosene (e-SAF) in fuel blending will reach up to 35% by 2050. Since such global policies will also cover airlines flying from Türkiye to Europe, the use of SAF will become practically mandatory for the Turkish aviation sector. In short, the global policy trend is rapidly spreading SAF usage, and Türkiye’s adaptation to this transformation will be beneficial both environmentally and economically. ICAO’s CORSIA program started in 2021, and airlines are obliged to offset emission increases from international flights; since SAF is calculated with a lower emission factor in this mechanism, it reduces airlines’ carbon offsetting burden. Although there is not yet a specific legal incentive or obligation regarding SAF use in Türkiye, our national airline companies, such as Turkish Airlines, have voluntarily started blending SAF especially on European routes and have taken concrete steps to align with the global trend.

Today, the majority of SAFs produced on a commercial scale are obtained from biomass- or waste-based feedstocks (e.g., used cooking oil, animal fats, vegetable oils, agricultural residues, etc.). However, the supply of feedstocks based on biological waste is generally quite limited on a global scale. For example, since waste cooking oil and similar low-carbon intensity waste oils are used in both biodiesel production for road transport and SAF production, the global supply of waste oils may soon fall short of meeting the demands of these two sectors. In this case, biofuel producers may turn to more abundant but agriculturally controversial crops such as oilseeds (e.g., rapeseed, palm, soy); however, since these crops require new cultivation areas, they may compete with the food sector and cause additional emissions due to indirect land use change (ILUC). Indeed, according to the sustainability criteria set by IATA, SAF feedstock must not compete with food cultivation areas or water resources and must not cause environmental degradation.⁴⁰ Under these conditions, it is quite difficult to scale up global SAF production to very large volumes using only waste biomass based on residues and wastes. According to data from the International Council on Clean Transportation (ICCT), in 2022, only one-thousandth of jet fuel consumption in the USA could be met with SAF. The main reason for this is the limited supply of sustainable feedstock and high production costs.⁴¹ This statistic shows how small today’s biomass-based SAF production remains compared to the emerging demand. At this point, considering that Türkiye’s biomass-based SAF production capacity will also remain insufficient against global supply constraints, it is recommended to invest in “Power-to-Liquid (PtL) technologies.”

4. Biogas and Biomethane: Incentives and Regulations for Emission Reduction and Energy Supply Security:

During the period in which the deep dive study was conducted, it was determined that some new liquid biofuel technologies did not receive sufficient demand from sectoral users and that the commercial readiness levels (CRL) of the relevant technology were low. For example, although an opportunity area has been identified in our country for biomethanol production, it has been observed that the national maritime sector, which is the main user of this fuel, has not yet shown sufficient demand for biomethanol. Therefore, considering such developments in liquid biofuels and our country’s need for natural gas, gaseous biofuels have been investigated in depth. The deep dive study observed that our country’s biogas potential is high but the installed capacity remains

insufficient, falling below the world average. At this point, it is recommended to provide incentives for these biogas plants not only for electricity generation from biogas but also for the sustainable production of higher-purity biomethane, so that the number of biogas plants in our country can increase and operate sustainably.

The biogas production process is based on the biological decomposition of biomass containing organic carbon in an anaerobic environment together with special microorganisms. Biomethane obtained in biogas plants is among the rare energy sources considered carbon neutral. These plants, on the one hand, prevent uncontrolled methane emissions by disposing of waste at the source and converting it into clean energy, thereby reducing the greenhouse gas effect; on the other hand, the fermented sludge remaining as a result of the process is used as organic fertilizer in the agricultural sector, reducing the farmer's use of synthetic mineral fertilizers with a higher carbon footprint. All these advantages make biogas plants stand out as a hybrid clean energy solution that reduces both carbon emissions and methane emissions. Moreover, unlike renewable energy sources such as solar and wind, which have an intermittent production profile, biogas production plants, which can operate continuously for 24 hours, can be used to balance the electricity grid by acting as base load power plants. According to 2022 data, among developed economies, China ranks first in the world with more than 100,000 biogas plants. Europe follows with more than 20,000 biogas plants (with more than 9,500 plants in Germany alone), the USA with 2,251 active biogas plants, and India with 1,194 biogas plants. In contrast, as of the end of 2024, there are a total of 116 registered biogas plants in our country. Our existing biogas plants generally generate income by selling electricity to the grid within the scope of YEKDEM. Within the scope of the deep dive study, it was determined that due to the expiration of the 10-year YEKDEM supports given to the plants established in 2015, converting the produced biogas into electricity no longer provides profitability for the companies. Among the most important reasons for this are the very high initial investment, maintenance, and operating costs of the imported gas engines used in biogas plants (approximately 6.5 years of operating life and a total of 2.5 million Euros initial investment, maintenance, and operating cost for only 1 engine). Considering that an average biogas plant standardly has 3-4 gas engines, it can be said that the operating and installation costs are significantly high during the operating period of

the engines. In addition, the fixed price purchase guarantee (Feed-in Tariff) provided by YEKDEM supports expires at the end of its 10-year validity period. The fixed prices that companies benefit from within the YEKDEM support were also changed as of 2021. For plants commissioned before 2021, the purchase guarantee was \$0.133/kWh for 10 years and could reach up to approximately \$0.148/kWh together with domestic equipment supports. After 2021, tariffs have been redefined in TL terms and are much lower than previous unit prices (as of 2025, approximately 2.5 TL/kWh). Under these conditions, while electricity sales were highly profitable for old biogas plants within the scope of YEKDEM during the 10-year period, profitability has almost halved for biogas plants that have completed their YEKDEM period or were established after 2021. When the energy losses and inefficiencies experienced in the cogeneration systems of existing biogas plants are added to this situation (although the thermal energy of 1 m³ biogas is typically 6 kWh, the electricity produced with losses remains around 2.7 kWh), it can be easily concluded that the need for transformation is urgent. Therefore, considering that future biogas plant investments in our country will be made by taking these critical factors into account, it is clear that new regulatory arrangements, state incentives, and new business models are needed to accelerate biogas investments. In order for the biogas plants established in our country to ensure their continuity, it will be necessary to gradually switch to new generation technologies. In particular, options such as feeding the high-purity biomethane produced into the natural gas grid or supplying it as fuel to industrial facilities located close to the biogas plant stand out as options that offer higher profitability for biogas plants compared to electricity sales.

5. Methane Reduction:

The impact of greenhouse gases on the climate is determined by two main characteristics: their atmospheric lifetime and their ability to absorb infrared radiation. Compared to methane, which remains in the atmosphere for about 12 years, carbon dioxide, which can accumulate and persist in the atmosphere for hundreds of years, is the greenhouse gas with the greatest long-term contribution to climate change. However, while the entire world focuses on the long-term destructive effects of carbon emissions and their negative consequences in combating the climate crisis, the fact that methane emissions, which cause our planet to warm more rapidly and whose effects are felt in a shorter time, are 80 times more dangerous than carbon dioxide in

terms of global warming (on a 20-year time scale) often goes unnoticed.⁴² All efforts and global commitments to reduce carbon dioxide emissions to net zero by 2050 and to limit the global temperature increase to 1.5°C are alone insufficient to reach the targeted point in the short term, and future projections indicate that methane emissions must also be taken into account. At this point, addressing carbon and methane emissions together is extremely important both to slow down global warming rapidly and to contribute to climate stability earlier. Global methane emissions have rapidly increased since 2006, reaching record levels in 2019 and attaining the highest known value to date of 580 million tons in 2023 (with the energy sector alone accounting for 130 million tons of methane emissions). This increase in methane emissions, which are released through natural processes and anthropogenic activities, has led countries to recognize the seriousness of the situation and to commit to joint emission reduction efforts, especially following the launch of the “Global Methane Pledge (GMP)” initiative in 2021, which targets at least a 30% collective reduction in methane emissions by 2030. Anthropogenic methane emissions resulting from activities such as oil and gas exploration (including drilling new wells and leaks from poorly sealed old wells), agricultural practices, uncontrolled biomass and waste burning constitute approximately 60% of global methane emissions.⁴³ Challenges in monitoring and detecting methane emissions during fossil fuel exploration, the high costs of leak-proof equipment, and the lack of preventive regulatory frameworks make it difficult to prevent such anthropogenic methane emissions. Therefore, in order to rapidly mitigate human-caused methane emissions, it is critical worldwide to systematically control emission sources arising from agricultural activities and waste burning by employing new technologies. In particular, any global improvements in waste management (such as composting and biogas production) and fertilizer management are effective in both directly and indirectly reducing methane emissions.

6. Updating the Türkiye Biomass Energy Potential Atlas:

The existing BEPA (Biomass Energy Potential Atlas) data primarily focus on agricultural and animal wastes. It would be beneficial to include biomass sources such as Used Cooking Oils (UCO) and industrial by-products in the atlas. Continuous revision of the atlas with updated field measurements, satellite data, recent reports, and farmer data is recommended. Additionally, quantitative data for UCO and other waste fractions should

be incorporated into the atlas. This approach will enable accurate capacity planning for next-generation fuel investments, including biogas, biomethane, and biodiesel.

7. Systems for Collecting Used Cooking Oil (UCO):

Countries such as South Korea and Japan in Asia, and Canada in North America, have relatively high capacities for collecting UCO compared to their per capita vegetable oil consumption. In contrast, countries like Brazil and Argentina, which rank high in vegetable oil consumption, exhibit considerably lower collection rates.⁴⁴ Although per capita vegetable oil consumption in Türkiye exceeds that of Japan, UCO collection rates are observed to be significantly lower than in Japan. According to the 2022 Waste Statistics published by the Ministry of Environment, Urbanization, and Climate Change of the Republic of Türkiye, 21,113 tons of waste vegetable oil have been declared within waste management practices. However, it is estimated that approximately 150,000 tons of used cooking oil are generated annually in Türkiye.⁴⁵ To fully utilize the actual UCO capacity and ensure proper management of collected UCO, it is recommended to develop new and innovative solutions for UCO tracking and collection.

8. Studies on the Development of Catalysts and Membrane PSA Systems, Critical Subcomponents of Next-Generation Fuel Technologies:

The efficiency and commercial scalability of next-generation fuel production processes directly depend on the supply and R&D costs of critical components that affect reaction rates, separation efficiency, and energy consumption (such as Fischer-Tropsch, Sabatier, or PtL synthesis catalysts; water electrolysis membranes; PSA units for CO₂ separation). International competitors have identified domestic production and improvement of these components as strategic priorities, accelerating the process through R&D incentives, industrial demonstration projects, and intellectual property support. In Türkiye, programs should be established to diversify the supply chain for these critical technologies, promote local manufacturing, and strengthen research infrastructures.

9. On-Site Carbon Utilization Scenarios from Point Sources:

The insufficiency of readily available capacity and the yet-to-be-determined potential capacity of suitable carbon storage sites in our country highlights on-site utilization scenarios as the most rapidly implementable option for at least partial use of CO₂

captured from point sources. For certain sectors aiming to valorize carbon emissions and convert them into high value-added chemicals such as SAF, methanol, and ethanol, converting captured CO₂ is expected to be economically meaningful, as it can subsidize a portion of the private sector's transition costs to CCUS technologies. Especially regarding the proposed guided project for e-SAF production, in future scaling studies, it is recommended to prioritize sectors with high carbon concentration and minimal carbon capture costs as point carbon sources (for example, emissions from geothermal energy plants).

10. Legislation and Regulations for Türkiye's 2053 Carbon Neutrality Target and Alignment with EU Policies:

To ensure the effective implementation of commitments made under Türkiye's Updated First Nationally Determined Contribution submitted to the United Nations Framework Convention on Climate Change in 2023, sectoral roadmaps should be prioritized and

6.

Conclusion

Although the advancements in next-generation fuel technologies over the past decade have been significant, the pace of transformation observed in the hard-to-decarbonize sectors examined in this report requires greater effort for Türkiye to achieve its 2053 net-zero emissions target. Next-generation fuel solutions such as sustainable aviation fuel in aviation, biomethanol-ammonia in maritime, and biomethane in industry have yielded successful results in reducing emission intensity. However, since these sectors are projected to continue growing until 2050, the reduction in emission intensity must be accelerated at a much faster rate. The scale of investments needed to achieve this momentum exceeds what the private sector alone can undertake under current conditions. Therefore, unless long-term off-take agreements, effective carbon pricing mechanisms, and fiscal incentives are implemented, capital costs are not expected to decrease to sustainable levels.

In addition to the financial dimension of the transition, establishing strong and institutionalized collaboration across the entire value chain is critical. If the stakeholder ecosystem—from biogenic feedstock suppliers to airports, and from refineries to grid operators—does not operate in coordination, achieving the net-zero emission targets with the current national technology readiness levels will become increasingly difficult.

Therefore, it is recommended to urgently implement pioneering Power-to-Liquid (PtL) and Power-to-Gas (PtG) projects that integrate point-source CO₂ emitters such as geothermal and iron-steel facilities, the methane potential in biogas infrastructure, and rapidly increasing solar and wind capacities, with a focus on on-site utilization. These demonstration projects will not only mitigate technological risks through field data but also accelerate the transition to economies of scale by shortening the market learning curve.

The next decade will be decisive for achieving long-term emission targets. The implementation of the National Emission Trading System (ETS), trade regulations compatible with the Carbon Border Adjustment Mechanism (CBAM), and the systematic promotion of domestic R&D in critical components such as catalysts, membranes, and PSA systems are expected to enhance Türkiye's resilience of the new generation fuel ecosystem against global market fluctuations. Within this scope, it is considered that the Guided Projects under TTGV's Pioneer Project Investment Program will serve as a catalyst for the aforementioned multi-stakeholder transformation mobilization. The decisive and coordinated steps to be taken after 2025 will support strong long-term targets with concrete and measurable progress, contributing to Türkiye's potential to become a regional clean fuel hub.

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