Zero Carbon Technology Roadmap

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Colophon

The Strategic Study was conducted by The European House - Ambrosetti on behalf of Eni. The project team is composed an Advisory Board, responsible for the strategic steering of the research, whose members provided scientific advice and paved the way for the direction for the study, and of a Working Group, in charge of the development of the study.

The Advisory Board is composed by:

- **Joaquìn Almunia**, Professor, Paris School of International Affairs-Sciences Po; Chairman of the Board of the Centre for European Studies (CEPS); former Professor in Practice, London School of Economics; Honorary President, Barcelona Graduate School of Economics; Former European Commissioner for Competition [2010 - 2014]; former European Commissioner for Economic and Monetary Affairs [2004 - 2010]
- **Valerio De Molli**, Managing Partner and Chief Executive Officer, The European House - Ambrosetti
- **Claudio Descalzi**, Chief Executive Officer, Eni
- **Fabiola Gianotti**, General Director, CERN; member of several international committees, such as the Scientific Council of the CNRS (France), the Physics Advisory Committee of the Fermilab Laboratory (USA), the Council of the European Physical Society, the Scientific Council of the DESY Laboratory (Germany), the Scientific Advisory Committee of NIKHEF (Netherlands)
- **Markus Kerber**, Chief Strategist, CDU; Former State Secretary, Ministry of the Interior - Government of the Federal Republic of Germany; former CEO and Director General, Bundesverband der Deutschen Industrie - BDI; former Director, Financial and Economic Affairs Department, Federal Ministry of Finance - Government of the Federal Republic of Germany

The Working Group of **The European House - Ambrosetti** is composed by:

- **Corrado Panzeri**, Partner & Head of InnoTech Hub
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- **Marco Margheri**, Head, USA International Relations Office
- **Marco Piredda**, Head, International Affairs Analysis and Business Support
- **Monica Spada**, Head, Research and Technological Innovation
- **Claudia Squeglia**, Head, Domestic Regulatory Analysis and Institutional Positioning

Special thanks to Eni's management, who contributed to the development of the Strategic Study trough dedicated interviews:

- **Adriano Alfani**, Chief Executive Officer, Versalis
- **Stefano Goberti**, Chief Executive Officer, Plenitude
- **Giuseppe Ricci,** COO, Energy Evolution
- **Francesca Zarri**, Director, Technology, R&D & Digital
- **Antonino Abbate**, Accounting and Reporting Specialist
- **Cristiana Argentino**, Head, Scenarios, Strategic Options & Climate Change
- **Emanuele Banfi**, Head, Credit Management and CO2 Volumes Capture
- **Luigi Ciarrocchi**, Director, CCUS, Forestry & Agro-Feedstock
- **Roberto Ferrario**, Head, CCUS Innovation Solutions
- **Francesca Ferrazza**, Head, Magnetic Fusion Initiatives
- **Rosanna Fusco**, Head, Climate Change Strategy & Positioning
- **Luca Giansanti**, Head, Relations with European Institutions
- **Federico Maria Grati**, Head, Agroenergy Services
- **Raffaella Lucarno**, Head, R&D Business Partner Energy Evolution
- **Andrea Marsanich**, Head, Carbon Offset Solutions
- **Maria Francesca Nociti**, Head, Services and Conjunction with the Territory and Entities Support
- **Dario Pagani**, Head, Digital & Information Technology
- **Thomas Pasini**, Head, R&D Business Partner EE/Bio-Fuel and Next Generation Downstream
- **Marco Piredda**, Head, International Affairs Analysis & Business Support
- **Andrea Pisano**, Head, Energy Evolution Hydrogen Initiatives
- **Francesco Robillotta**, Head, Monitoring, Analysis and Valorization CCUS & Forestry Activities
- **Ernesto Roccaro**, Head, R&D Business Partner EE/Hydrogen

- **Fabrizio Rollo**, Head, CCUS Opportunities Identification and Portfolio Management
- **Giuseppe Sammarco**, Head, Natural Resources Studies & Analysis
- **Carmela Sarli**, Head, Carbon Storage & Valoritation
- **Monica Spada**, Head, Research & Technological Innovation
- **Claudia Squeglia**, Head, Regulatory Analysis and Italian Institutional Positioning
- **Michele Viglianisi**, Head, Biorefining and Supply

To address the analysis and gather strategic insights, 13 key experts were engaged in a confidential one-on-one interview:

- **Robert C. Armstrong,** Professor of Chemical Engineering, MIT; Director, MIT Energy Initiative
- **Alessandra Beretta**, Professor of Chemical Engineering, Politecnico di Milano
- **Klaus-Dieter Borchardt,** Senior Energy Advisor, European & Competition Law Practice, Baker McKenzie, Brussels
- **Maria Chiara Carrozza,** President, National Research Council; Full Professor of Industrial Bioengineering, Scuola Superiore Sant'Anna
- **Valerio Cozzani,** Full Professor Department of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna; industrial plant safety expert
- **Giulia Galli,** Liew Family Professor of Electronic Structure and Simulations, Pritzker School of Molecular Engineering and University of Chicago
- **Mark Alan Hughes,** Founding Faculty Director, Kleinman Center for Energy Policy
- **Christopher Jay Faranetta**, CEO and Co-Founder, Nearstart
- **Zoe Knight,** Managing Director and Group Head, HSBC Centre of Sustainable Finance
- **Jan Laubjerg,** Global Sector Head for Natural Resources, HSBC
- **Giacomo Luciani,** Scientific Advisor, Paris School of International Affairs - Sciences Po
- **Ennio Macchi**, Professor Emeritus in Energy and Environmental Systems, Politecnico di Milano
- **Thomas Pellerin-Carlin,** Director, Jacques Delors Energy Centre

To develop a different view on European value chains, three working tables have been organized with the following forty-three stakeholders.

Working table #1: Hard to Abate industries

- **Koen Coppenholle**, CEO, Cembureau - European Cement Association
- **Maurizio Fusato**, Head of Ecological and Energy Transition, Feralpi Group
- **Rolando Paolone**, CTO, Danieli
- **Marco Geneletti**, Energy Senior Director, Tenaris
- **Renaud Batier**, Director General, Cerame-Unie
- **Łukasz Gajkowski**, Chief Strategy Officer, Cersanit
- **Florie Gonsolin**, Director, Climate Change Transformation, European Chemical Industry Council - CEFIC
- **Astrid Palmieri**, Senior Sustainability Community Manager EMEA, BASF
- **Tim Heisterkamp**, Head of Technology & Environmental Policy, Linde
- **Silvio Di Cesare**, Head of Value Chain and Sustainability Strategy, Sasol
- **Marco Rosso**, Global Corporate Affairs Director, Valagro
- **David Cast**, Climate Change Director, NSG Group
- **Luca Sassoli**, CEO, Burgo Energia; Climate Change and Energy Committee Chairman, Confederation of European Paper Industries – CEPI
- **Heinz Felder**, SVP Group Technology & Investments, Stora Enso

Working table #2: Heavy Transport

- **Michele Ziosi**, Senior Vice President Institutional Relations & Sustainability, IVECO Group
- **Lars Mårtensson**, Environment and Innovation Director, Volvo Trucks
- **Riccardo Cornetto**, After Sales Director, Solaris Italia Srl
- **Martina Di Palma**, Sustainability Manager, European Region Airlines Associations
- **Roberto Garavaglia**, Senior Vice President Strategy & Innovation, Leonardo
- **Martin Gorricho**, Regional Lead-EU Sustainability Policy and Partnership, Boeing
- **Sandro De Poli**, President, AvioAereo
- **Val Miftakov**, Founder and CEO, ZeroAvia
- **Andy Kershaw**, Environment Manager, British Airways
- **Hemant Mistry**, Director of Energy Transition, International Air Transport Association
- **Davide Canuti**, Head of Environmental Assessment and Certifications, SEA Milan Airports
- **Roberto Barbieri**, CEO, GESAC
- **Michele Miedico**, Head of Salerno Project, Planning & Environment, GESAC
- **Giulio Tirelli**, Director of Business Development Marine Power, Project Services, Wartsila
- **Hyun-ho Lee**, Vice President and Managing Director of Maritime Research Institute, Hyundai Heavy Industries

- **Pierpaolo Da Fieno**, Managing Director, MAN Energy Solutions
- **Dario Bocchetti**, Head of Energy Saving, R&D and Ship Design, Grimaldi Group

Working table #3: Nuclear Fusion initiatives

- **Roberto Adinolfi,** President, Ansaldo Nucleare
- **Paola Batistoni,** Head of Fusion Development, ENEA
- **Chris Martin**, Chairman, Tokamak Energy
- **Mark Anderton**, Project Development Engineer, Oxford Sigma
- **Johan Öijerholm,** Project Manager, Nuclear Materials and Water Chemistry, Studsvik
- **Elisabetta Bragagni Capaccini,** Group CEO, Tratos Cavi
- **Norbert Heinzle**, Chief Operation Officer, Butting Group
- **Francesco Volpe**, Founder, CEO and Chief Technology Officer, Renaissance Fusion
- **Melanie Windridge**, Founder, Fusion Energy Insights
- **Marco Ricotti**, Chairman of Technical Working Group on Small Modular Reactors, IAEA; Full professor in Nuclear Engineering, Politecnico di Milano
- **Alessandro Maffini,** Assistant Professor & Researcher, Project ENSURE, Politecnico di Milano
- **Dan Brunner**, Chief Technology Officer, Commonwealth Fusion Systems
- **Christopher Jay Faranetta**, Vice President & Co-Founder, NearStar Fusion

The contents of this Study refer exclusively to the analysis and research carried out by The European House - Ambrosetti and represent its opinion which may not coincide with the opinions and viewpoint of the individuals interviewed and involved in the initiative.

Preface

Foreword by **Claudio Descalzi**

The summer we are experiencing – with elevated temperatures, high prices and energy and water shortages – is a strong indicator of the challenges we face: containing the rise in global temperatures in line with the Paris Agreement's objectives whilst guaranteeing reliable, low-cost and sustainable energy to a global population that is expected to exceed 9 billion people in 2040.

We are talking about challenges which call into play a multitude of factors, from the research into new energy sources and solutions to the transformation of industrial processes, to the ways in which we produce and consume energy, right up to new alliances among the stakeholders to design low carbon futures for assets and territories.

Above anything else, it is my strong belief that the energy transition requires the adoption of a neutral approach to energy solutions, one which allows us to deploy every option in a synergic and complementary manner, based on the maturity of each option and its effectiveness to reduce emissions.

Over the last six years, Eni has invested more than 7 billion Euro in the research, development and deployment of different technologies, signed more than 70 partnership agreements with various universities and research centres all over the world, engaging 1,500 professionals in such activities.

In the short term, Eni, in line with an unbiased vision of a decarbonisation technologies portfolio, aims to deploy at the industrial scale every technology that can provide an immediate, tangible, and substantial contribution to emissions reduction. With regards to this, through Plenitude, Eni is committed to increase its capacity from renewable sources to more than 2 GW in 2022 and to 6 GW by 2025. With the conversion of traditional refineries to bio-refineries, by 2025 we will reach a bio-refining capacity of 2 million tons per annum (MTPA), contributing to the decarbonisation of the transport sector. Furthermore, this process is integrated with vegetable oil production from agricultural value chains in Africa, through agri-business projects, and with new technological solutions aimed at reusing waste and residues. Additionally, through the development of hubs for the capture and storage of CO_2, Eni will be capable of contributing to the decarbonisation of industrial areas, maintaining competiveness and employment levels as well as opening up the blue hydrogen value chain. Finally, Eni is working on green hydrogen projects, with an estimated total production of 4 MTPA by 2050.

At the same time, Eni believes it is necessary to focus the long term, by contributing to the development of *breakthrough* technologies such as magnetic fusion, something that could revolutionise the energy-production world by guaranteeing a sustainable, clean, and prosperous future. Eni is substantially contributing to the development of magnetic fusion by being the largest shareholder in the Commonwealth Fusion Systems (CFS) project, an MIT spin-out aiming to build the first experimental device by 2025, with a first commercial plant within the next decade.

All technologies, especially proprietary technologies, along with the creation of new business models and stakeholder alliances are, in fact, a fundamental element of Eni's strategy.

It is through all above-mentioned technologies that the collaboration between Eni and The European House - Ambrosetti was born, leading us to this Strategic Study. The Strategic Study offers a detailed mapping of the technological options we have at our disposal to endure the decarbonisation pathway, highlighting that a significant change is necessary to reach energy transition objectives: all technologies must be considered in a complementary way and judged on their ability to make a real contribution to reducing CO_2 emissions following a life cycle assessment logic, avoiding the temptation to turn it into an ideological matter. The Strategic Study provides practical examples as to how the principle of technological neutrality alongside detailed policy proposals can help the European Union reach full decarbonisation by 2050.

I also believe it is crucial to maintain an open and continuous dialogue on energy transition among institutions, citizens, businesses, and research bodies: we need to discuss objectively, select the best options to fit each context and then move swiftly to the deployment of the solutions that have been identified. It is not just about our ability to preserve the climate, but also about our competitiveness as an industrial system and its ability to create high quality employment. Lastly, it is about cohesion in our societies.

I would like to thank The European House - Ambrosetti, the members of the Advisory Board, all Eni colleagues who have contributed, as well as those representatives of other companies and industry associations in different sectors for having enriched the Study with their expertise and opinions.

Claudio Descalzi
CEO, *ENI*

Preface by **Valerio De Molli**

"Climate change cannot be solved
without substantial advancements in technology".
H. Lawrence Culp, Jr.

The IPCC Report published in August 2021 and the conclusions of the subsequent COP26 contain some clear indications on the risks and costs of climate change. Over the past 30 years, despite numerous commitments, **governments, institutions, and companies have failed to implement concrete and effective measures to reduce greenhouse gas emissions.** In fact, it has been demonstrated that, to date, the most ambitious plans put in place by the governments of the world's major economies will not be sufficient to contain the temperature increase within the 1.5°C threshold, as envisaged by the Paris Agreement.

What is needed, therefore, is **a change of pace of the decarbonisation process** of our society to reduce greenhouse gas emissions faster than hitherto, multiplying the rate of reduction of the last decade by four times to reach net zero emissions in 2050, without sacrificing welfare and social equity. To this end, research and technological development are our most important allies.

The Strategic Study "**Proposal for a Zero Carbon Technology Roadmap - *The alternative decarbonisation for Europe***", the first of its kind, was developed with the aim of defining, with the utmost authority and according to *super partes* criteria, a reference framework of the technologies required to manage the decarbonisation process.

Through a rigorous analysis of **185 sources of academic-scientific literature** and intensive discussions with **56 stakeholders**, including academic experts and *managers* from Europe's major Hard to Abate supply chains, the **100 key technologies for decarbonisation** were identified.

The mapping process highlighted the fact that, in order to reach the decarbonisation targets, renewables and electricification must be put in synergy with a broader set of technologies including **Carbon Capture Utilisation & Storage (CCUS)**, **Carbon Dioxide Removal (CDR)**, **hydrogen**, **biofuels** and **synthetic fuels**.

To maximise the development potential of decarbonisation technologies, the Strategic Study has identified **nine** timely and concrete **policy proposals** that we want to bring to the attention of *policy makers*. Notably, the set of proposals detailed by the Strategic Study aims to promote a principle of **technology neutrality** in Europe in the field of decarbonisation, in which the synergetic and the complementary contribution of all available technologies must be harnessed to achieve the goal of net zero CO_2 emissions.

The Strategic Study demonstrated that, only through the adoption of the principle of technology neutrality and the promotion of a diversified set of technologies, it is possible to achieve **complete decarbonisation** even in the Hard to Abate sectors. Moreover, according to the estimates of an econometric model constructed by The European House - Ambrosetti, between 2023 and 2050, the diffusion of the set of technologies identified could generate more than **2,700 billion Euro in added value**, creating **1.7 million jobs** by 2050 at the European level.

The development of the analyses contained in the Report benefited from the participation of **56 stakeholders** from various economic sectors and the academic world, who contributed by participating in working tables (43 participants) and through confidential interviews (13 experts). My heartfelt gratitude goes to all of them.

I would like to thank the Advisory Board, composed by **Claudio Descalzi** (Chief Executive Officer, Eni), **Joaquín Almunia** (Professor, Paris School of International Affairs-Sciences Po; former Professor, London School of Economics; Honorary President, Barcelona Graduate School of Economics; former European Commissioner for Competition [2010 - 2014]; former European Commissioner for Economic and Monetary Affairs [2004 - 2010]), **Fabiola Gianotti** (Director General, CERN; Member of numerous international committees, such as the Scientific Council of the CNRS (France), the Physics Advisory Board of the Fermilab laboratory (USA), the Council of the European Physical Society, the Scientific Council of the DESY laboratory (Germany), the Scientific Advisory Board of NIKHEF (Netherlands)) and **Markus Kerber** (Chief Strategist, CDU; Former State Secretary, Ministry of the Interior - Government of the Federal Republic of Germany; Former CEO and Director General, Bundesverband der Deutschen Industrie - BDI; Former Director, Department of Economic and Financial Affairs, Federal Ministry of Finance - Government of the Federal Republic of Germany).

We also thank the Eni managers who contributed, through interviews and discussions, to the analyses contained in this Strategic Study.

Lastly, a heartfelt thank you to my colleagues of The European House - Ambrosetti Working Group formed, in addition to myself, by Corrado Panzeri, Alessandro Viviani, Gherardo Montemagni, Giorgia Rusconi, Matteo Radice and Rossella Carugno.

Valerio De Molli
Managing Partner & CEO,
The European House - Ambrosetti

Preface by **Joaquín Almunia**

Nowadays, climate change is no longer a possibility, but a reality. The factors behind the global warming had been anticipated by experts and now are fully confirmed by the data available so far and the events we are observing almost every day. The worldwide governance needs serious improvements to tackle the challenges ahead and will require from political and economic leaders a lot of decisiveness and coordination. In parallel, the financial resources, both public and private, to support the costs associated with an efficient and fair green transition will be huge and demand serious efforts from the fiscal authorities as well as from many economic and social sectors. Moreover, in addition to the political awareness, the adequate orientation of policy strategies and the level of its funding, the contribution of technological solutions essential.

Some of these technologies are already being used to contribute to the reduction of carbon dioxide and other greenhouse gases. Wind and solar renewable energy are competitive in price and their use is growing. But it will not be enough. Other technologies that should also contribute to reach the medium to long term targets defined by international agencies and the European Union are not yet available and will surely be needed to complement the present efforts.

The present study offers a very comprehensive and robust analysis of around one hundred of such technologies, from hydrogen to synthetic fuels and from carbon capture and storage to direct removal of CO_2 from the atmosphere. The expectations to finally succeed with the employability of nuclear fusion technologies to generate electricity without depending on any inputs from abroad are also analysed.

It has been a real pleasure to participate as an Advisor of the authors of this Study, learning a lot from the highly qualified teams from The European House - Ambrosetti and ENI, as well as from the views of the numerous stakeholders that were consulted. I very much look forward that the conclusions presented will be useful to foster the efforts developed by all those who wants to contribute, be it as industrials or policymakers, to preserve our planet for the next generations.

Joaquín Almunia
Professor, Paris School of International Affairs-Sciences Po

Preface by **Fabiola Gianotti**

Curiosity, the desire to understand how things work and answer complex and fascinating questions, and the need to find solutions to everyday challenges have always driven scientific research and enabled human beings to achieve extraordinary goals and build modern society.

The need to cope with climate change is surely one of the greatest challenges mankind has ever faced, and there is an urgent need to identify channels of scientific research and technologies that can help slow down and subsequently reverse the process of transformation of the climate and the planet.

Today more than ever, it is necessary to look to science and technology, without which the climate problem and other planetary challenges cannot be successfully addressed. In this context, the role of governments is to set goals and provide policy support, financial resources and mechanisms to encourage large investments in research, development and implementation of new solutions, enhancing as much as possible the relationship between research institutions and other public actors, private companies and citizens.

The energy system and emission sources constitute a highly complex problem for which 'one-size-fits-all' solutions cannot be identified. Therefore, a broad approach is needed to pursue multiple channels of research and development and to identify a coherent set of solutions. Global coordination is needed to achieve concrete goals in this and the other fields identified in the 17 UN Sustainable Development Goals.

The energy transition is urgent, but it must be carried out wisely, with a coherent strategic vision for the short, medium and long term. To this end, it is necessary to invest in optimising existing technologies, while at the same time examining long-term opportunities. In the nuclear field, fusion promises to be one of the energy sources of the future, being practically unlimited and emission-free. But its implementation on an industrial scale still requires investments and time. Interesting developments are underway to make nuclear fission cleaner and safer using thorium as fuel and particle accelerator-based technologies.

Finally, it is crucial to train and prepare the human capital needed to achieve the energy transition by attracting young people to study STEM subjects (Science, Technology, Engineering and Mathematics). Today, in Europe, the number of young people trained in these fields does not match the demands of the labour market.

This Strategic Study is a tool of great interest. It highlights the need for an open approach to support different technological options with potential impact on climate change, together with the importance of frontier research and the relevance of collaboration between *policy makers*, the research community and industry.

Fabiola Gianotti
Director General, CERN

Preface by **Markus Kerber**

Climate change is one of humanity's biggest challenges in the 21st century. This proposal for a Zero Carbon Technology Roadmap is an enormously important contribution in the discussion around the right strategy for decarbonisation as it comes at a crucial moment for Europe's future policymaking. Based on a broad scientific and technological canvas as well as numerous in-depth interviews with industry practitioners and scientist alike, The European House - Ambrosetti has carried out an Initiative with strong and relevant policy conclusions that European policymakers and European institutions must not ignore.

Amid the energy crisis that Russia's attack on Ukraine has created, the Initiative requests nothing less than a step change in all areas of climate sustainability for Europe to achieve all decarbonisation goals. This rather harmless sounding conclusion entails serious and wide-ranging alterations to existing European Commission and European Member States' climate policy designs. The present Initiative has identified 100 decarbonisation technologies that will need to be promoted following a principle of technological neutrality if Europe wants to achieve climate neutrality. The leveraging of all these decarbonisation technologies is a *conditio sine qua non* if Europe wants to meet its internationally agreed and contracted climate policy goals in the global attempt to limit global warming to below 1.5 degrees Celsius compared to pre-industrial levels.

European industry is the key developer and provider of critical know-how and technologies to limit global warming processes. Carbon Capture Utilization and Storage (CCUS) and Carbon Dioxide Removal (CDR) are secure and reliable technologies that must be a lot more widely applied across Europe. In addition to these technologies, hydrogen, biofuels, and synthetic fuels technologies are together indispensable for achieving full decarbonisation by 2050. The extent to which nuclear energy technologies can and shall contribute more widely to the decarbonisation goal must be a top short-term policy agenda item in both Brussels as well as so far sceptical member states such as Germany or Austria. The coincidence of an ambitious European climate policy promise, and a war-induced energy crisis must be used to integrate energy and climate policies across Europe at a much faster pace.

Any crisis should always be interpreted as an opportunity to overcome inertia and complacency. Europe is currently being faced with the opportunity to design and implement a coherent and integrated European climate and energy policy design that fulfils climate neutrality requirements, and at the same time ensures secure, resilient and competitive access to energy for citizens and enterprises alike. European policy makers need to act fast and in a decisive fashion, and The European House - Ambrosetti and the conclusions of the present Initiative can serve as a roadmap to guide these necessary decisions. If European policy makers do make bold decisions, they will reap trust and gratitude by European citizens politically as well as economically. Alongside the possibility to reach 100% decarbonisation in Hard to Abate sectors – a target that cannot be reached without the proposed set of technologies – the full and early wide adoption of the proposed roadmap between 2023 and 2050 will generate more than Euro 2.7 trillion and about 1.7 million new jobs in Europe as of 2050. There is no more time to be wasted, the roadmap is clear. The time for making the right decisions has come.

Markus Kerber
Chief Strategist, Christian Democratic Union

Executive Summary

The mission of the Strategic Study conducted by The European House - Ambrosetti on behalf of Eni, is to promote a principle of **technological neutrality** in Europe in the field of decarbonisation, in which the synergic and complementary **contribution of all available technologies** needs to be exploited to reach the Zero Carbon target.

The Study presents, with the utmost authority and according to *super-partes* criteria, a **reference framework to manage decarbonisation** in Hard to Abate sectors providing a first of a kind technology framework and mapping of available solutions to achieve the decarbonisation objectives. The aim is to encourage the adoption of a **broad scope for dedecarbonisation technologies** based on the cost-effective ability to reduce CO_2 emissions.

The Initiative was guided by an Advisory Board, responsible for the strategic steering of the research, whose members provided scientific advice and paved the way for the direction for the Study. The Advisory Board is composed by:

- **Claudio Descalzi**, CEO, Eni;
- **Valerio De Molli**, Managing Partner and CEO, The European House - Ambrosetti;

- Three Scientific Advisors:
  - **Joaquín Almunia,** Professor, Paris School of International Affairs -Sciences Po and Chairman of the Board of the Centre for European Studies (CEPS); Former European Commissioner for Competition [2010 - 2014]; Former European Commissioner for Economic and Monetary Affairs [2004 - 2010];
  - **Fabiola Gianotti**, General Director, CERN; Member of several international committees (Scientific Council of the CNRS, Physics Advisory Committee of the Fermilab Laboratory, Council of the European Physical Society);
  - **Markus Kerber,** Chief Strategist, CDU; Former State Secretary, Ministry of the Interior – Government of the Federal Republic of Germany; former CEO & Director General, Bundesverband der Deutschen Industrie (BDI).

The Initiative was carried out through an **intense stakeholder engagement activity**: **thirteen key experts** with a scientific, institutional, and industrial background were engaged in a **confidential one-to-one interview** to address the analysis and gather strategic insights. Additionally, **Eni's management** contributed to the development of the Strategic Study trough **dedicated interviews**. Lastly, to develop a different view on European value chains, three Working Tables have been organized with **forty-three stakeholders**, who represented the viewpoints of three key areas: **Hard to Abate industries**, **Heavy Duty transport**, and **nuclear fusion initiatives**. The whole stakeholder engagement process was conducted following a **bottom-up approach**, with the aim to bring together several points of view. Lastly, the stakeholder engagement process was coupled with an extensive analysis of the scientific literature, whereby **185 scientific sources** have been consulted.

The ten questions which guided the development of the Strategic Study are summarized in the following figure. First, the reference context was identified; then all the available technologies for the alternative decarbonisation of the reference context were mapped; based on the combination of the identified technologies, a Zero Carbon Technology Roadmap has been constructed; lastly, the policy requirements to facilitate the implementation of the Roadmap have been developed.

Figure 1

The guiding questions of the Strategic Study

Source: The European House - Ambrosetti, 2022

The reference context	1	How are **emissions distributed among different sectors** (e.g.: manufacturing, transport, etc.)?
	2	What are the **scenarios for reducing emissions** and absorbing CO_2?
Technologies for the alternative decarbonisation	3	What are the **available technologies and technological developments** with the greatest impact on decarbonisation targets?
	4	What **criticalities** in the current system do they help to solve? What is the **impact** on the ability to meet climate targets?
	5	What are the **potential breakthrough technologies** that will be available in the future?
Zero Carbon Technology Roadmap	6	What are the criteria for **technological neutrality?**
	7	What are the **impacts of technologies on different sectors?**
	8	What are the **recommendations for a Zero Carbon Technology Roadmap for Europe?**
Zero Carbon innovation governance	9	What are the possible **policies for the governance of energy innovation?**
	10	What are the consequent **economic** and **social impacts** for European value chains?

The Strategic Study revolves around ten key messages summarising the main findings. In addition, nine policy proposals were identified with the aim to promote and foster the deployment of the set of 100 technologies identified by the analysis.

Key message #1

A step change is required in all areas of climate sustainability to meet the European decarbonisation goals. It is crucial that the decarbonisation process ensures at the same time secure, resilient and competitive access to energy. Technological dependence must be considered on a par with energy dependence.

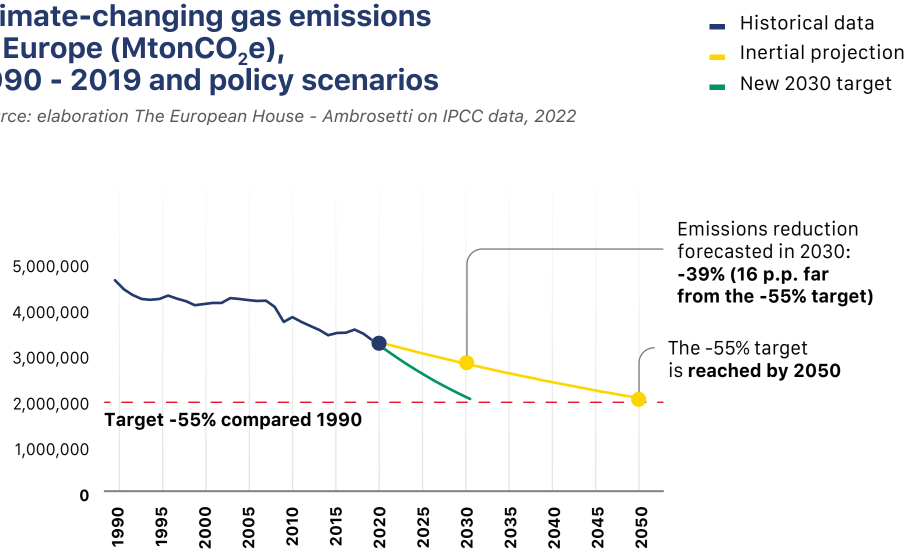
The Paris Agreement was signed in **2015** by **196** countries, with the objective to "limit global warming to **well below 2°C**, **preferably to 1.5 degrees Celsius**, compared to pre-industrial levels". In **2021**, during the COP 26, most participant countries agreed to **reduce emissions by 2030** and reach **zero emissions by 2050**, planning the related financings. Notably, since 1919, temperature has already reached **+1.1°C** (in 2019) and in the period 1980-2020, the cumulative economic damages of climate change are equal to **487 billion Euro** in the European Union.

Clearly, a **step change** is required to meet the European decarbonisation goals: emissions must be reduced by 5.5% per year to achieve a negative emissions balance, but at the current trend the **-55% emissions target** will be **missed by 16 percentage points in 2030** and will only be reached in 2050.

Figure 2

Climate-changing gas emissions in Europe (MtonCO$_2$e), 1990 - 2019 and policy scenarios

Source: elaboration The European House - Ambrosetti on IPCC data, 2022



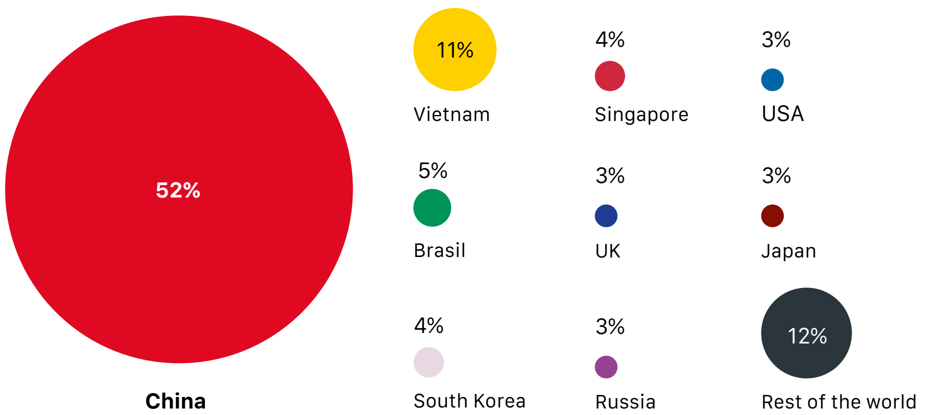
Furthermore, **technological dependence must be considered on a par with energy dependence:** it is crucial that the decarbonisation process ensures at the same time **secure**, **resilient,** and **competitive** access to energy. The European Commission has identified **137 product categories in which the EU is strategically dependent**, of which 52% are imported from China. These products are divided in three clusters:

- Raw materials: includes beryllium, cobalt, antimony, lithium, aluminium, manganese, chromium, nickel, tungsten, molybdenum, etc.;
- Health products: includes personal protective equipment, antibiotics, vitamins, hormones, heterocyclic organic compound;
- **Renewable technologies and digital products.**

Figure 3

Country of origin of dependency (percentage of total), 2019

Source: The European House - Ambrosetti on European Commission data, 2022



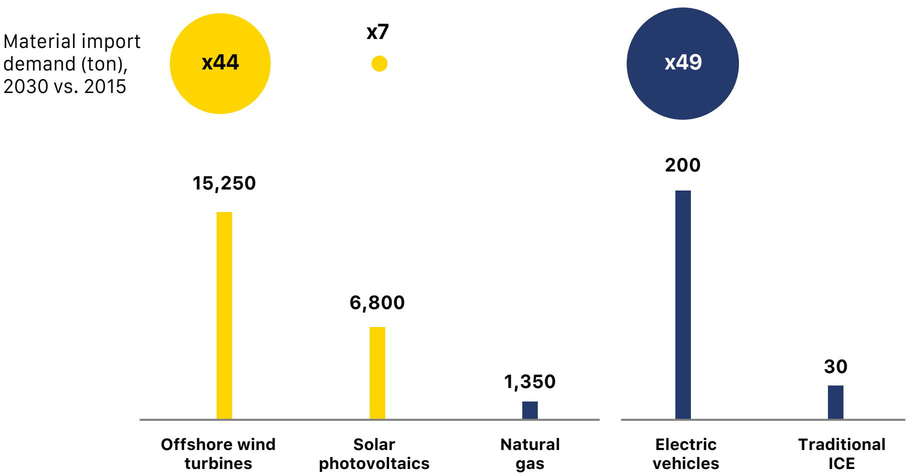
Four decarbonisation technologies (batteries, fuel cells, solar and wind) are dependent on high risk supply chains materials, such as rare earths and other imported raw materials, according to the European Commission. This issue becomes even more pressing since material demand is expected to increase dramatically; in 2030, wind power material demand is expected to increase by 44 times, solar photovoltaic demand by 7 times and electric vehicles demand by 49 times, considering 2015 demand as the baseline. **Access to materials and rare earths** is proving to be a major area of **risk** for the European energy transition: the high dependency might jeopardise the energy and electric vehicles shift, and eventually the achievement of the Union's climate objectives.

Notwithstanding, the EU has been working to mitigate such risks. Among the solutions, the EU is supporting the implementation of a Circular Economy in the raw materials value chain so as to reduce pressure on primary demand, decrease environmental impacts, and create new job opportunities.

Figure 4

Materials exploited in renewables and fossil fuels (kg/MW) and Materials exploited in electric and traditional ICE vehicles (kg/vehicle), 2022

Source: The European House - Ambrosetti on European Commission data, 2022



Key message #2

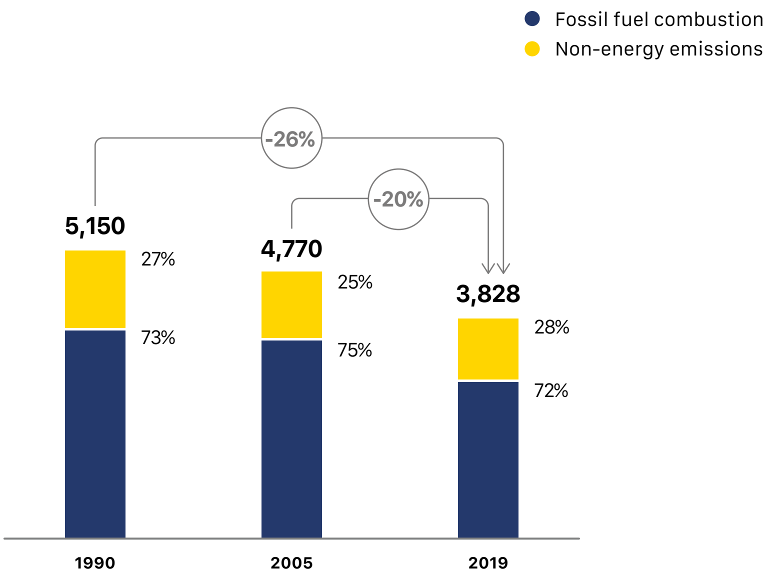
The most strategic and effective way to address decarbonisation is by working on both energy and non-energy emissions, with a focus on Hard to Abate industries, power generation and heavy transports.

The data collected through scientific analyses, and the evidence emerged during the Working Table discussions and dedicated interviews point out that the most strategic and effective way to address decarbonisation is by **working on both energy** and **non-energy** emissions, such as **industrial process emissions**. Although most **emissions (72%) are generated from fuel combustion**, **non-energy emissions account for 28% of the ones in the the European Union.** Both components must be addressed to achieve full carbonisation.

Figure 5

Share of GHG emissions from different source sectors in Europe (% and Mton), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



Notably, the focus should be on **Hard to Abate industries**, **Heavy Duty transport** and **power generation from fossil fuels.** These sectors are the **hardest to decarbonise**, considering the nature and scope of their emissions:

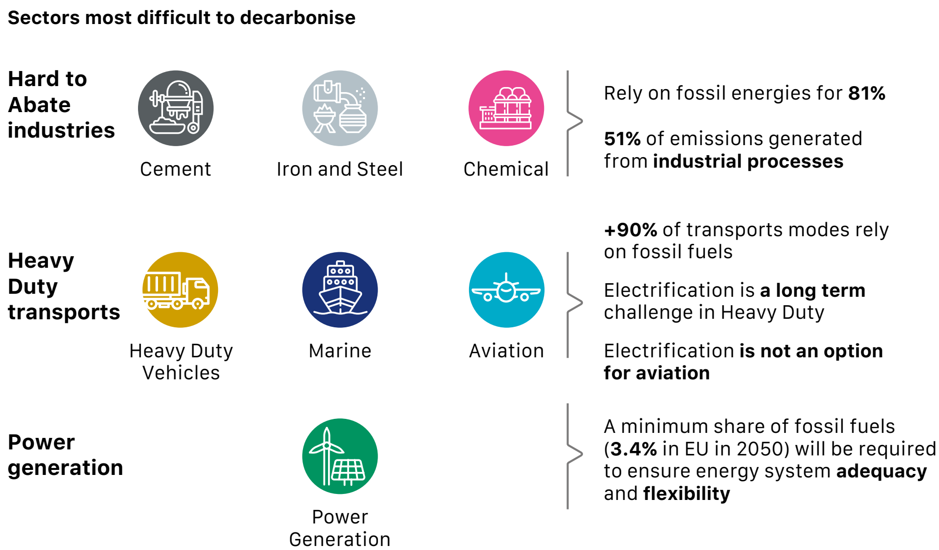
- **Hard to Abate industries**, such as **cement**, **iron** and **steel**, and **chemical** sectors, rely on fossil energies for **81%** of their final consumption and, on average, **51%** of emissions are generated from **industrial processes;**
- **Heavy Duty transports** rely on fossil fuels **for more than 90%** of fuel consumption, and electrification is a **long-term** challenge in Heavy Duty, and is also **not an option for aviation**;
- **Power generation** poses a challenge because a minimum share of fossil fuels (**3.4%** in EU in 2050) will be required to ensure energy system **adequacy** and **flexibility.**

Europe is faced with a **technological development challenge** to decarbonise these sectors; hence all available technologies must be leveraged to achieve the target of full decarbonisation.

Figure 6

The most difficult sectors to decarbonise and corresponding challenges

Source: The European House - Ambrosetti on Eurostat data, 2022



Key message #3

All net zero scenarios and the main long-term strategies of European Member States agree on the need to leverage a plurality of technologies to achieve the international target of limiting global warming to below 1.5°C compared to preindustrial levels.

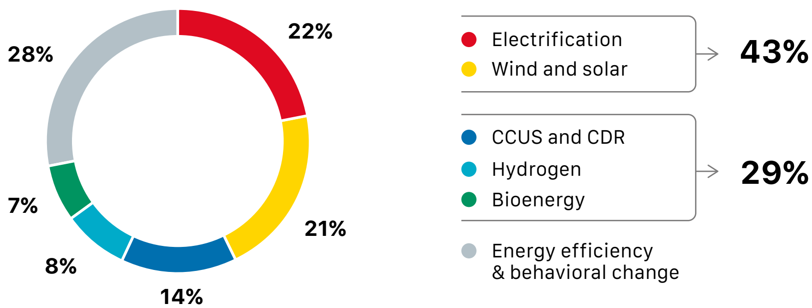
The only way to effectively achieve full decarbonisation is **to leverage all possible technological levers**: renewables, electrification of end-uses and energy efficiency will play a crucial role in the energy transition, but they must be coupled with other mitigating measures. The most effective strategy is to combine, on a case-by-case basis, energy efficiency, renewable energies, decarbonised carriers, and CO_2 capture technologies. As a matter of fact, **all net zero emissions scenarios** developed by the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and the main long-term strategies of European Member States agree on this requirement. Carbon Capture Utilization &

Storage (CCUS) and Carbon Dioxide Removal (CDR), hydrogen, as well as biofuels and synthetic fuels are all key technologies to achieve full decarbonisation that are considered relevant in the IEA scenario, whereby **43%** of the mitigation measures relates to **electrification and wind and solar technologies**, but **57%** of CO_2 reduction requires other **technological levers** – of which CCUS and CDR, hydrogen and bioenergies combined represent 29% of total emission reduction contribution.

Figure 7

Share of contribution of each mitigation measure in the NZE 2050 scenario (% of total emission reduction), 2020-2050

Source: The European House - Ambrosetti on IEA data, 2022



Key message #4

Achieving climate neutrality requires leveraging all possible technological levers, combining, on a case-by-case basis, renewable energies, decarbonised carriers and CO_2 capture technologies. A total of 100 decarbonisation technologies have been identified that need to be promoted in order to optimise investments following a principle of technological neutrality.

Following an in-depth analysis of all decarbonisation plans, scientific papers and data collected through the stakeholder engagement process, a total of **100 decarbonisation technologies** have been identified that need to be promoted to optimise investments **following a technological neutrality principle** along the whole energy production value chain.

Figure 8

Technologies underlying the Zero Carbon Technology Roadmap

Source: The European House - Ambrosetti, 2022

CARBON NEUTRAL ENERGY PRODUCTION

Technology readiness level
- Low: 1-4
- Intermediate: 5-7
- High: 8-9

Source: elaboration The European House - Ambrosetti, 2022

FOSSIL FUELS & CCUS / CDR

- **Fossil fuel combustion with CCUS & CDR**

CCS technologies require a CO_2 infrastructure to effectively:

1. **Decarbonise fossil fuel combustion** through **Carbon Capture & Storage**
2. **Offset emissions** through Carbon Dioxide Removal technologies that absorb **CO_2 from the atmosphere**

ELECTRIC & THERMAL RENEWABLES

Electric renewables

- Photovoltaic
- Wind
- Concentrated solar power
- Geothermal
- Hydropower
- Marine

Thermal renewables

- Solar
- Geothermal
- Ocean

NUCLEAR ENERGIES

Fission

- IV Generation reactors

Fusion

- Magneto-inertial fusion
- Hybrid electrostatic confinement
- Inertial confinement
- Non-thermal laser fusion

CO_2 INFRASTRUCTURE

	CO_2 source	Capture	Transport	Storage
Carbon Capture & Storage CCS is used to decarbonise **Hard to Abate** processes by reducing emissions from **fossil fuels combustion** or **industrial processes**	CO_2 captured directly **from emitting sources** with **artificial techniques**	Physical absorption Chemical absorption Fluidized solid adsorption Polymeric membrane Static solid adsorption Pure oxygen combustion Supercrytical CO_2 cycles	*Depending on distance & distribution* Ship Pipeline Truck	*Depending on distance & availability* Geological sites CO_2 injection & management Simulation of geological storage Monitoring of geological storage
Carbon Removal Captured CO_2 can be used: • To **offset non-abatable** emissions in case of **long-term** storage • To produce **decarbonised** energy **carriers** in case of **short-term** storage	CO_2 captured from **bioenergies production** with **artificial techniques**	Bioenergies with CCS (BECCS)		
	CO_2 captured from the **air** with **artificial techniques**	Direct Air CCS (DACCS)		
	Atmospheric CO_2 captured **naturally** with **Biomasses & silicate rocks**	Afforestation & reforestation	*Not necessary*	*Trees, biomass*
		Biochar	Truck	*Arable fields*

Existing reservoir management know-how is exploited for the geomechanical, hydraulic and chemical modelling of underground reservoirs, in an aim to ensure safety and stability of CO_2 storage

PRODUCTION AND USAGE OF CARBON NEUTRAL ENERGY VECTORS

Technology readiness level
- 🔴 Low: 1-4
- 🟡 Intermediate: 5-7
- 🟢 High: 8-9

CARBON NEUTRAL ELECTRICITY

Vector generation

Electric energy coming from Zero Carbon primary energy source (see dedicated section)

Storage

Battery
- 🟡 Redox flow
- 🟢 Lithium-ion
- 🟢 Solid-state batteries

Mechanical
- 🟢 Flywheel
- 🟢 Pumped
- 🟡 Compressed air energy
- 🟢 Liquid air energy

Thermal
- 🟡 Latent heat
- 🟡 Sensible heat

Chemical
- 🟡 Power to gas
- 🟢 Hydrogen

Electrical
- 🔴 Capacitor
- 🔴 Superconducting magnetics

Transmission, distribution & dispatching

Dispatching
- 🟡 Virtual power plant
- 🟢 Demand-response
- 🟢 Demand-side management
- 🟢 Vehicle to grid

Transmission
- 🟡 Ultra-high voltage
- 🟡 Flexible high-voltage grid
- 🟡 Superconducting high-voltage
- 🟢 Flexible alternating current transmission system
- 🟢 Dynamic line rating

Distribution
- 🟢 Recharging
- 🔴 Transactive energy

Consumption

Transports
- 🟡 Plug-in hybrid
- 🟢 Fuel cell electric
- 🟢 Battery electric

Buildings
- 🟢 Electric heat pumps
- 🟢 Electric boilers

Industry
- 🟢 Electric pump
- 🟢 Direct heating
- 🟢 Induction heating

CARBON NEUTRAL HYDROGEN

Input source	Vector generation
Methane	🟢 Steam methane reforming 🟢 Autothermal reforming 🟢 Partial oxidation 🟡 Methane pyrolysis
Coal	🟢 Gasification of coal
Electricity & water	🟢 Alkaline electrolysis 🟢 Polymer electrolyte membrane 🔴 Microbial electrolysis 🟡 Solid oxide electrolyser cells
Biomass	🟢 Biomass pyrolysis 🔴 Bio-photolysis
Water & solar energy	🔴 Photo-electrochemical
Organic plant & sunlight	🔴 Photosynthesis
Bacteria & sunlight	🔴 Photofermentation
Microalgae & sunlight	🔴 Microalgae photofermentation
Microorganisms	🟡 Dark fermentation
Calcinated iron ore & biomass pyrolysis gas	🟡 Chemical Looping with CCUS

Storage
- 🟢 Salt cavern storage
- 🟢 Storage tank
- 🔴 Depleted oil and gas fields
- 🟡 Liquid organic hydrogen carrier

Transportation
- 🟢 Pipeline
- 🟡 Hydrogen blending in natural gas networks
- 🟡 Liquid hydrogen tanker
- 🟡 Liquid organic hydrogen carrier tanker

Consumption

Buildings and industry:
- 🟢 Pure blended hydrogen-fired technology

Transports sector (Road, rail, maritime shipping, aviation)
- 🟡 Ammonia fuel cell
- 🟡 Hydrogen fuel cell
- 🟡 Hydrogen ICE

CARBON NEUTRAL FUELS

Input source

Biofuels

Biomasses not in competition with food: residual, non-edible oils, agricultural and municipal waste, algae, discarder animal fats and glycerine, microbial processes

Agritech research is necessary to identify additional biomasses not in competition with food for the production of **biofuels**

Synthetic fuels

Carbon Neutral H_2, CO_2 from DACCS or BECCS, Carbon Neutral energy (or alternatively CCUS or CDR)

Vector generation
- 🟢 Hydrotreated Vegetable Oils (HVO) and transesterification
- 🟢 Anaerobic digestion
- 🟡 Gasification
- 🟢 Pyrolisis
- 🟡 Fischer-Tropsch synthesis (FTS) and Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK)
- 🟡 Methanization
- 🟡 Fischer-Tropsch and hydrocraking
- 🟡 Methanol synthesis and methanol to gasoline

Storage, transportation, distribution & consumption

Low-carbon fuels can easily **replace fossil fuels**: they are fully **compatible** with the existing infrastructures for **storage, transportation, distribution, and consumption.**

They can be **used in conventional internal combustion engines** and **jet** engines: regular cars, planes, and ships can be fueled with synthetic fuels without changes or refitting required.

The mapped technologies rely on five decarbonisation levers:

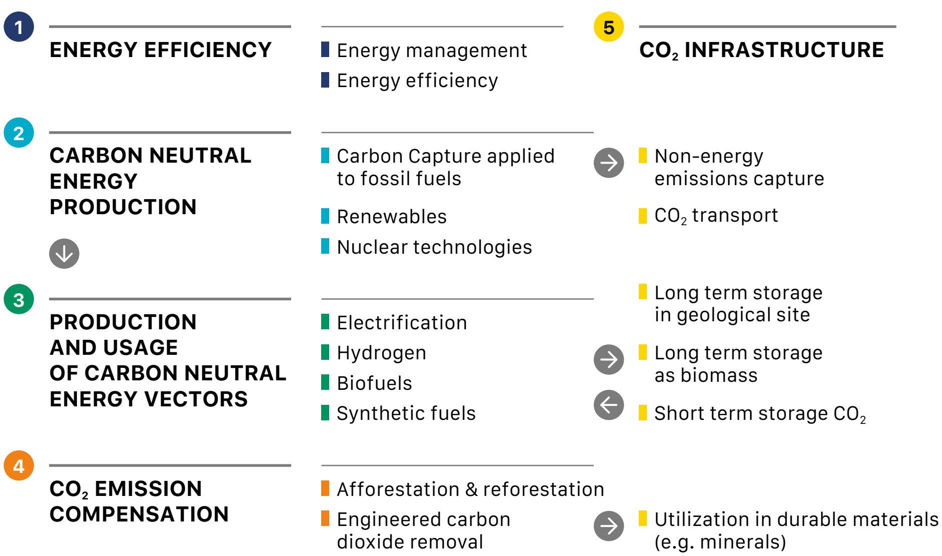
- **energy efficiency** to decrease energy demand without compromising the fulfillment of societal needs;
- **Carbon Neutral energy production** that does not emit greenhouse gases (GHG) or can capture, permanently store or compensate their GHG emissions;
- **production and use of Carbon Neutral energy vectors** that **do not emit** GHG apart from biogenic emissions generated from the exploitation of biofuels, or can **capture** permanently CO_2 or **compensate** GHG emissions;
- **CO_2 emission compensation** allows to **offset unabated emissions**, by subtracting CO_2 from the atmosphere;
- **CO_2 infrastructure technologies** to enable the transport, use or storage of the captured CO_2 with **CCUS** in fossil fuel combustion and in non-energy emissions or hydrogen production, **CDR** for the capture of atmospheric CO_2. These infrastructures are also necessary to provide the **CO_2** necessary to produce synthetic Carbon Neutral fuels, along with other industrial products.

Figure 9

Decarbonisation levers

The arrows show the exchange of CO_2 between levers and sub-levers for production and usage of the reference technologies

Source: The European House - Ambrosetti, 2022



The implementation of these technologies will **enable the Carbon Neutrality of each emitting activity**, and the application of this principle to whole **value chains** allows to achieve **full decarbonisation** under a **Life Cycle Assessment** perspective. Notably, the Strategic Study has identified three high-potential technological areas, which can be exploited to complement renewables and electrification to achieve the decarbonisation objectives: CCUS and CDR, hydrogen and, finally, biofuels and synthetic fuels.

Key message #5

Carbon Capture Utilization & Storage (CCUS) and Carbon Dioxide Removal (CDR) are ready, scalable, competitive and safe technologies to accelerate the decarbonisation path.

There are currently 135 CCUS projects worldwide, 38 are located in Europe (28% of total). The 43% of worldwide projects is in an advanced development phase, while only 20% are operational. Notably, **11 European National Energy and Climate Plans contain explicit mention of CCUS and CDR** as a measure to achieve the net zero emissions objectives, especially for the decarbonisation of Hard to Abate sectors, and dedicate parts of their National Resilience and Recovery Plans to develop national CCUS infrastructures.

Figure 10

CCUS and CDR mentions and fundings in European Member States

Source: The European House - Ambrosetti on NECP and NRRP data, 2022

€1.85 bn to capture **0.4 Mtons CO_2/yr** from a cement factory in Norway. Development of a CO_2 transport and storage solution with a final capacity of 5 Mtons/yr

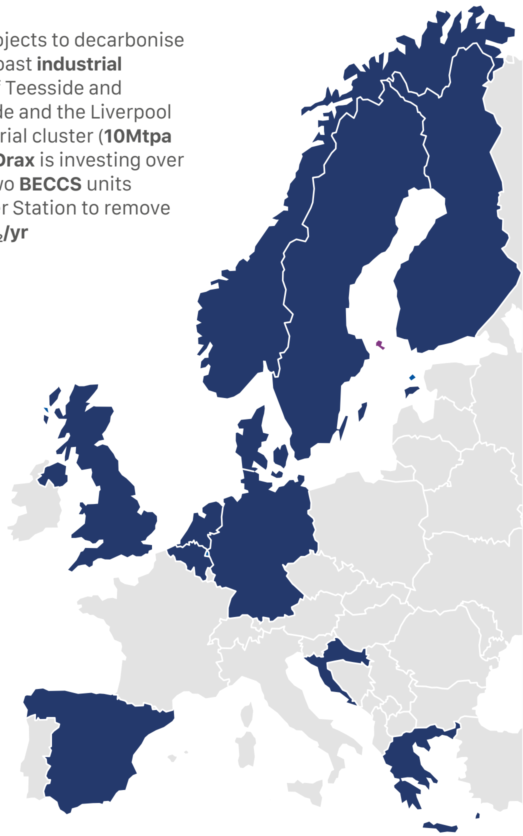
€27 mln to support the development and demonstration of **CO_2 storage** sites in depleted oil and gas fields in the Danish North Sea

A Finnish oil refinery was granted **€88 mln** by the European Commission for its Sustainable Hydrogen & Recovery of Carbon project

The Swedish government will subsidize **€37.9 mln** per **year**, over the period 2026-2040 to players investing in **bio-CCS** facilities

2 CCUS projects to decarbonise the East Coast **industrial clusters** of Teesside and Humberside and the Liverpool Bay industrial cluster (**10Mtpa** by 2030). **Drax** is investing over **£2 bn** in two **BECCS** units at its Power Station to remove **8 MtonCO_2/yr**

The Belgian NRRP allocated **€10 mln** to support the CCUS project **Antwerp@C, €50 mln** for the development of **low-carbon emission industry, €95 mln** to develop a network for **H_2 and CO_2 transport**



The Dutch NECP regards CCUS as an **inevitable transition technology** to reduce CO_2 emissions in sectors where **no cost-effective alternative is available** in the short term

Germany announced a **funding directive** for commercialising capture technologies and supporting CO_2 transport infrastructure options

The Spanish NECP proposes the integration of **CCUS technologies to reduce emissions**

€658 mln of the Croatian PNRR to develop innovative CCS projects, support the production of advanced biofuels and renewable hydrogen

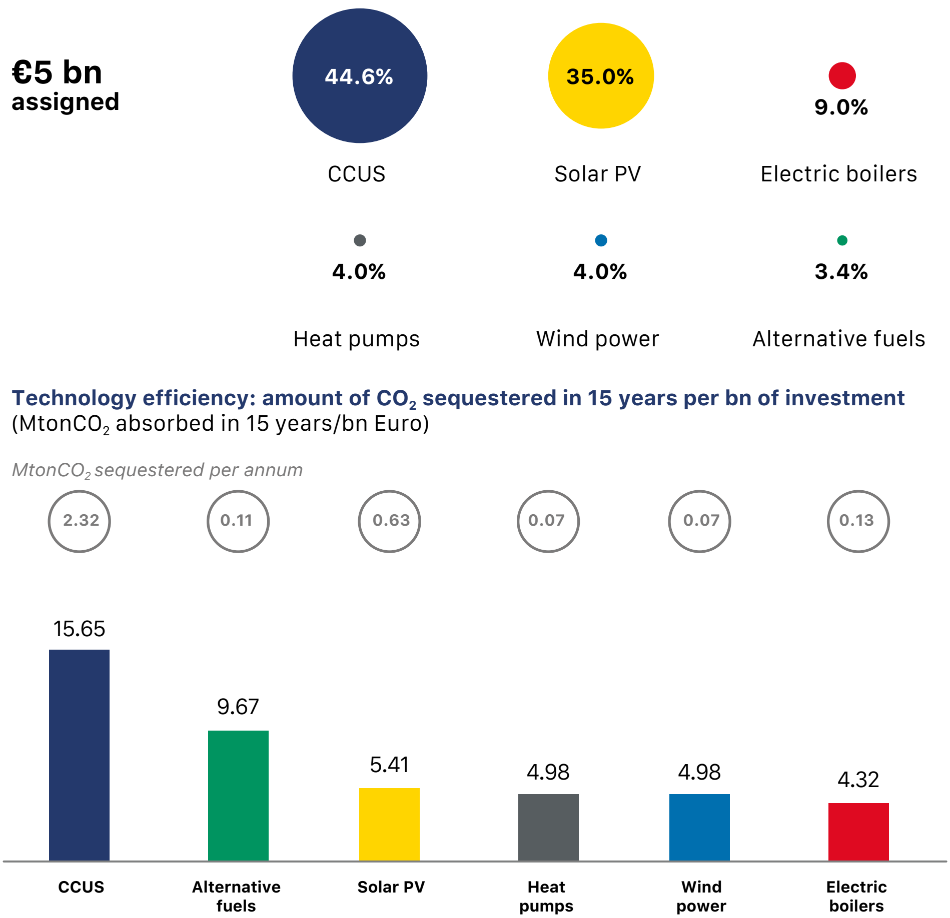
The Greek NRRP destinates **€300 mln** to develop the **Prinos CCS project**, with CO_2 stored in the depleted offshore fields

Among these plans, a special mention goes to the Dutch government, which has awarded **CCUS as the most cost-effective technology** in its "Stimulation of sustainable energy production and climate transition" program. **Considering a fifteen-year span, the amount of CO_2 abated by the CCUS technologies per Euro invested is about three time larger than Solar PV, heat pumps, wind power and electric boilers.**

Figure 11

Sustainable energy transition subsidy scheme (SDE++) 2020 budget allocation (% and billion of Euros) and Technology efficiency: amount of CO_2 sequestered in 15 years per bn of investment (MtonCO$_2$ absorbed in 15 years/bn Euro)

Source: The European House - Ambrosetti on SDE++ data, 2022



To foster the implementation of CCUS and CDR at the European level and increase their decarbonisation potential while leveraging on a technology neutrality principle, the following policy proposals have been defined:

Policy Proposal #1

- **Envisage the development of a regulatory framework for CCUS** according to a single European market logic, providing the creation of infrastructures with access for all Member States
- Foster the **inclusion of CCUS in the energy and climate planning** of all EU Member States

Policy Proposal #2

- Put in place a **policy mechanism that allows to account for negative emissions**, currently not possible under the EU Emissions Trading System (ETS)
- Introduce a **financing mechanism to de-risk industrial investments** in large-scale **CDR** demonstration facilities

Key message #6

Hydrogen should be exploited as a Carbon Neutral energy carrier with great potential for decarbonising end-uses without increasing competition for access to renewable electric energy.

The production of Carbon Neutral hydrogen from fossil fuel coupled with CCUS i.e., blue hydrogen, is required to enable fast and competitive market growth on both the demand and supply side, without increasing competitions with renewables.

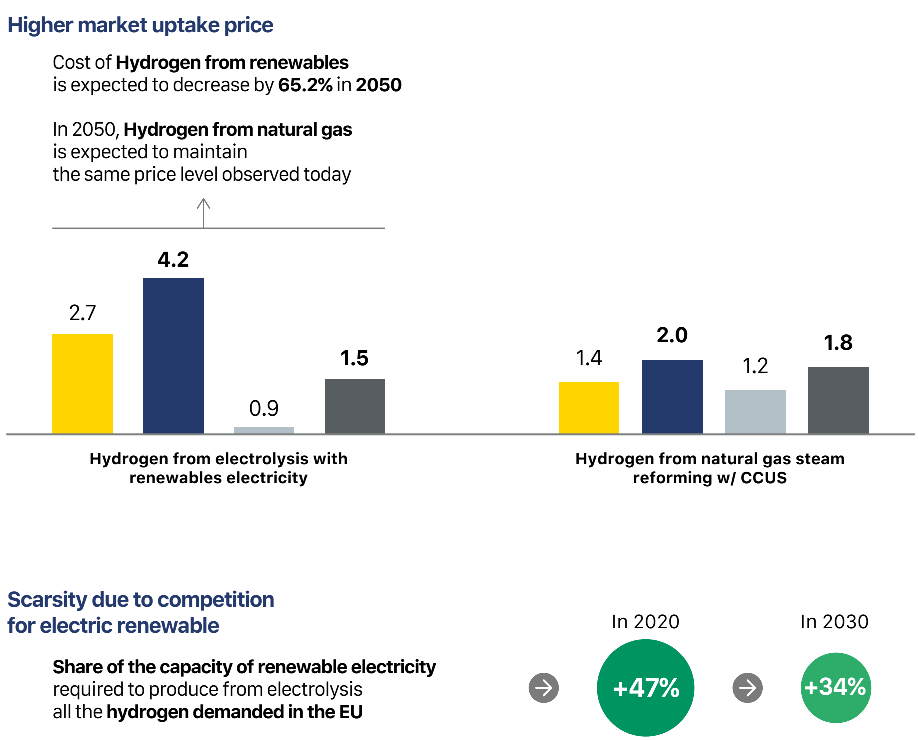
As of 2020, the cost of **hydrogen from renewables** was twice the price of **hydrogen from natural gas with CCUS**. Even though the former is expected to decrease by **65.2%** in **2050**, it is necessary to foster the production of hydrogen coupled with CCUS in the short term to facilitate the future employment of renewable hydrogen by creating a market for hydrogen and a value chain. Another challenge posed by the production of renewable hydrogen is the **additional capacity of renewable electricity** necessary to generate from electrolysis all the **hydrogen consumed in the EU**: in 2020, the additional capacity required was 47%, whereas in 2030 it is expected to be 34%.

Figure 12

Hydrogen's costs according to different technologies (€/KgH_2), based on 2020 prices

Source: The European House - Ambrosetti on Paper «Cost-effective Decarbonisation Study», European University Institute and Florence School of Regulation (2020) and other sources, 2022

2020 Min. Val.
2020 Max. Val.
2050 Min. Val.
2050 Max. Val.

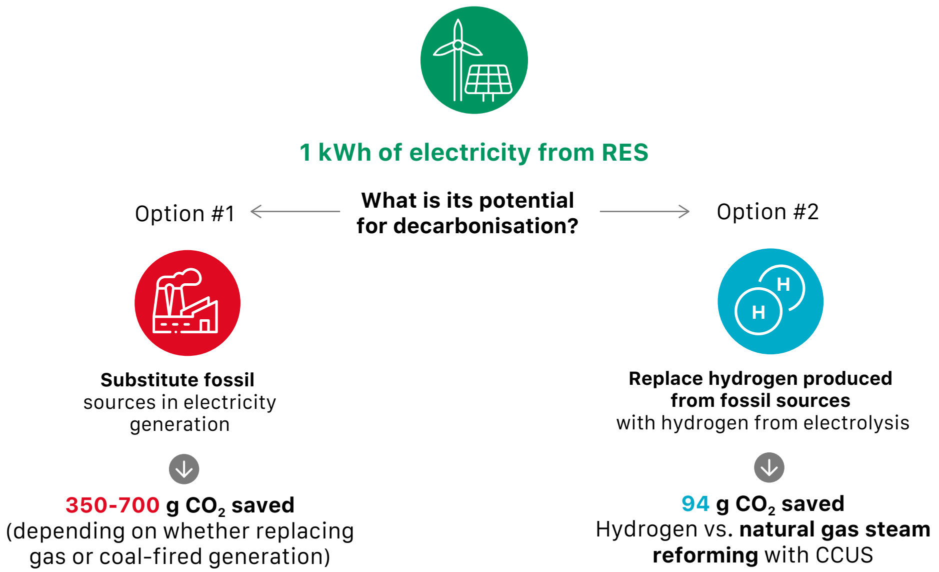


Finally, it is important to underline that, in the medium term, **the production of hydrogen with electrolysis reduces of about three times the decarbonisation potential of electric Renewable Energy Sources (RES)**.

Figure 13

The decarbonisation potential of 1 kWh of electricity from Renewable Energy Sources

Source: The European House Ambrosetti on literature review data, 2022



To encourage the production and usage of blue hydrogen and create a market for hydrogen at the European level that will simplify the future large-scale deployment of green hydrogen, the following policy proposal has been defined:

Policy Proposal #3

- **Recognize as sustainable the hydrogen generated from fossil fuel with CCUS when demonstrated that there are no unabated or uncompensated emissions under a Life Cycle Assessment.** This will make it possible to sustain the conversion of current gray hydrogen plants and support the diffusion of hydrogen fuelled technologies in the short-term, facilitating the future uptake of hydrogen from electrolysis
- Promote the diffusion of a **European policy reference standard** to be applied in all Member States to provide **technical** and **regulatory** clarity for companies involved in hydrogen valley and other implementation projects

Key message #7

Biofuels, whose production is not in competition with food, can be a Carbon Neutral solution that can replace traditional fuels while minimizing the necessary changes in consumption systems and supply chains.

Notably, biofuels not in competition with food and feed chains are those derived from residuals, non-edible oils, agricultural and municipal waste, algae, discarder animal fats and glycerine. The important aspect of biofuels is that they can be used right away in existing systems, accelerating the decarbonisation process. As an example, almost all circulating diesel truck can run on 100% biodiesel. Bio-feedstock can be even used to substitute fossil carbon in some chemical productions. This must be considered taking into account the possibility to act on the existing fleets and facilities immediately, not requiring considerable investment in new vehicles and facilities.

Another important aspect is that the biofuels supply chain can foster the creation of a circularity economy paradigm in Europe. There are currently **34.9 million tons of waste per year** available in EU for biofuels production that are not being exploited.

Additionally, the production of biofuels from **energy crops grown on marginal land** (not in competition with food and feed-chains), provides a chance to create the local development of new business models in agriculture. Marginal lands have little or no agricultural value, characterized by physical isolation (like being far from any available road), no water, severe slope, or industrial pollution. In the European Union, there are **60 million hectares** of marginal lands that can be exploited for biofuels production crops.

Figure 14

Sources for biofuels generation not in competition with food

Source: The European House - Ambrosetti, 2022

Residues and wastes

34.9 million tons of waste per year available in EU for biofuels production

Agriculture crops not in competition with food

60 million hectares of marginal lands in EU can be exploited for biofuels production

Biofuels can be used right away in existing systems, accelerating the decarbonisation process

Considering the global scenario, Africa is the world's first area for marginal lands, with **784 million hectars** that can be exploited to cultivate energy crops, fostering **economic and social development**. The main socio-economic benefits for local African communities involved in the cultivation of energy crops in marginal lands are:

- Up to **171% differences in income** perceived between workers in energy crops plantation and "normal" workers;
- Up to **181% differences in expenditure capacity** between workers in energy crops plantation and "normal" workers;
- Up to **30 percentage points** earned in the comparison of **multidimensional poverty**[1] between workers in energy crops plantation and "normal" workers.

Considering the large-scale availability of waste and residues, together with the existing marginal land at the European level, and the possibility to introduce biofuels in current consumption systems with minimal changes required, the following policy proposal has been developed:

1 *The global Multidimensional Poverty Index (global MPI) is a poverty measure that reflects the multiple deprivations that poor people face in the areas of education, health, and living standards (Oxford University).*

Policy Proposal #4

- Ensure that all the feedstocks sourced from **wastes, residues and crops, not in competition with food and feed chains, are considered sustainable** to produce Carbon Neutral biofuels when demonstrated that there are no emissions other than biogenic ones

Key message #8

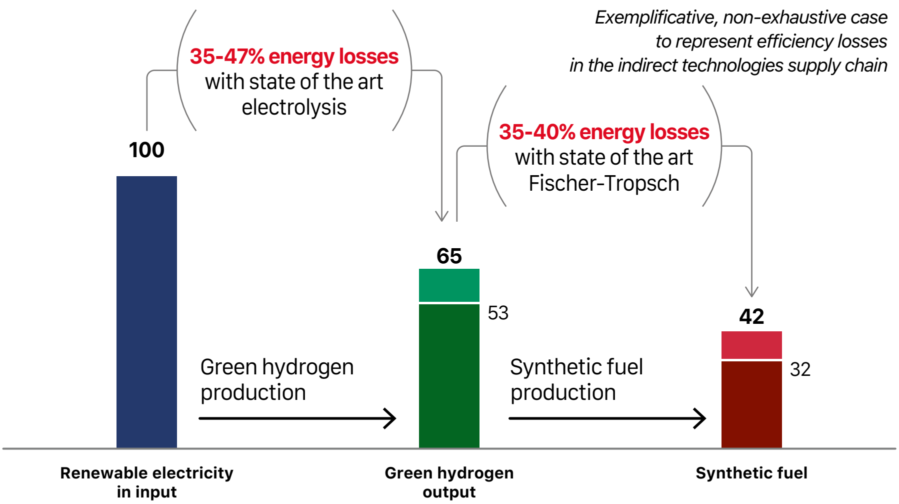
Synthetic fuels, while facing efficiency losses in the processing steps, are a Carbon Neutral solution to replace fossil fuels because they require minimal infrastructure adjustments to be integrated into specific Hard to Abate sectors (e.g., aviation).

Synthetic fuels are produced from the mix of hydrogen and CO_2, **leveraging on well-known technologies** with **high maturity**. Anyway, the integration of these technologies into efficient plants still requires industrial improvements. Overall, synthetic fuels offer multiple advantages, but one major downside that needs to be addressed: the supply chain is associated to efficiency losses at each transformation stage, leading to higher costs. **There is still a need of value chain integration to compete with other alternatives**.

Figure 15

Technology efficiency losses in the production of green hydrogen and synthetic fuel from renewable electricity, (%, TWh of renewable electricity = 100) - Light and dark colours indicate value ranges

Source: The European House - Ambrosetti on various data, 2022



Notwithstanding the efficiency losses, similarly to biofuels, the production and usage of synthetic fuels should be fostered at the European level, given their potential to easily replace fossil fuels in the short term – thanks to the minimal changes required. Synthetic fuels are required in all non-electrifiable application in which high performance, stable and easy to handle sustainable fuels are required, as in the aviation sector.

Key message #9

The extensive application of Carbon Capture Utilization & Storage (CCUS), Carbon Dioxide Removal (CDR), hydrogen, biofuels and synthetic fuels technologies is indispensable to achieve full decarbonisation of the Hard to Abate, heavy transport and fossil fuel power generation by 2050. Between 2023 and 2050, the application of the recommended technologies in the analysed sectors will generate more than 2,700 billion of value added in Europe, and about 1.7 million employees in 2050.

To assess the potential of CCUS and CDR, hydrogen, biofuels and synthetic fuels on the sustainability of the European Union, a bottom-up work was conducted **analyzing more than 185 academic papers** and involving **thirty** stakeholders: fifteen representatives of **Hard to Abate industry sectors** were interviewed in an aim to identify the best strategies to adopt new **technologies for the decarbonisation of energy-intensive industrial plants**; similarly, the other fifteen stakeholders representing the **Heavy Duty transport sector** were engaged to identify the role of new technologies to decarbonise the Hard to Abate modes on road, maritime and aviation.

Policy Proposal #5

- To incentivize investments in decarbonisation infrastructures and technologies, resources should be allocated according to the **economic efficiency to abate CO_2**, evaluating the potential in comparison with other alternative technologies and according to a **technology neutrality principle**

Policy Proposal #6

- Introduce a **Carbon Contracts for Difference** model that encourages the investments in Zero Carbon technologies by reducing the risks in the investment phase, in a similar way as done to incentivize the diffusion of electric renewable energies

Policy Proposal #7

- **Moving beyond the "tank-to-well" emissions calculation** approach and promoting a "**well-to-wheel**" Life-Cycle Assessment (LCA) approach in assessing overall fuel emissions
- Recognize, in the European taxonomy, the status of "carbon neutral fuels" to **biofuels** and **hydrogen** produced from fossil sources in **combination with CO_2 Capture technologies**
- Foster the **creation of infrastructure**, such as refilling stations, required for a massive deployment of alternative fuels on roads, ports and airports and introduce **fiscal policies to reduce the price gap with traditional fuels**

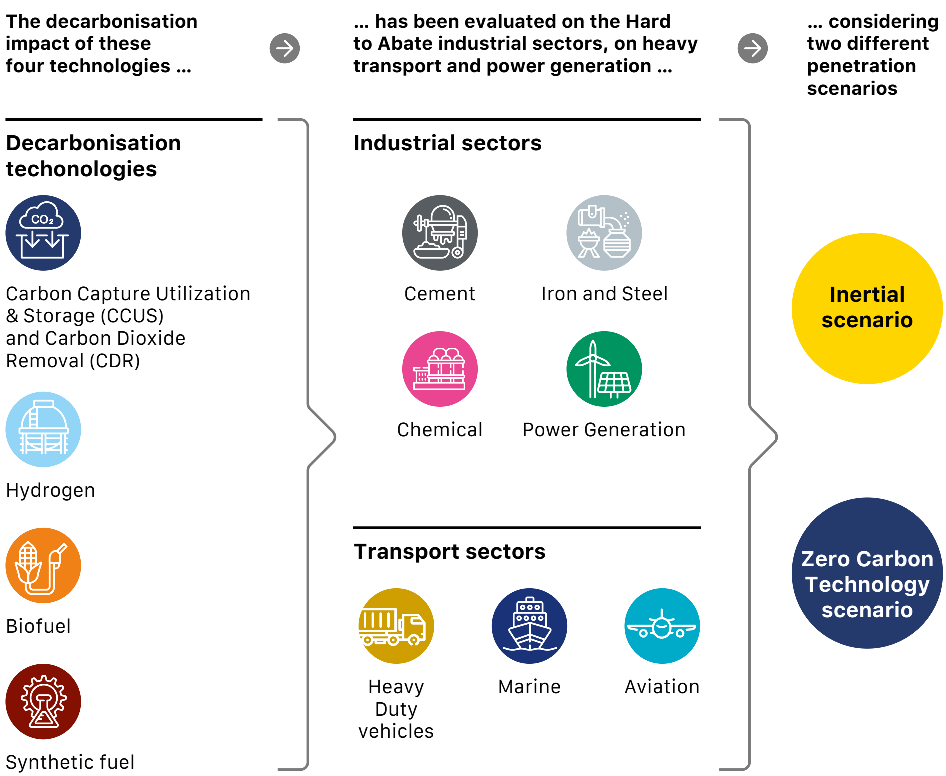
The evidence gathered during the **Working Tables** allowed to develop the above-mentioned set of policy measures to facilitate the decarbonisation process. These proposals laid the foundations of the **decarbonisation model** developed by The European House - Ambrosetti, where all the **policy proposals have been implemented and their impact on the European value chain has been assessed in terms of sustainability, employment, and value-added creation.**

Decarbonisation levers – CCUS and CDR, hydrogen, biofuels, and synthetic fuels – have been applied to two different scenarios to assess their impact on CO_2 abatement in Hard to Abate industries, Heavy Duty transport, and fossil fuel power generation. Two different penetration scenarios have been considered, a so-called Inertial Scenario and a Zero Carbon Technology Scenario. **The difference between the two is the implementation of the policy recommendations developed by the present Study.**

Figure 16

Model infrastructure

Source: Elaboration by The European House - Ambrosetti, 2022



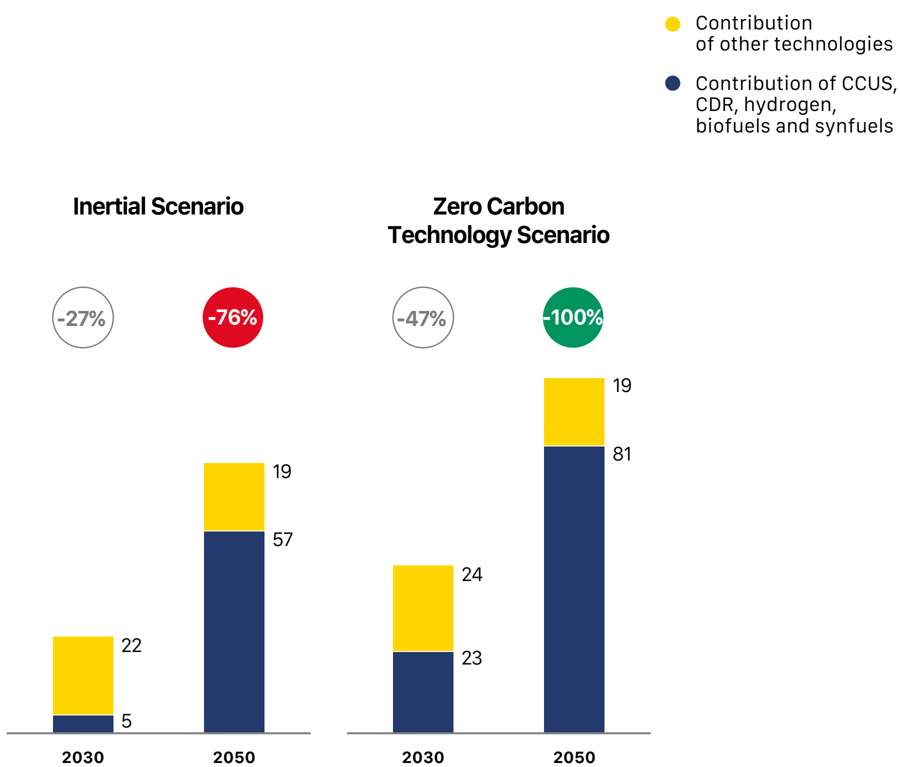
The implementation of the two models pointed to the conclusion that **a technology neutrality approach is indispensable to achieve full decarbonisation by 2050:** only in the Zero Carbon Technology Scenario the target of full decarbonisation is reached in 2050. Furthermore, this scenario allows to **accelerate the decarbonisation pathway in 2030** with a total abatement of CO_2 emissions 20 percentage points lower compared to the Inertial Scenario.

Thus, from 2023 to 2050 the Zero Carbon Technology Scenario **CO_2 cumulated emissions reduction** are **31% higher than the Inertial Scenario (8.8 Gton of CO_2)**, corresponding to **6 years** of **total emissions** of the considered sectors.

Figure 17

CO_2 emissions reduction, Inertial Scenario and Zero Carbon Technology Scenario, in EU27 (%), 2030 and 2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



The model has found that the extensive application of CCUS, CDR, hydrogen, biofuels and synfuels is **indispensable to achieve full decarbonisation of the Hard to Abate, Heavy Duty transport, and fossil fuel power generation** sectors in the European Union by 2050.

Besides the positive environmental impact generated by these technologies, the econometric model developed has found that, **between 2023 and 2050**, the application of the recommended technologies in the analysed sectors will generate more than **€2,700 billion of cumulative value added** in Europe – of which **€181 billion** solely in 2050, and about **1.7 million employees** in 2050, considering the direct, indirect, and induced impact.

Figure 18

Main results of the econometric model

Source: The European House - Ambrosetti on data from proprietary model, 2022

€ 181 billion
total Added Value in 2050

€ 2,700 billion
cumulative Added Value from 2023 to 2050

1.7 million
employees generated in 2050

Key message #10

Discontinuity in the decarbonisation process will be generated by some breakthrough technologies, the development of which is accelerating thanks to new models of Open Innovation.

On a final note, it is crucial for Europe to invest in frontier technologies to develop an industrial advantage. Among these, **magnetic confinement fusion** offers virtually **limitless, clean power**, and it could complement renewables by providing electricity during peaks and throughs, it could provide **clean industrial heat**, and it can **generate hydrogen** to replace natural gas. Nuclear fusion produces **no harmful emissions or radioac-**

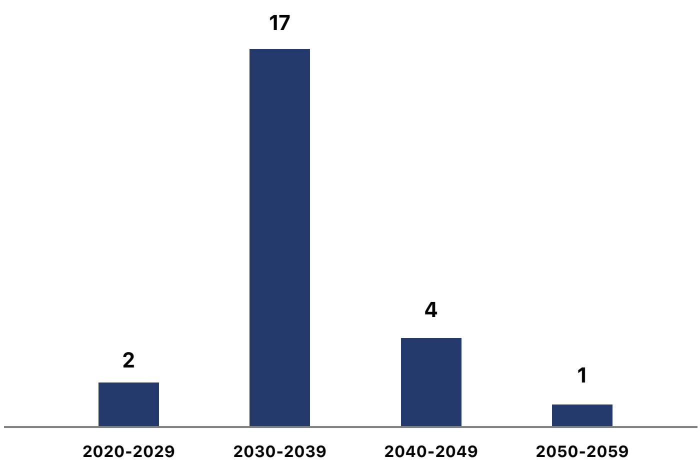
tive waste, and the elements required are easily attainable and readily available. As of 2021, the survey conducted by the Fusion Industry Association reveals that **17 fusion initiatives around the world** expect fusion to be commercial in the **2030s**, a positive outlook motivated by recent historical results:

- In February 2022, the **JET project experiments produced 59 megajoules of energy in 5 seconds** (11 megawatts of power);
- In the UK, Tokamak Energy achieved important milestones in early 2022: **the spherical Tokamak ST40 touched a plasma temperature of 100 million degrees Celsius**, the threshold required for nuclear fusion;
- In September 2021, **the MIT CFS generated a magnetic field of 20 Tesla in just two weeks**, enabling a temperature suitable for the nuclear fusion process, demonstrating that the new technology based on high-temperature superconducting magnets is suitable for the nuclear fusion process and enables small-scale power plants.

Figure 19

Perception of the time horizon for implementing nuclear fusion plants

Source: The European House - Ambrosetti on Fusion Industry Association data, 2022



The European Union must not pass on the opportunity to gain and maintain a leadership role in this technology, which offers the opportunity to be easily "exported" outside of the Union to help other countries face the energy transition process. Given the major opportunities offered by nuclear fusion and other breakthrough technologies in terms of **sustainability and technological leadership advantage**, together with the evidence gathered during a **dedicated Working Table with eleven stakeholders** representing the industrial and academic worlds, the following policy proposals have been developed:

Policy Proposal #8

- Foster the **leadership in research and development of frontier technologies** that will potentially be disruptive in decarbonisation processes, such as nuclear fusion
- Ensure **policy support** (regulatory framework, incentives, ...) **to promote the creation of public-private partnerships** between academia, research centres, industries and public authority to accelerate the developments of such technologies

Policy Proposal #9

- Provide **clarity on the overall regulatory regime** for fusion energy facilities, considering all the differences with respect to nuclear fission technology
- Ensure regulators have the **technical capability** to regulate fusion energy facilities effectively
- **Maximise public confidence** in the regulatory framework for fusion, envisioning occasions for public debate and discussion
- Create a **platform mechanism through which innovation projects and financial investors** can be brought together

Chapter 1
The reference context

1.1 Introduction

The aim of the present chapter is to intruduce the **reference context of the Strategic Study conducted by The European House - Ambrosetti to develop a proposal for a Zero Carbon Technology Roadmap for Europe**. The first part of the chapter describes the European energy strategy according to international agreements, European legislation and other crucial requirements such as technological independence and energy system flexibility. The second part of the chapter illustrates the requirements for a sustainable, affordable, secure, and resilient European energy system. The third and last part of the chapter provides a breakdown of the main sources of emissions from fossil fuels as well as other emitting processes in Europe.

The aim of this chapter is to demonstrate that **a step change is required in all areas of climate sustainability to meet the European decarbonisation goals.** At the same time, it is crucial that, alongside sustainability targets, the **decarbonisation process ensures resilient and competitive access to energy.** The risks associated with global competition for access to resources is evolving very rapidly. In this scenario, access to metals and rare earths is proving to be the major area of risk for the European economy, introducing additional and higher risks.

Furthermore, the present analysis, differently from what done in many other studies, highlights the **strategic need of working on both energy and non-energy emissions, with a focus on Hard to Abate industries, power capacity from fossil fuel and heavy transports**. In this regard, all net zero emissions scenarios and the main long-term-strategies of European Member States agree on the need to leverage a plurality of technologies to achieve the international target of limiting global warming to below 1.5°C compared to pre-industrial levels.

1.2 International agreements and European strategies to meet the decarbonisation objectives

Key message #1

A step change is required in all area of climate sustainability to meet the European decarbonisation goals. It is crucial that the decarbonisation process ensures at the same time secure, resilient and competitive access to energy. Technological dependence must be considered on a par with energy dependence.

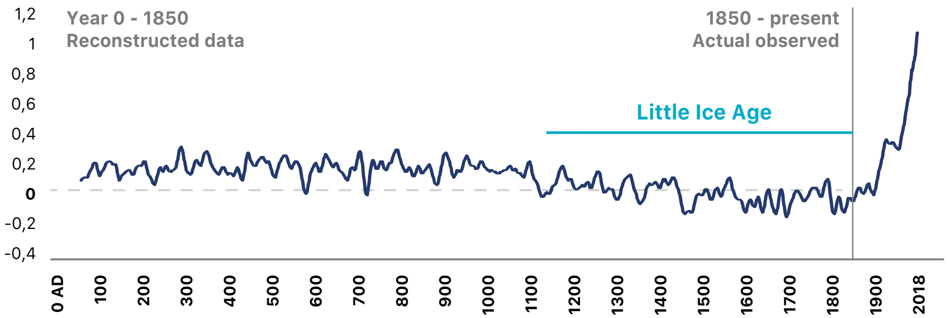
The latest Intergovernmental Panel on Climate Change (IPCC) report published in August 2021 and the conclusions of the subsequent UN Climate Change Conference of the Parties (COP26) have once again highlighted the risks and costs of climate change that have already occurred, and those that are expected in the coming decades unless a radical change of pace occurs. The conclusions of both reports contain warnings to governments, institutions, businesses, and citizens who have failed to implement tangible and effective measures to reduce climate-altering gas emissions over the past 30 years, despite numerous commitments to do so.[1] The planet's temperature is rising at an unprecedented pace: the current level is higher than that of the warmest period in the last 100,000 years, leading to dangerous environmental, social, and economic consequences: **only in Europe, damages from extreme events have exceeded USD 4.4 trillion between 2000 and 2021.**[2]

1 *Source: The European House - Ambrosetti on IPCC data, 2022.*
2 *Source: elaboration by The European House - Ambrosetti on European Environment Agency data, 2022.*

Figure 1

Annual global temperature changes (Celsius degrees), year 0-2018

Source: The European House - Ambrosetti on IPCC data, 2022



Signed in 2015, the Paris agreement legally binds 196 countries to participate in the fight against climate change, with the objective "to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels". Every 5 years, countries shall revise their emission reduction targets and measures. In 2021, signatory countries defined their targets to reduce emissions by 2030 and reach zero emissions by 2050. According to the scenario developed by the IPCC, in order **to limit the global temperature increase to less than 1.5 °C, emissions must be reduced by 5.5% per year and, eventually they will have to become negative by 2060 through carbon capture and carbon dioxide removal technologies**.

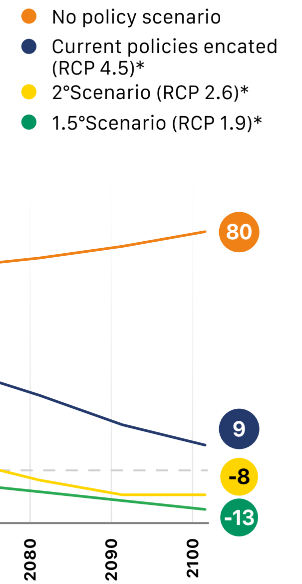
It has been demonstrated that the most ambitious plans put in place by the world's major economies will not be sufficient to contain the temperature increase within the 1.5°C threshold as envisaged by the Paris Agreement. What is needed, therefore, is a shift in the pace of the decarbonisation pathway to reduce greenhouse gas (GHG) emissions faster: **the rate of reduction of the last decade must increase four times to reach net zero emissions in 2050** and, as predicted by the IPCC scenarios, to achieve 'negative' emissions by 2100 without sacrificing welfare and social equity. This effort must be further emphasized for the decarbonisation of the so-called Hard to Abate sectors for which technologies with sufficiently effective and affordable market maturity have not been developed yet.[3]

3 *Source: The European House - Ambrosetti on IPCC data, 2022.*

Figure 2

CO_2 emission trends in the main scenarios considered by the IPCC ($Gton$ of CO_2), 2015-2100

Source: The European House - Ambrosetti on IPCC data, 2022



* *A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC*

In December 2019, the European Union launched the Green Deal, and in July 2021 it reinforced it with the Fit for 55 Package. Both contain a set of legislations to achieve the climate goals and carbon neutrality by 2050:

- -55% of GHG emissions compared to 1990;
- 40% share of energy consumption from renewable sources;
- +36% improvement in energy efficiency on final energy consumption (39% in primary energy consumption).

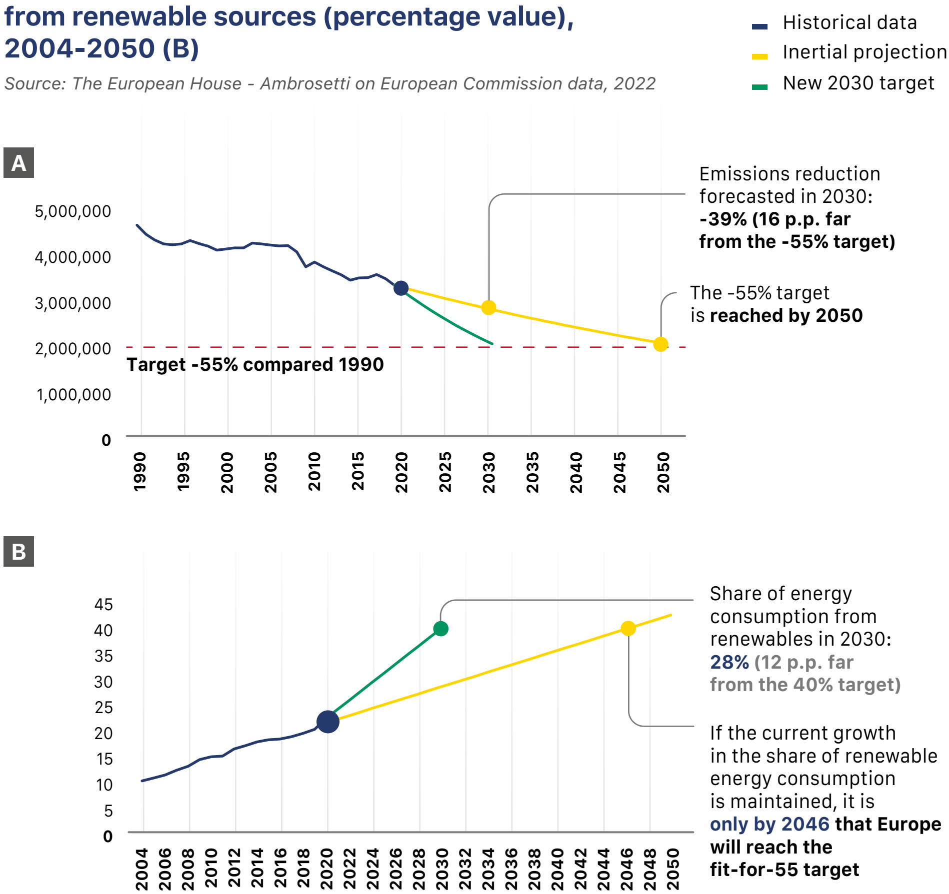
The Fit for 55 acts by reforming existing regulations to achieve the established targets. Among other measures, the plan is focused on the Emissions Trading System (ETS) and the Effort Sharing Regulation (ESR), which were established in 2005 to decrease the level of GHG emissions in the European Union. ETS works on a «cap and trade» principle to reduce GHG emissions in electricity and heat production, energy-intensive industrial sectors, aviation and maritime transport (from 2023), building and road transport (from 2025). The revised reduction target is -61% GHG emissions from the 2005 level (previously -43%). ESR regulates all sectors not covered by the ETS or land use legislation to decrease GHG emissions in transport (except aviation and international maritime transport), construction, agriculture, industrial plants (less energy intensive sectors), and waste. The revised reduction target is -40% GHG emissions from the 2005 level (previously -29%).[4]

This new legislation is necessary to push forward efforts from member states to achieve the net zero emissions target: **with the current trend, the target of zero emissions and increase of renewable consumption will not be reached by 2050.**[5]

Figure 3

Climate-changing gas emissions in Europe (Mtons CO_2eq), 1990 - 2019 and policy scenarios (A) and European share of energy consumption from renewable sources (percentage value), 2004-2050 (B)

Source: The European House - Ambrosetti on European Commission data, 2022



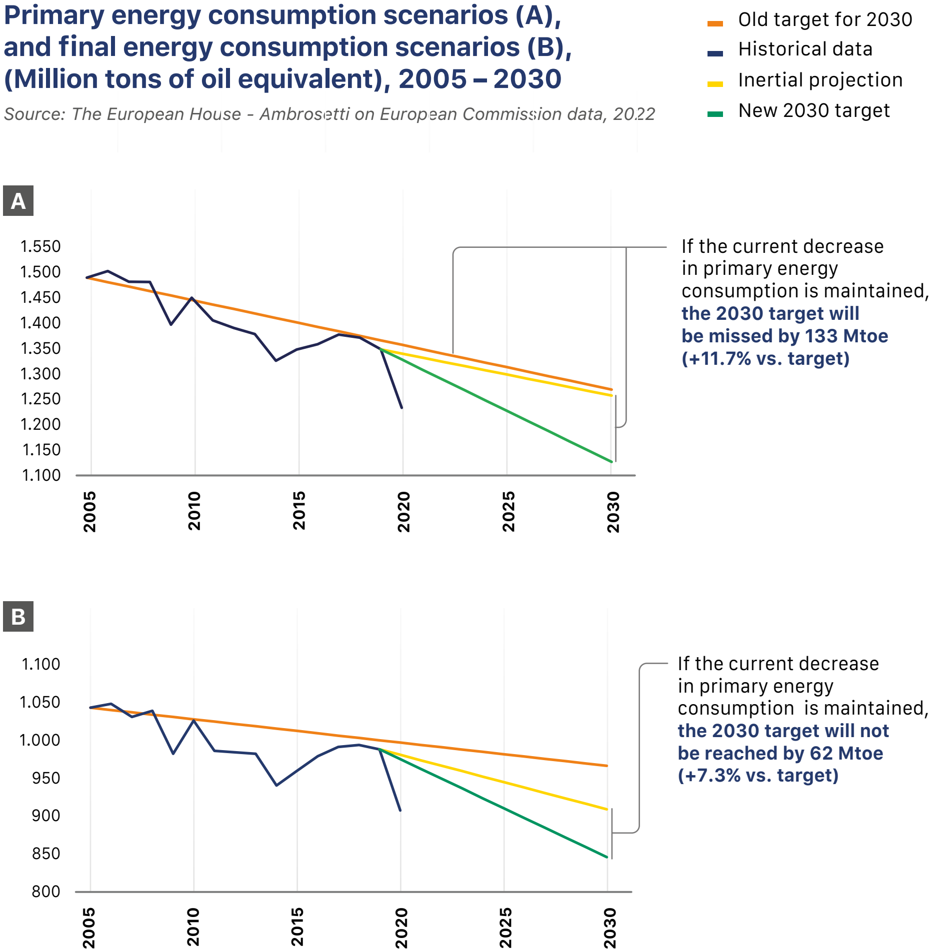
4 *Source: The European House - Ambrosetti on European Commission data, 2022.*
5 *Source: elaboration The European House - Ambrosetti on European Commission data, 2022.*

With respects to the 40% share of energy consumption from renewable sources objective, at the current growth rate of the share of renewables, Europe will miss the Fit for 55 targets set in 2030. From 2004 to 2020 the share of renewable energy consumption has more than doubled (from 9% to 22%). To reach the target share of 40% for 2030, an increase of 18 percentage points it is needed, given that, if the current growth in the share of renewable energy consumption is maintained, it is only by 2046 that Europe will reach the fit-for-55 target.[6]

Figure 4

Primary energy consumption scenarios (A), and final energy consumption scenarios (B), (Million tons of oil equivalent), 2005 – 2030

Source: The European House - Ambrosetti on European Commission data, 2022



6 *Source: The European House - Ambrosetti on Eurostat and European commission data, 2022.*

With respects to the energy efficiency improvement target, if the current rate of reduction is maintained, Europe will miss the 2030 -39% target in primary energy consumption by 133 million tons of oil equivalent (Mtoe). Similarly, the 2030 -36% target in final energy consumption will be missed by 62 Mtoe.[7]

Together with sustainability, **two other elements shall be considered in order to ensure secure, resilient and competitive access to energy: energy and technological dependence as well as system adequacy and flexibility**.

The European energy dependency[8] has increased for most fuels since the 1990 levels, especially solid fossil fuels (+91%) and natural gas (+61%). The increase in natural gas as a primary source of energy is reflected in the EU's high dependency ratio: 84% of natural gas consumed is imported.[9] **Technological dependence must be considered on a par with energy dependence: batteries, fuels cell, solar and wind technologies draw essential elements from a value chain that is considered "high risk"** from the European Commission, which has identified 137 product categories out of a total of 5,000 in which the EU is strategically dependent, divided in three clusters:

- Raw materials: includes beryllium, cobalt, antimony, lithium, aluminium, manganese, chromium, nickel, tungsten, molybdenum, etc.;
- Health products: includes personal protective equipment, antibiotics, vitamins, hormones, heterocyclic organic compound;
- Renewables and digital products.

The risks associated with global competition for access to resources is evolving very rapidly.

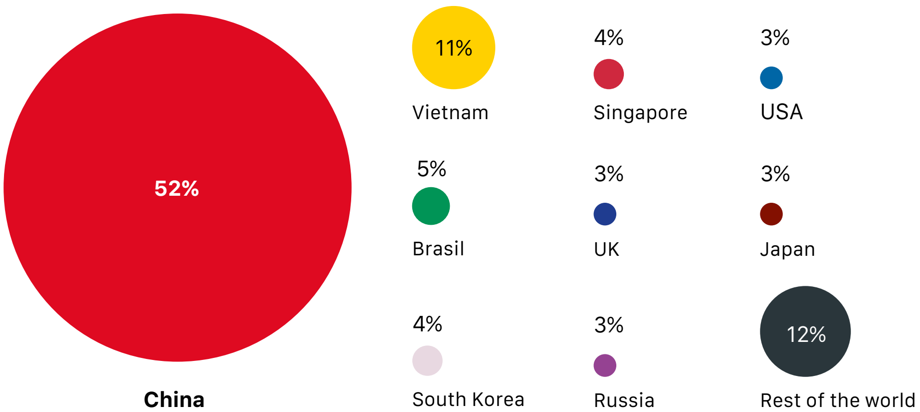
52% out of 137 product categories is imported from China, which is the main country of origin on which the European Union depends. The USA, on the other hand, is residual, with only 3%.[10]

7 *Ibid.*
8 *Energy dependency is calculated as the share of energy that an economy must import, defined as net energy imports divided by gross available energy.*
9 *Source: The European House - Ambrosetti on Eurostat data, 2022.*
10 *Source: The European House - Ambrosetti on European commission data, 2022.*

Figure 5

Country of origin of dependency (percentage of total), 2019

Source: The European House - Ambrosetti on European Commission data, 2022



Batteries, fuel cells, wind and solar technologies are highly dependent on rare earths and other imported raw materials, which are crucial to enable the energy transition: in this scenario, **the EU might not meet the demand for wind and solar energy and electric vehicles, as the current global yearly supply of key raw materials is likely to be scarce**. In particular, the supply of 4 critical raw materials will likely be insufficient compared to the projected demand: dysprosium, praseodymium, neodymium and lithium – with an estimated total gap of over 53,000 tons in 2030.

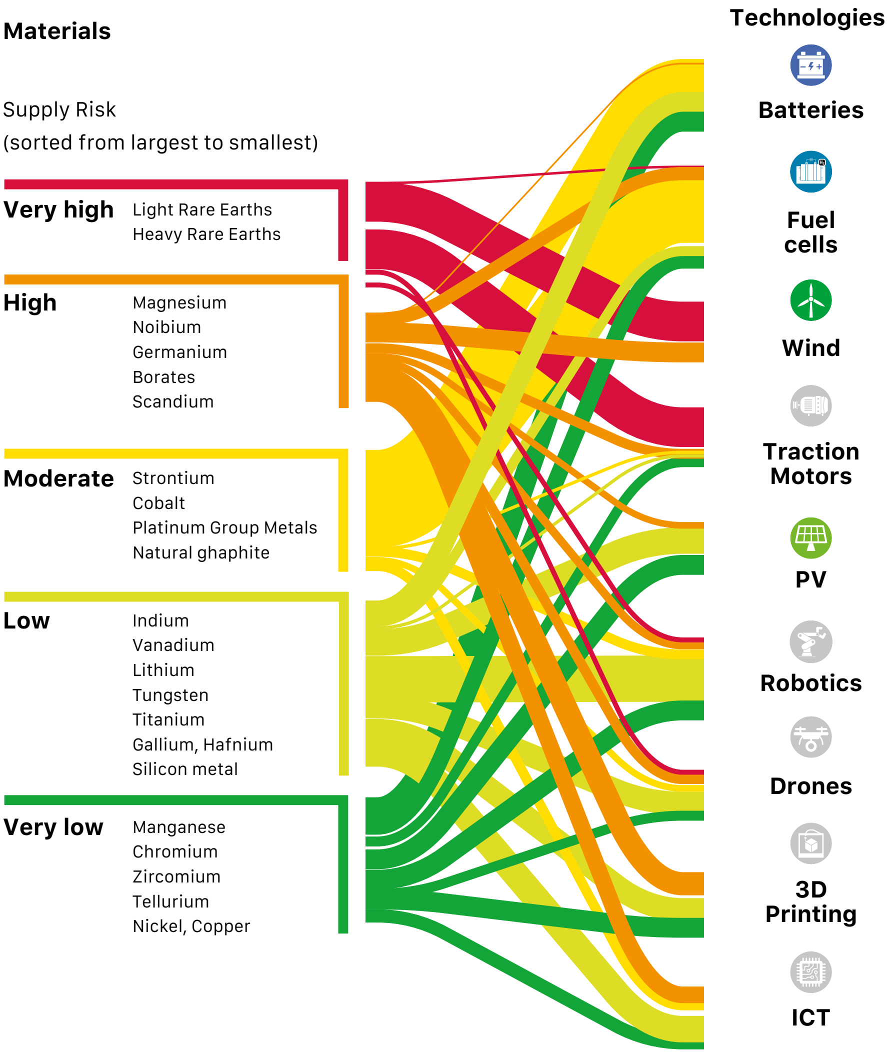
Since 2011, the European Commission has assessed a 3-year list of Critical Raw Materials (CRMs) within its Raw Materials Initiative adopted in 2008. To date, **14 CRMs were identified in 2011, 20 in 2014, 27 in 2017 and 30 in 2020**. In September 2020, along with the 4th list of Critical Raw Materials, **the EU presented the Action Plan on Critical Raw Materials, aimed at concretely developing resilient value chains for EU industrial ecosystems, reducing dependency, strengthening domestic sourcing and diversifying sourcing from third countries**. In its resolution of November 2021, the European Parliament called for an EU strategy to boost Europe's strategic autonomy and resilience regarding the supply of CRMs.

Additionally, the Versailles Declaration published in March 2022 following an Informal meeting of the Heads of State or Government, contains an explicit mention of CRMs: "*We will secure EU supply by means of strategic* *partnerships, exploring strategic stockpiling and promoting a circular economy and resource efficiency*". Finally, as mentioned in the RePower EU plan published in May 2022, the Commission will intensify work on the supply of critical raw materials and prepare a legislative proposal.[11]

Figure 6

Critical raw materials supply chain risk and impacted sectors

Source: The European House - Ambrosetti on European Commission data, 2022



11 *Source: elaboration by The European House - Ambrosetti on Versailles Declaration (2022), 2022.*

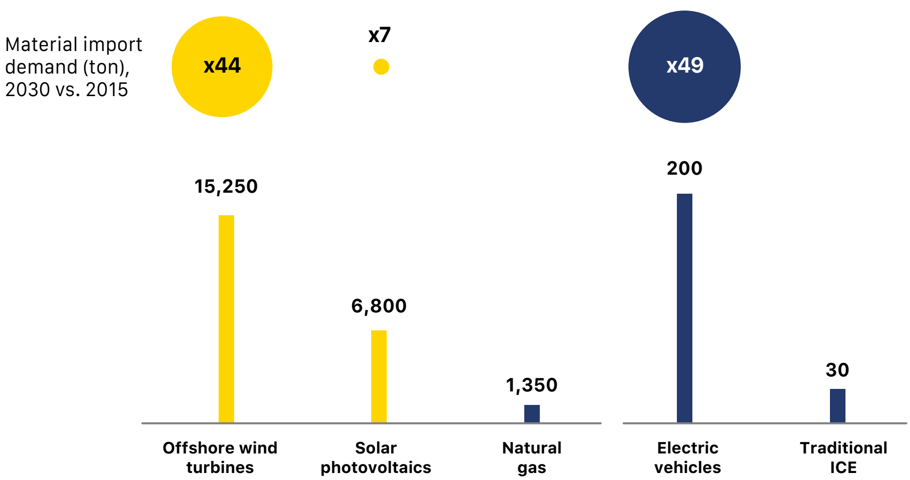
The very high dependency might jeopardise the energy transition and eventually the achievement of the Union's climate objectives, especially when comparing the imported raw materials exploited in renewables and electric vehicles with respects to traditional technologies. The materials required by offshore wind turbines (15,250 kg/MW) are 11.3 times the amount required by natural gas (1,350 kg/MW). Similarly, the amount required by electric vehicles (200 kg/vehicle) is 6.7 times the amount required by traditional vehicles (30 kg/vehicle). This issue becomes even more pressing when considering the fact that material demand is expected to increase dramatically; in 2030, wind power material demand is expected to increase by 44 times, solar photovoltaic demand by 7 times and electric vehicles demand by 49 times, considering 2015 demand as the initial level.

Another issue that should not be neglected is social acceptance for new mining projects in the EU, which could jeopardise efforts to increase primary production at home to offset imports. As a result, boosting circular economy initiatives in the raw materials value chain could represent both a mitigating factor as well as a market opportunity.

Figure 7

Materials exploited in renewables and fossil fuels (kg/MW), and Materials exploited in electric and traditional Internal Combustion Engine (ICE) vehicles (kg/vehicle), 2022

Source: The European House - Ambrosetti on European Commission data, 2022

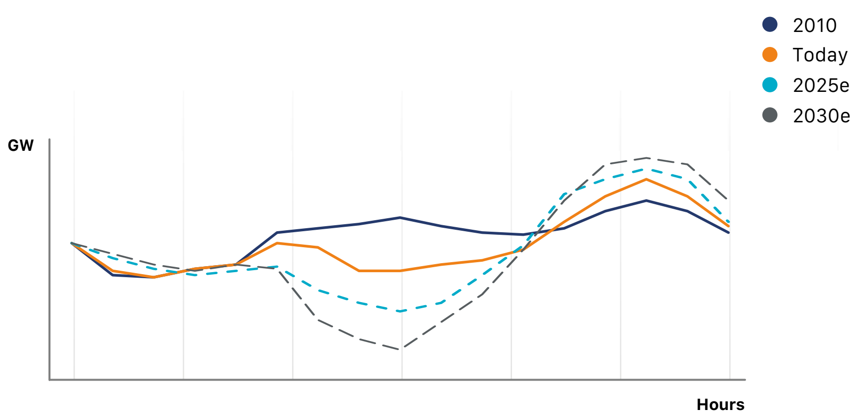


Additionally, **system adequacy and energy flexibility are required due to the increase of energy production from non-programmable renewable energy sources:** a relevant change in demand pattern driven by the deployment of decentralised renewable energy sources generation is expected. The future scenario is likely to see high ramp up in energy demand due to overlaps with shortages in power generation. These variations can be observed on a daily basis, for instance due to the decrease in photovoltaic solar generation during the day, but also over the year, for example droughts during summers compromise hydroelectricity production. In this setting, energy flexibility becomes crucial for maintaining energy security and ensure stability of supply on a daily basis and throughout the year.[12]

Figure 8

Net hourly energy demand within a representative day (GW), 2010 vs. today, vs. 2025e, vs. 2030e

Source: The European House - Ambrosetti on market data, 2022



These issues need to be addressed with the introduction of new energy technologies: in the European Union, by 2050, **coal and oil phase-outs and climate change impacts on water availability – hence, hydropower – will likely lead to a reduction in the flexibility provided by traditional sources.** As of 2020, fossil fuels and nuclear represent 64% of energy system flexibily; their overall contribution is expected to decrease to 6%

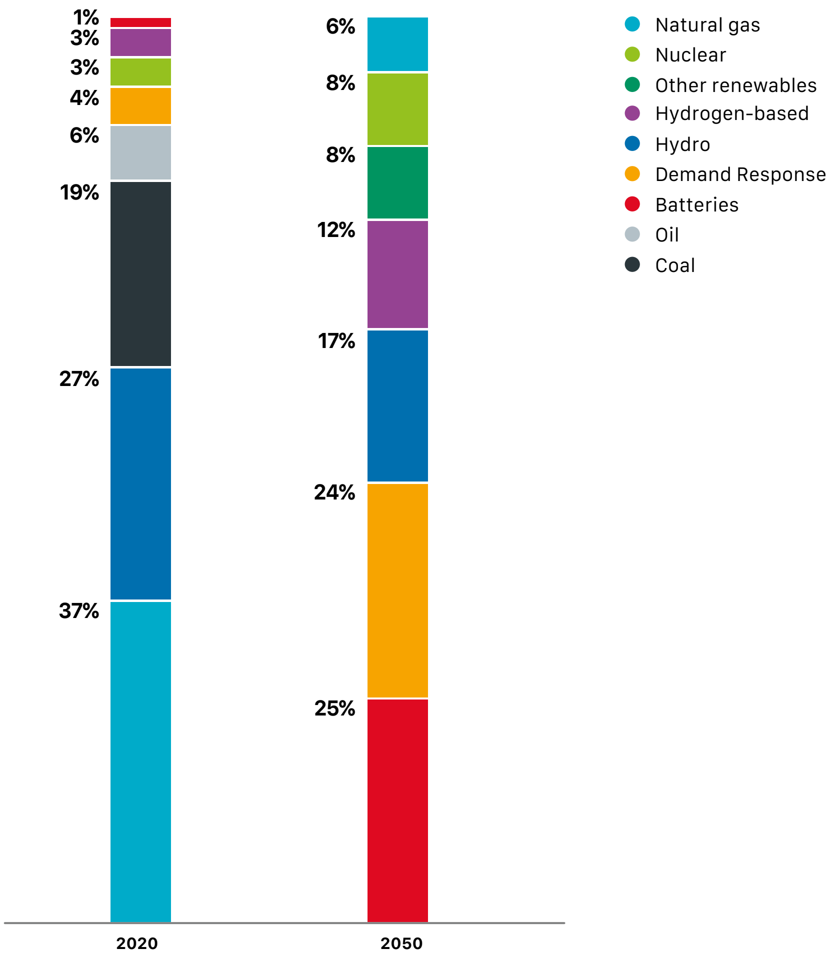
12 *Source: The European House - Ambrosetti on market data, 2022.*

in 2050. In this sense, storage technologies, such as batteries, and demand response measures[13] will be crucial: together they will provide 49% of system flexibility in 2050.[14]

Figure 9

Global electricity system flexibility by source, 2020 and 2050 in the Net Zero Scenario (%), 2020 and 2050

Source: The European House - Ambrosetti on market data, 2022



13 *Changes in electricity use on the demand side in response to changes in price/supply.*
14 *Source: The European House - Ambrosetti on IEA data, 2022.*

1.3 The requirements for a sustainable, affordable, secure and resilient energy system

Key message #2

All net zero emissions scenarios and the main long-term strategies of European Member States agree on the need to leverage a plurality of technologies to achieve the international target of limiting global warming to below 1.5°C compared to pre-industrial levels.

According to the International Energy Agency (IEA), alongside an increasing use of renewable electricity, carbon capture, utilisation & storage (CCUS), carbon dioxide removal (CDR), hydrogen and biofuels are key technologies to achieve full decarbonisation. In the 2050 scenario forecast, electric and heat renewables supply 48% of total energy, biofuels account for 19% of final energy supply, and nuclear for 11%; fossil fuels (solid and liquid fuels as well as natural gas) still make up 22% of the global supply – equal to 543 Exajoules.

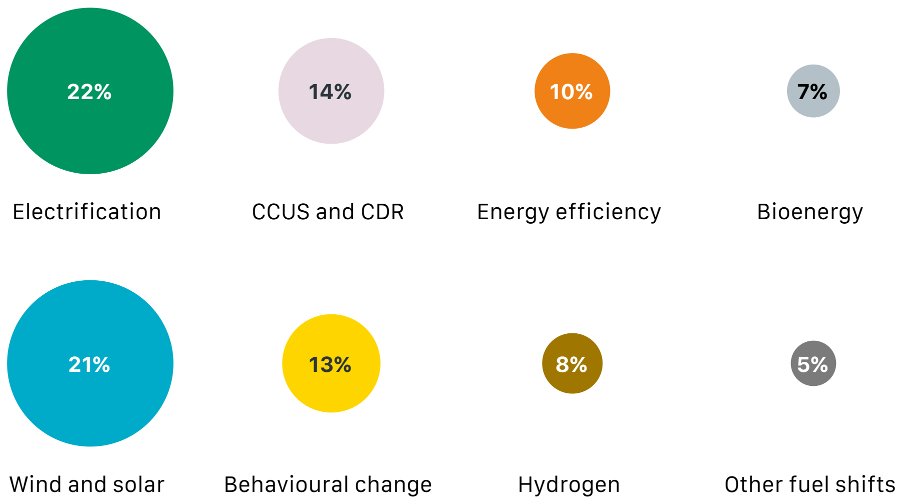
In order to go from 33.9 Gton of CO_2eq emitted globally in 2020, to 21.1 Gton in 2030 and, finally, to net zero emissions in 2050, renewable energies and electrification have a crucial role – together, they contribute to 43% of emission reduction, **but they must be exploited synergically with other technologies and a behavioural change**; for instance, CCUS and CDR's contribution amounts to 14%.[15]

15 *Source: The European House - Ambrosetti on IEA data, 2022.*

Figure 10

Share of contribution of each mitigation measure in the NZE 2050 scenario (% of total emission reduction), 2020-2050

Source: The European House - Ambrosetti on IEA data, 2022



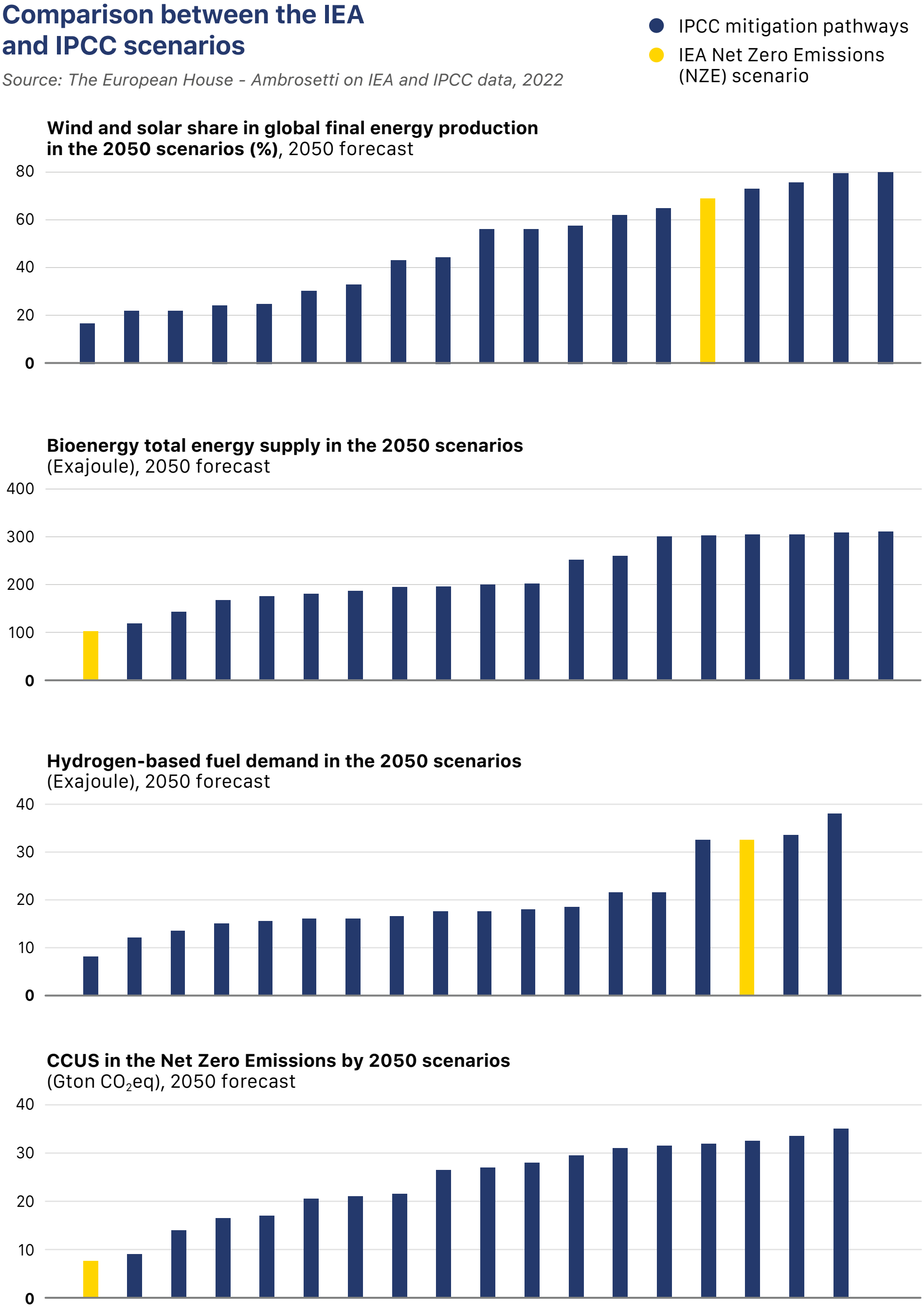
Considering other studies, the IPCC has foreseen 90 different scenarios, the so-called "mitigation pathways" where the contribution of each component differs, but all scenarios have at least a 50% chance of limiting global warming to 1.5°C above pre-industrial levels in 2100. This implies reaching net zero CO_2 emissions globally around 2050, hence the IPCC and IEA scenarios are comparable. Only 18 of these scenarios foresee a 2050 net zero CO_2 emissions from the energy sector and industrial processes, and they can be compared with IEA's scenarios for different technologies.

With respects to the IPCC mitigation pathways, the IEA net zero emissions scenario tends to attribute a large share (69%) to wind and solar in the global final energy production. Similarly, it tends to be more optimistic about the supply of hydrogen-based fuel. Instead, the IEA scenario is more conservative about bioenergy production and the deployment of CCUS.

Figure 11

Comparison between the IEA and IPCC scenarios

Source: The European House - Ambrosetti on IEA and IPCC data, 2022



Focusing on the European case, within the scope of the European Long Term Strategy, multiple national plans rely on CDR and CCUS to achieve the net zero emissions by 2050 target:

- The Italian plan foresees the persistence of 50Mton CO_2eq with a potential limited offsetting of domestic forestation and land use in 2050. It cites the possibility to have a CCUS contribute of about 20-40 Mtons per annum (corresponding to 10.5% of total emissions generated in 2018 - baseline of the long-term strategy analysis) but without a detailed implementation plan;
- According to the Spanish plan, CCUS and CDR are expected to absorb 37 Mtons CO_2eq in 2050, corresponding to 14% of total emissions generated in 2020 (baseline of the long-term strategy analysis);
- In the French plan CCUS and CDR are expected to absorb 95 Mtons CO_2eq in 2050 corresponding to 23% of total emissions generated in 2014 (baseline of the long-term strategy analysis).[16]

Instead, with respects to biofuels, the analyzed plans consider the following scenarios:

- Italy – In 2050, fossil fuel consumption will decrease by 96% on average with respects to 2018 levels, while non-electric renewables will increase by 170% to achieve a total share in energy supply of 33%. Even if not specified, this should include biofuels;
- Spain – In 2050, fossil fuel consumption will decrease by 93% on average with respects to 2020 levels, while biofuels will increase by 133% to achieve a total share in energy supply of 11%;
- France – In 2050, fossil fuel consumption will decrease by 72% on average with respects to 2020 levels, while biofuels will increase by 171% to achieve a total share in energy supply of 23%.[17]

By analyzing the decarbonisation pathways under a different lense, a 2020 Irish study published on Applied Energy Journal by the Environmental Research Institute and School of Engineering of Cork University, has demonstrated that **biofuels, CCUS and CDR are required to achieve the decarbonisation target and to lower the marginal costs to reach such goal.** If biofuels are not taken into consideration, it is unfeasible to reduce emissions by more than 83%. Additionally, if CCS technologies are not applied, the marginal costs can be extremely high (4,237 € per ton of CO_2e if CCS is not applied and 12,232 € per ton of CO_2e if CCS and biofuels are not applied).[18]

16 *Source: The European House - Ambrosetti on National Energy and Climate Plans and National Recovery and Resilience Plans data, 2022.*
17 *Ibid.*
18 *Source: "Identifying Decarbonisation Opportunities Using Marginal Abatement Cost Curves And Energy System Scenario Ensembles", Xiufeng Yue et Al., Environmental Research Institute and School of Engineering, University College Cork (2020), 2022.*

Figure 12

Marginal Abatement Cost in different technology scenarios

Source: The European House - Ambrosetti on academic paper "Identifying Decarbonisation Opportunities Using Marginal Abatement Cost Curves And Energy System Scenario Ensembles", Environmental Research Institute and School of Engineering, University College Cork (2020), 2022

Marginal abatment cost at different stage of decarbonisation (€ / ton CO_2)

	20%	40%	60%	80%	>95%
Reference scenario: international bioenergy imports and CCS are available	106	154	240	513	2.759
No bio scenario: international bioenergy imports are not available	104	156	400	816	**Infeseasible beyond 83%**
No CCS: assumes that CCS technologies are not applied	106	154	240	550	4.237
NO CCS & BIO: both bioenergy imports and CCS technologies are not available	104	156	780	12.232	**Infeseasible beyond 83%**
+ BEECS:* alongside bio and CCS also CDR is available	106	154	240	513	641

* *The study refers to Bioenergy with CCS technologies*

1.4 CO_2 emissions breakdown

Key message #3

The most strategic and effective way to address decarbonisation is by working on both energy and non-energy emissions, with a focus on Hard to Abate industries, power generation and heavy transports.

A comprehensive analysis of emissions at the European level was carried out, including both emissions from fuel combustion and emissions from other non-energy processes, in order to assess the results achieved in terms of energy efficiency and sustainability of energy consumption and identify proper future decarbonisation levers. Notably, the analyses consider the time span from 1990 to 2019 to exclude Covid-19 effects.

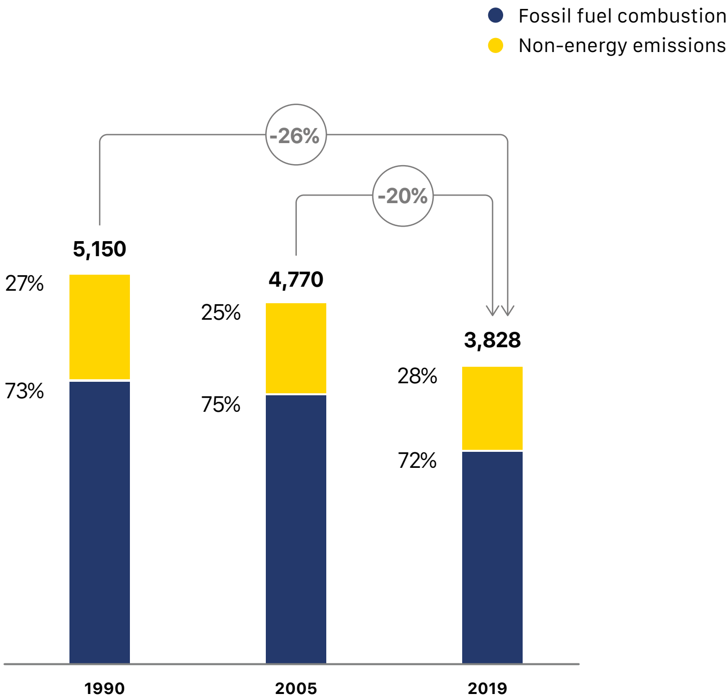
In Europe, 72% – 2.8 Million tons of CO_2 (Mton CO_2e) – of current CO_2 emissions are generated by the combustion of fossil fuels: this is the most significant component, but it is not the only one: **industrial and other emitting processes account for 28% – 1.1 Mton CO_2e – of emissions.** Emissions from the two components together have decreased by 26% between 1990 and 2019.[19]

19 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

Figure 13

Share of GHG emissions from different source sectors in Europe (% and Mton), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



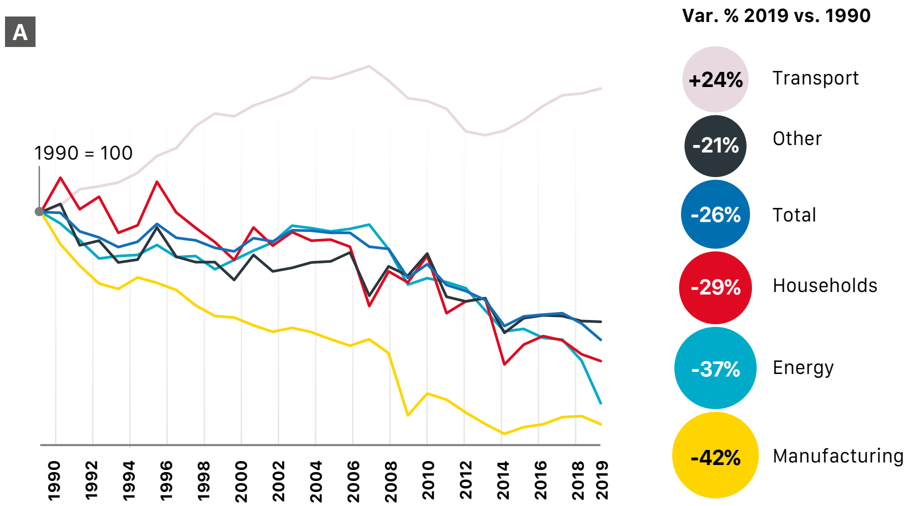
The European emissions from fuel combustion are mainly driven by energy industries (34% – 900 Mton CO_2e), transports (32% – 835 Mton CO_2eq), and manufacturing (14% – 377 Mton CO_2e; together, they account for 80% of GHG from fuel combustion. Notably, emissions from energy industries have decreased by 37% and those from manufacturing by 42% since 1990, whereas transport is the only sector that has increased emissions since 1990 (+24%).[20]

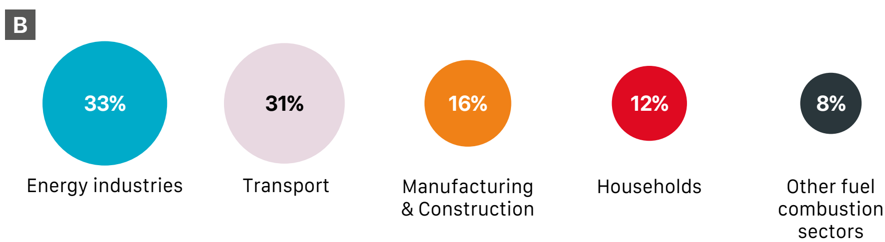
20 *Ibid.*

Figure 14

Evolution of GHG emissions by fuel combustion by source sector in Europe (%, 1990=100), 1990-2019 (A), and share of GHG emissions from fuel combustion by source sectors in Europe (%), 2019 (B)

Source: The European House - Ambrosetti on Eurostat data, 2022





Instead, non-energy GHG emissions are associated to three main sectors, namely agriculture and livestock, industrial processes and waste management:

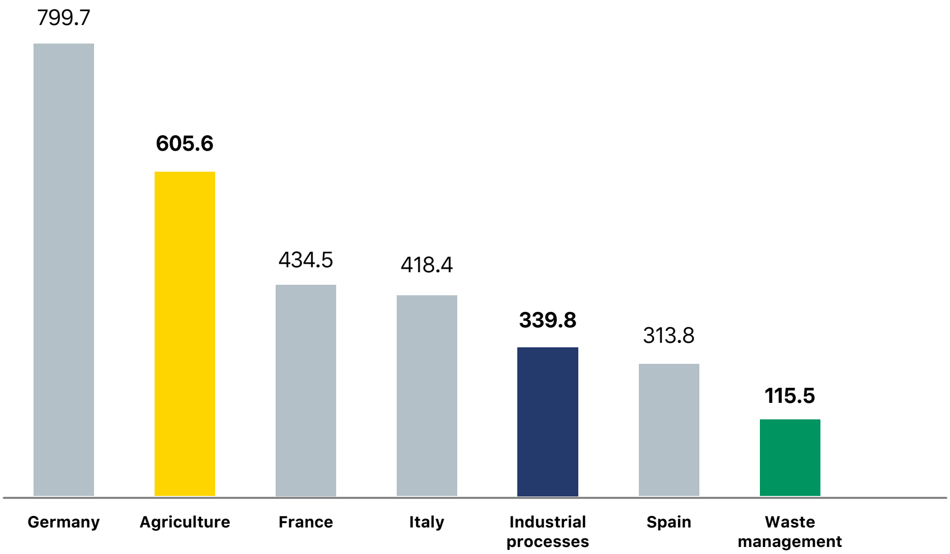
- In agriculture and livestock, non-energy emissions are generated by enteric fermentation, manure management, field burning, and soil fertilization;
- In industrial processes, non-energy emissions are generated by chemical reactions occurring during the production process, especially in steel and concrete manufacturing;
- In waste management, non-energy emissions are generated by biomass and waste disposal or incineration, as well as wastewater treatment.

To give a sense of the scale, **GHG emissions from these sectors are larger than those of most countries, both at European level and worldwide**. For instance, Germany is the only reference country in the European Union whose annual emissions (799.7 Mton CO_2e in 2019) are larger than the yearly non-process agricultural emissions in the European union (605.6 Mton CO_2e in 2019). Non-energy emissions reached 339.8 Mton CO_2e in industrial processes and 115.5 Mton CO_2e in waste management. At a global scale, China (12.06 Gton CO_2e in 2019) is the only country with annual GHG emissions higher than the whole global agriculture non-energy emissions (6.97 Gton CO_2e in 2019). Global non-energy emissions reached 3.06 Gton CO_2eq in industrial processes and 1.70 Gton CO_2e in waste management.[21]

Figure 15

European non-energy GHG emissions from different sources vs. total GHG emission in larger Member States (Mton CO_2e), 2019

Source: The European House - Ambrosetti on literature review, 2022



21 *Source: The European House - Ambrosetti on CAIT data, 2022.*

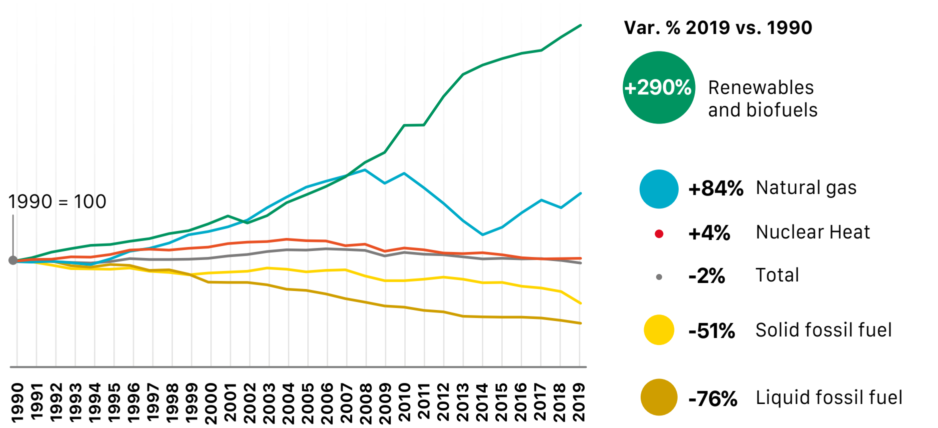
Emissions from energy industries

In the energy industry, fuel combustion in the production of electricity and heat is the main driver of emissions, accounting for 84% of total emissions from this sector (760 Mton CO_2e in 2019). Compared to 1990, emissions from fuel combustion have decreased by 37%, mainly thanks to a shift in the energy sources: nowadays, electricity production relies more on renewables and natural gas, and less on fossil fuels.[22]

Figure 16

Evolution of the public electricity and heat generation process by source in Europe, (1900=100 and Var. %), 1990-2019

Source: The European House - Ambrosetti on Eurostat data, 2022.



In the last 30 years there has been a significant shift in the share of sources due to the growth of renewables and biofuels (+290% since 1990), which accounted for 35% of gross public electricity and heat production in 2019, the largest share among all sources.[23]

Although an increase in the share of renewables is expected, **fossil fuels will still be required to guarantee electric system adequacy and flexibility in Europe, according to the IEA scenarios**. Even in the best case scenario (Announced Pledge), 14.7% of electricity will be supplied by non-renewables in 2030, and this share is expected to drop to 2.1% in 2050.[24]

22 *Source: The European House - Ambrosetti on Eurostat data, 2022.*
23 *Ibid.*
24 *Source: The European House - Ambrosetti on report «World Energy Outlook», IEA, 2022.*

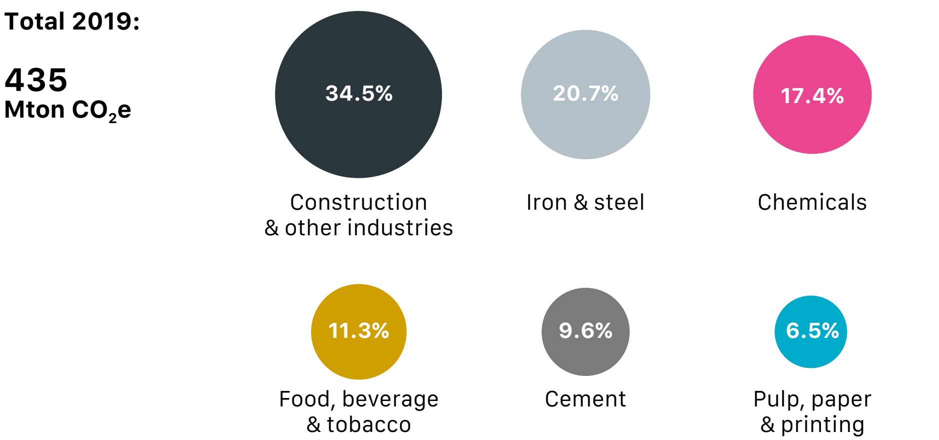
Emissions from fuel combustion and industrial processes in the manufacturing and construction sector

The manufacturing and constructions sectors have reduced their CO_2 emissions by 41.5% since 1990, a change driven by the 51% emission reduction of constructions and other residual manufacturing sectors. **Energy-intensive industries are struggling, as their CO_2 reduction is less pronounced than the construction sector** – on average, emissions decreased by 30% between 1990 and 2019. In 2019, **metals, non-metallic minerals & chemical industries made up 49.4% of all industrial GHG emissions by fuel combustion.**[25]

Figure 17

Share of GHG emissions from fuel combustion by manufacturing source sector in Europe (%), 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



Although reducing energy-related emissions generated by fuel combustion is crucial to decarbonise the manufacturing and construction sector, there is another set of emissions equally as relevant that must be addressed: emissions arising from industrial processes.

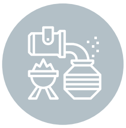
In the iron and steel sector, process emissions arise from the chemical reactions occurring during the extraction of iron metal from iron ore (2-stage production process).

25 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

Figure 18

Process emissions generation in the iron and steel sector

Source: The European House - Ambrosetti on various data, 2022.



CO_2 emissions in iron and steel manifacturing arise from

- **Fossil fuel combustion**
- **Chemical reactions** occurring during the extraction of iron metal from iron ore (2-stage production process)

1. Ironmaking process

A blast furnace is filled with hematite (Fe_2O_3), coke, pure solid carbon (C), and hot air containing molecular oxygen gas (O_2) is forced up the bottom of the blast furnace. It generates carbon monoxide (CO) and heat:

$$2C + O_2 = 2CO + heat$$

At high temperatures (2,550°C), the Fe_2O_3 reacts with CO and coke to produce molten iron and CO_2:

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2$$

The limestone ($CaCO_3$) heats up and thermally decomposes to quicklime (CaO) and CO_2:

$$CaCO_3 + heat = CaO + CO_2$$

2. Steelmaking process

In **primary steelmaking, new molten iron** is mixed with scrap steel and placed in a **basic oxygen furnace**. Oxygen is then blown through the furnace and reacts with carbon to form **CO_2**:

$$C + O_2 = CO_2$$

With **secondary steelmaking**, **recycled scrap steel** is melted in an **electric arc furnace**. O_2 is blown through the metal to remove carbon and accelerate the meltdown:

$$C + O_2 = CO_2$$

In the chemical sector, process emissions are associated to the chemical reaction generated from the transformation of input materials (Hydrocarbon feedstock, biomass, oleochemicals etc.) into final products (plastics, fibers and solvents).

Figure 19

Process emissions generation in the chemical sector

Source: The European House - Ambrosetti on various data, 2022

CO_2 emissions in the chemical industry arise from

- **Fossil fuel combustion** for energy use
- **Chemical reactions** of the production process

Chemical sector process

Differently from the iron, steel and concrete sectors, the chemical industry is associated to multiple production processes (high value chemicals, ammonia, methanol and carbon black). The main production process responsible for CO_2 emissions can be summarized as follows.

Hydrocarbon feedstock
Hydrocarbon energy
Intermediates
Oleochemicals
Biomass
Oxygen,nitrogen, chlorine
Surfactants
Solvents
Synthetic rubber
Fibers
Plastics

In the cement sector, process emissions are generated from chemical reactions occurring during the production process, such as calcination of limestone in cement production.

Figure 20

Process emissions generation in the cement sector

Source: The European House - Ambrosetti on various data, 2022

CO_2 emissions in concrete manufacturing arise from

- **Fossil fuel combustion** for energy use
- **Chemical reactions** occurring during the production process, such as calcination of limestone in cement production

Cement manufacturing process

Concrete is a mixture of aggregates (sand, gravel, and crushed stones) and a paste (water and Portland cement). Most emissions in concrete production are associated to the cement manufacturing step. All the aggregates containing calcium carbonate are mixed with clay at high temperatures (1,500°C). The CO_2 emitted during the cement manifacturing process originates from calcium carbonate

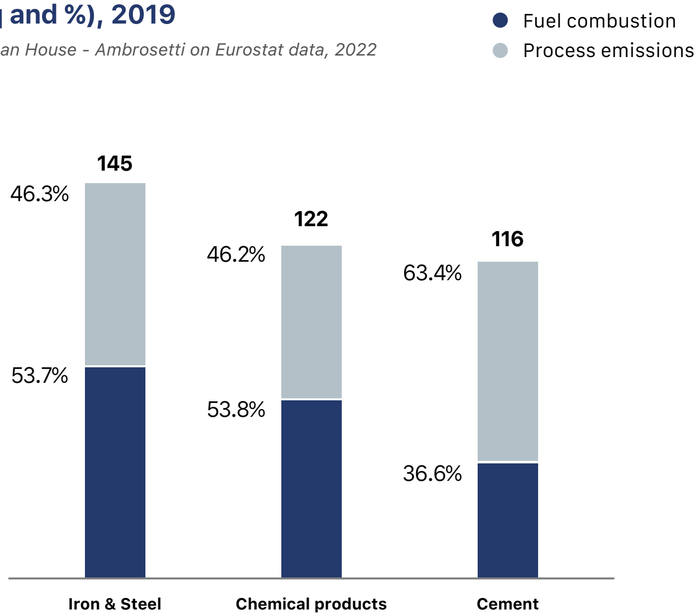
$$CaCO_3 + heat + clay = Clinker\ (SiO_2, Fe_2O_3, Al_2O_3, CaO) + CO_2$$

On average, 52% of total emissions in these three sectors are generated from processes. Cement production has the highest share of process emissions – 63%. These types of emissions cannot be addressed in a "traditional" way, hence through electrification and substitution of fossil fuels with renewables. **There are three sets of measures that can be exploited to reduce process emissions: circular economy measures**, such as exploiting renewable feedstock for chemical processes; **CCUS and CDR to capture process emissions and eventually offset them; switch from fossil fuels exploited for the production process itself** (not for energy consumption), such as use of biomass or hydrogen as reducent in the steel-making process.[26]

Figure 21

GHG Emissions by fuel combustion and industrial processes in the most emitting sectors in Europe (Mton CO_2eq and %), 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



26 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

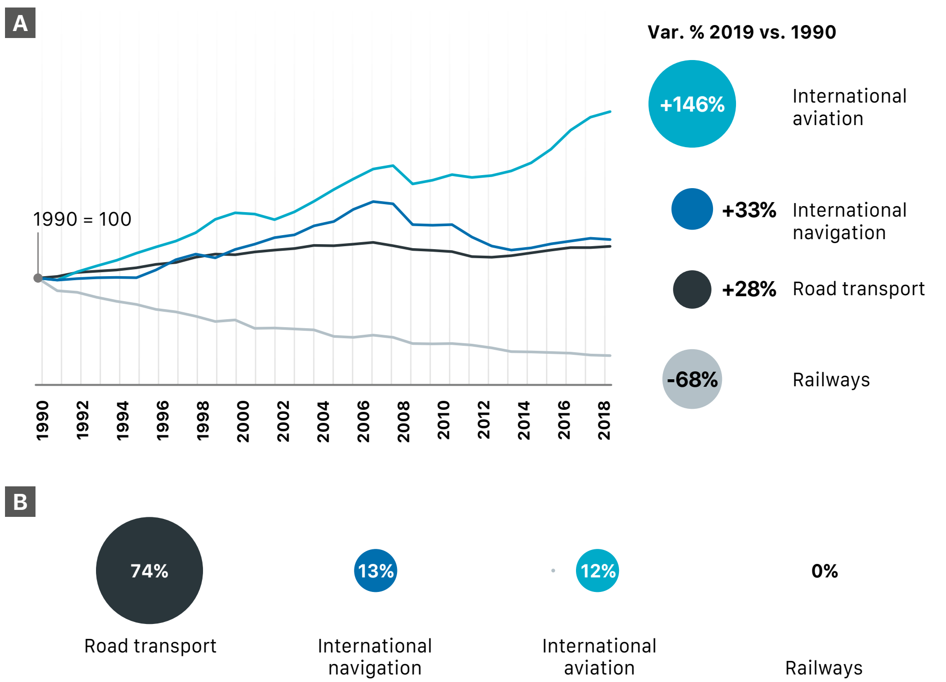
Emissions from the transports sector

In the transport sector, the combustion of fuel in road vehicles is the main driver of GHG emissions, accounting for 74% of transport emissions in 2019. Railways is the only transport mode whose emissions have declined over time (-68%), while international aviation is the sector with the highest increase since 1990 levels (+146%). Within road transport modes, besides motorbikes, all types of vehicles contributed to the increase in emission levels, with a greater increase for light commercial vehicles (+63% since 1990) and Heavy Duty trucks and buses (+29% since 1990).[27]

Figure 22

GHG Emissions by fuel combustion in the transports sector in Europe (%, 1990=100) 1990-2019 (A) and Share of GHG emissions in transport sectors, in Europe (%), 2019 (B)

Source: The European House - Ambrosetti on Eurostat data, 2022



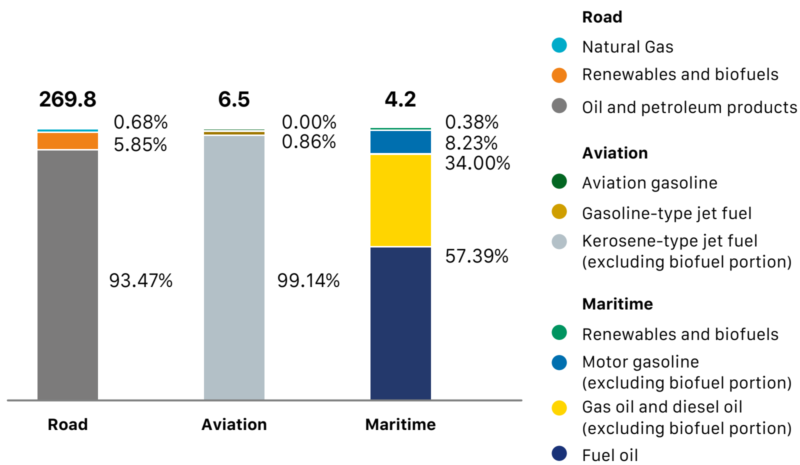
27 *Ibid.*

As of 2019, **road transport still relied on oil and petroleum for more than 93.5% of consumption**, although the share of overall consumption has decreased by almost 7 percentage points since the 1990 levels, mostly thanks to an increase in the share of renewables and biofuels. Similarly, as of 2019, **navigation and aviation relied on fossil fuels for 99.6% and 99.1% of final consumption**, respectively.[28]

Figure 22

Road, Aviation and maritime transports consumptions by source, in Europe (Mtoe and %), 2019

Source: The European House - Ambrosetti on Eurostat data, 2022.



Notably, on the 29th of June 2022, European Environment Ministers approved a **regulation to end the sale of vehicles with Internal Combustion Engines (ICE) in Europe by 2035**, with the aim to reach the target of net zero emissions by 2050. This measure will halt sales of petrol and diesel cars as well as light commercial vehicles and will result in a complete shift to electric engines from 2035 onwards; by then, new vehicles put on the EU market will need to reduce their CO_2 emissions by 100%, with an intermediate objective of 55% for cars and 50% for vans, by 2030. At the request of some countries, especially Germany and Italy, **lawmakers agreed to enable the use of alternative technologies such as synthetic fuels or plug-in hybrids if they can achieve the complete elimination of GHG emissions.**

28 *Ibid.*

The regulation for **Heavy Duty trucks and buses** does not specify the 2050 objectives and does not consider electrification as a requirement yet. As a matter of fact, it is far more **difficult to apply electric technologies in these transport modes due to loss of payload associated to batteries space and weight, range limitations, recharging time and battery life**.[29]

29 *Source: The European House - Ambrosetti on European Commission data, 2022.*

Chapter 2

Technologies for the alternative decarbonisation

2.1 Introduction

The aim of the present chapter is to **support the principle of technology neutrality in European regulations** i.e. the principle according to which products, services or regulatory frameworks should not impose or discriminate against the use of a particular type of technology in order to achieve a specific objective that has been set by the regulator; instead, **the evidence provided by researchers, competition between alternative technologies and other market mechanisms should determine which technologies are the most cost-effective solutions to achieve carbon neutrality**. For instance, an emissions trading system that includes all economic sectors can be considered an example of technologically neutral regulation.[1]

To demonstrate the relevance and sustain the effectiveness of technology neutrality, the chapter is divided in two main parts: first, a map of available and under development technologies to achieve the decarbonisation objectives is presented. In total, **100 technologies relative to five different areas have been mapped**. The second part of the chapter is dedicated to the analysis of the degree of maturity and the technical decarbonisation potential of each technology in different application sectors in the European Union.

Evidence shows that it is necessary to leverage all available and easily attainable technological levers to achieve carbon neutrality, combining, based on the requirements of the economic activity to decarbonise, renewable energies, decarbonised carriers, and CO_2 capture technologies. The 100 decarbonisation technologies identified must be promoted to optimise investments.

Following a technological neutrality approach, The European House - Ambrosetti has identified four technologies with high potential, which should complement renewable energies, energy efficiency and electrification of end uses to accelerate the decarbonisation path of the European Union. First, Carbon Capture Utilization & Storage (CCUS) and Carbon Dioxide Removal (CDR) should be exploited given that they are available, scalable, competitive and their safety has been largely demonstrated. The second technology identified is hydrogen not in competition for access to renewable electric energy, a Carbon Neutral energy carrier with

1 *Source: "Technological Neutrality: A Critical Assessment", Lehmann P. et Al., Helmholtz Center for Environmental Research (2020), 2022.*

enormous potential for decarbonising end-uses. Third, biofuels, whose production is not in competition with food, can be a Carbon Neutral solution to replace traditional fuels while minimizing the necessary changes in consumption systems and supply chains. Lastly, synthetic fuels can be a Carbon Neutral solution to replace traditional fuels while minimising the necessary adjustments in consumption systems for specific Hard to Abate sectors (e.g., aviation) due to the overall low energy efficiency.

2.2 Mapping of available and under development technologies to achieve the decarbonisation objectives

Key message #4

Achieving climate neutrality requires leveraging all possible technological levers, combining, on a case-by-case basis, renewable energies, decarbonised carriers and CO_2 capture technologies. A total of 100 decarbonisation technologies have been identified that need to be promoted in order to optimise investments, following a principle of technological neutrality.

In an aim to identify the optimal combination of these technologies and the requirements for their implementation, The European House - Ambrosetti has developed a model based on five strategic decarbonisation levers:

- First lever: **energy efficiency** is the first, crucial lever that must be considered in order to decrease energy demand while fulfilling societal needs;
- Second lever: **Carbon Neutral energy production** refers to low-carbon energy productions that do not emit greenhouse gases (GHG) or can capture, permanently store or compensate their GHG emissions, namely CCUS applied to fossil fuels, renewables and nuclear technologies;
- Third lever: **production and use of Carbon Neutral energy vectors** namely those vectors that do not emit GHG apart from biogenic emissions,[2] can capture permanently CO_2, or compensate GHG emissions, namely electrification, hydrogen, biofuels and synthetic fuels;
- Fourth lever: **CO_2 emission compensation**, which allows to compensate for unabated emissions by subtracting CO_2 from the atmosphere, namely afforestation, reforestation and engineered Carbon Dioxide Removal. This lever can be implemented synergically with the other options;

2 *Biogenic emissions are those generated from the exploitation of biofuels.*

- Fifth lever: **availability of CO_2 infrastructure**, which refers to all those technologies and infrastructures that enable the capture, transport, use and storage of CO_2, namely non-energy emission capture, CO_2 transport, long term storage in geological sites, short term storage in end-uses materials and utilization in durable materials (e.g., minerals).

These technologies are both complementary and interlinked, given that hydrogen and the CO_2 captured from CCUS applied to fossil fuels and engineered Carbon Dioxide Removal enables the technologies belonging to the CO_2 infrastructure. At the same time, the CO_2 infrastructure provides the input materials required to produce synthetic fuels.

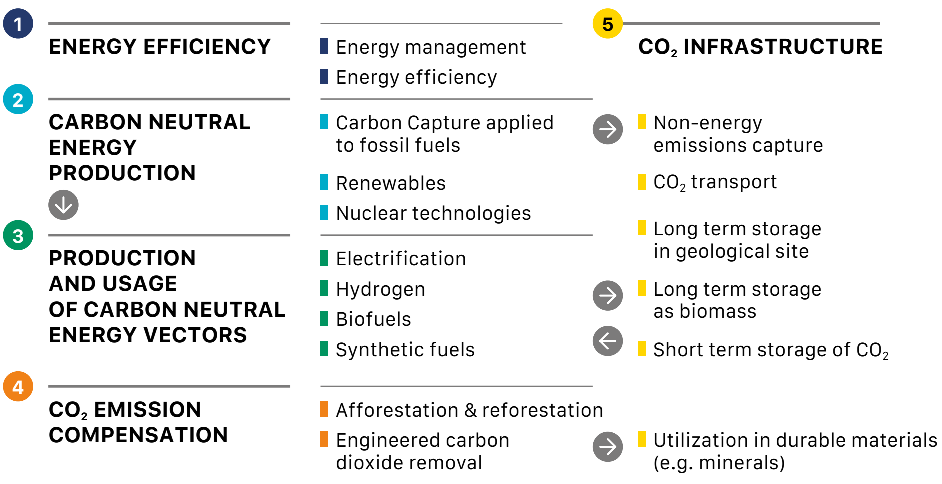
Notably, each lever includes certain technology domains, as summarized in the next figure. In total, seventeen domains were identified, associated to 100 technologies that need to be considered to achieve climate goals.

Figure 1

The technological domains of the five decarbonisation levers

The arrows show the exchange of CO_2 between levers and sub-levers

Source: The European House - Ambrosetti, 2022



The case-by-case, synergic combination of the five levers could enable the carbon neutrality of each economic activity. The application of this principle to whole value chains allows to achieve full decarbonisation under a Life Cycle Assessment perspective. The combination of the five levers needs to be evaluated considering four strategic elements:

- **Origin of GHG emissions**: it is necessary to identify the emitting economic sector as well as the emitting process; for instance, in the manufacturing and construction sector, different infrastructures and technologies are required to decarbonise emissions whether they are generated from fuel combustion or industrial processes;
- **Energetic performance required**: some industrial processes, such as iron and steel require extremely high temperatures;
- **Sources, technology and infrastructure availability**: these differ across sectors and locations;
- **Time horizon**: this is the fourth element to be considered, which is complementary with the three previous ones.

The scenarios presented in the first chapter envisage the need to combine electrification and renewables with other technologies to cover the entire emission spectrum and enable the decarbonisation process. The technology analysis carried out identified a set of five clusters of technologies that can be exploited to achieve the net zero emissions objectives. **The implementation of these five technology domains is envisaged to synergically complement renewable energies, energy efficiency and electrification of end uses to accelerate the decarbonisation path of the European Union**. Each technology offers unique opportunities, which motivate the decision to focus the present study on their potential:

- **Carbon Capture Utilization & Storage – CCUS** is a technology that, as will be seen, is indispensable for cutting emissions that cannot be abated by using Carbon Neutral energy sources and carriers. The use of this technology is also relevant for abating process emissions from various industries;
- **Carbon Dioxide Romoval – CDR** allows CO_2 to be captured from the atmosphere, and therefore offsets emissions that cannot be abated otherwise for technical (e.g., emissions from livestock farming) or economic reasons;
- **Hydrogen** is a carrier that does not emit CO_2 in end-uses and can be produced in a decarbonised manner. It can be exploited where grid-connected or battery-powered electrical technologies cannot be used. Hydrogen is also a feedstock already widely used in industrial processes and can be further exploited as a clean "reductant" in new industrial processes such as steel production;
- **Biofuels**, produced from sources that are **not in competition with food and food chains**, can be very easily integrated into current consumption systems (e.g., means of transport). In addition, they can be considered a sustainable feedstock for chemical and reduction processes to replace fossil fuels;
- **Synthetic fuels**, that similarly to biofuels, can be very easily integrated into existing consumption systems.

CARBON NEUTRAL ENERGY PRODUCTION

Source: elaboration The European House - Ambrosetti, 2022

Technology readiness level
- Low: 1-4
- Intermediate: 5-7
- High: 8-9

FOSSIL FUELS & CCUS / CDR

- **Fossil fuel combustion with CCUS & CDR**

CCS technologies require a CO_2 infrastructure to effectively:

1. **Decarbonise fossil fuel combustion** through **Carbon Capture & Storage**
2. **Offset emissions** through Carbon Dioxide Removal technologies that absorb **CO_2 from the atmosphere**

ELECTRIC & THERMAL RENEWABLES

Electric renewables

- Photovoltaic
- Wind
- Concentrated solar power
- Geothermal
- Hydropower
- Marine

Thermal renewables

- Solar
- Geothermal
- Ocean

NUCLEAR ENERGIES

Fission

- IV Generation reactors

Fusion

- Magneto-inertial fusion
- Hybrid electrostatic confinement
- Inertial confinement
- Non-thermal laser fusion

CO_2 INFRASTRUCTURE

CO_2 INFRASTRUCTURE	CO_2 source	Capture	Transport	Storage
Carbon Capture & Storage CCS is used to decarbonise **Hard to Abate** processes by reducing emissions from **fossil fuels combustion** or **industrial processes**	CO_2 captured directly **from emitting sources** with **artificial techniques**	Physical absorption Chemical absorption Fluidized solid adsorption Polymeric membrane Static solid adsorption Pure oxygen combustion Supercrytical CO_2 cycles	*Depending on distance & distribution* Ship Pipeline Truck	*Depending on distance & availability* Geological sites CO_2 injection & management Simulation of geological storage Monitoring of geological storage
Carbon Removal Captured CO_2 can be used: • To **offset non-abatable** emissions in case of **long-term** storage • To produce **decarbonised** energy **carriers** in case of **short-term** storage	CO_2 captured from **bioenergies production** with **artificial techniques**	Bioenergies with CCS (BECCS)		
	CO_2 captured from the **air** with **artificial techniques**	Direct Air CCS (DACCS)		
	Atmospheric CO_2 captured **naturally** with **Biomasses & silicate rocks**	Afforestation & reforestation	*Not necessary*	*Trees, biomass*
		Biochar	Truck	*Arable fields*

Existing reservoir management know-how is exploited for the geomechanical, hydraulic and chemical modelling of underground reservoirs, in an aim to ensure safety and stability of CO_2 storage

PRODUCTION AND USAGE OF CARBON NEUTRAL ENERGY VECTORS

Technology readiness level
- 🔴 Low: 1-4
- 🟡 Intermediate: 5-7
- 🟢 High: 8-9

CARBON NEUTRAL ELECTRICITY

Vector generation

Electric energy coming from Zero Carbon primary energy source (see dedicated section)

Storage

Battery
- 🟡 Redox flow
- 🟢 Lithium-ion
- 🟢 Solid-state batteries

Mechanical
- 🟢 Flywheel
- 🟢 Pumped
- 🟡 Compressed air energy
- 🟢 Liquid air energy

Thermal
- 🟡 Latent heat
- 🟡 Sensible heat

Chemical
- 🟡 Power to gas
- 🟢 Hydrogen

Electrical
- 🔴 Capacitor
- 🔴 Superconducting magnetics

Transmission, distribution & dispatching

Dispatching
- 🟡 Virtual power plant
- 🟢 Demand-response
- 🟢 Demand-side management
- 🟢 Vehicle to grid

Transmission
- 🟡 Ultra-high voltage
- 🟡 Flexible high-voltage grid
- 🟡 Superconducting high-voltage
- 🟢 Flexible alternating current transmission system
- 🟢 Dynamic line rating

Distribution
- 🟢 Recharging
- 🔴 Transactive energy

Consumption

Transports
- 🟡 Plug-in hybrid
- 🟢 Fuel cell electric
- 🟢 Battery electric

Buildings
- 🟢 Electric heat pumps
- 🟢 Electric boilers

Industry
- 🟢 Electric pump
- 🟢 Direct heating
- 🟢 Induction heating

CARBON NEUTRAL HYDROGEN

Input source	Vector generation
Methane	🟢 Steam methane reforming 🟢 Autothermal reforming 🟢 Partial oxidation 🟡 Methane pyrolysis
Coal	🟢 Gasification of coal
Electricity & water	🟢 Alkaline electrolysis 🟢 Polymer electrolyte membrane 🔴 Microbial electrolysis 🟡 Solid oxide electrolyser cells
Biomass	🟢 Biomass pyrolysis 🔴 Bio-photolysis
Water & solar energy	🔴 Photo-electrochemical
Organic plant & sunlight	🔴 Photosynthesis
Bacteria & sunlight	🔴 Photofermentation
Microalgae & sunlight	🔴 Microalgae photofermentation
Microorganisms	🟡 Dark fermentation
Calcinated iron ore & biomass pyrolysis gas	🟡 Chemical Looping with CCUS

Storage
- 🟢 Salt cavern storage
- 🟢 Storage tank
- 🔴 Depleted oil and gas fields
- 🟡 Liquid organic hydrogen carrier

Transportation
- 🟢 Pipeline
- 🟡 Hydrogen blending in natural gas networks
- 🟡 Liquid hydrogen tanker
- 🟡 Liquid organic hydrogen carrier tanker

Consumption

Buildings and industry:
- 🟢 Pure blended hydrogen-fired technology

Transports sector (Road, rail, maritime shipping, aviation)
- 🟡 Ammonia fuel cell
- 🟡 Hydrogen fuel cell
- 🟡 Hydrogen ICE

CARBON NEUTRAL FUELS

Input source

Biofuels

Biomasses not in competition with food: residual, non-edible oils, agricultural and municipal waste, algae, discarder animal fats and glycerine, microbial processes

Agritech research is necessary to identify additional biomasses not in competition with food for the production of **biofuels**

Synthetic fuels

Carbon Neutral H_2, CO_2 from DACCS or BECCS, Carbon Neutral energy (or alternatively CCUS or CDR)

Vector generation
- 🟢 Hydrotreated Vegetable Oils (HVO) and transesterification
- 🟢 Anaerobic digestion
- 🟡 Gasification
- 🟢 Pyrolisis
- 🟡 Fischer-Tropsch synthesis (FTS) and Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK)
- 🟡 Methanization
- 🟡 Fischer-Tropsch and hydrocraking
- 🟡 Methanol synthesis and methanol to gasoline

Storage, transportation, distribution & consumption

Low-carbon fuels can easily **replace fossil fuels**: they are fully **compatible** with the existing infrastructures for **storage, transportation, distribution, and consumption**.

They can be **used in conventional internal combustion engines** and **jet** engines: regular cars, planes, and ships can be fueled with synthetic fuels without changes or refitting required.

2.2 Analysis of the maturity and technical decarbonisation potential of each technology

Key message #5

Carbon Capture Utilization & Storage (CCUS) and Carbon Dioxide Removal (CDR) are available, scalable, competitive and safe technologies to accelerate the decarbonisation path.

Based on the origin and destination of $CO_{2,}$ there are two main approaches, available with different impacts on GHG abatement potential:

- Carbon Dioxide Removal (CDR) technologies can be used in two ways: in the case of long-term storage, to offset other non-abatable emissions, or to reduce CO_2 concentration in the atmosphere (as foreseen by the IPCC 1.5°C Scenario). In the case of short-term storage, CDR can be exploited for the production of Carbon Neutral carriers;
- Carbon Capture Utilisation & Storage (CCUS) technologies can be used to abate energy GHG emissions from fossil combustion or non-energy processes. Additionally, it can be used to decarbonise power generation and hydrogen production from fossil fuels in order to provide the stability required by an increasing share of non-programmable renewable sources in energy supply.

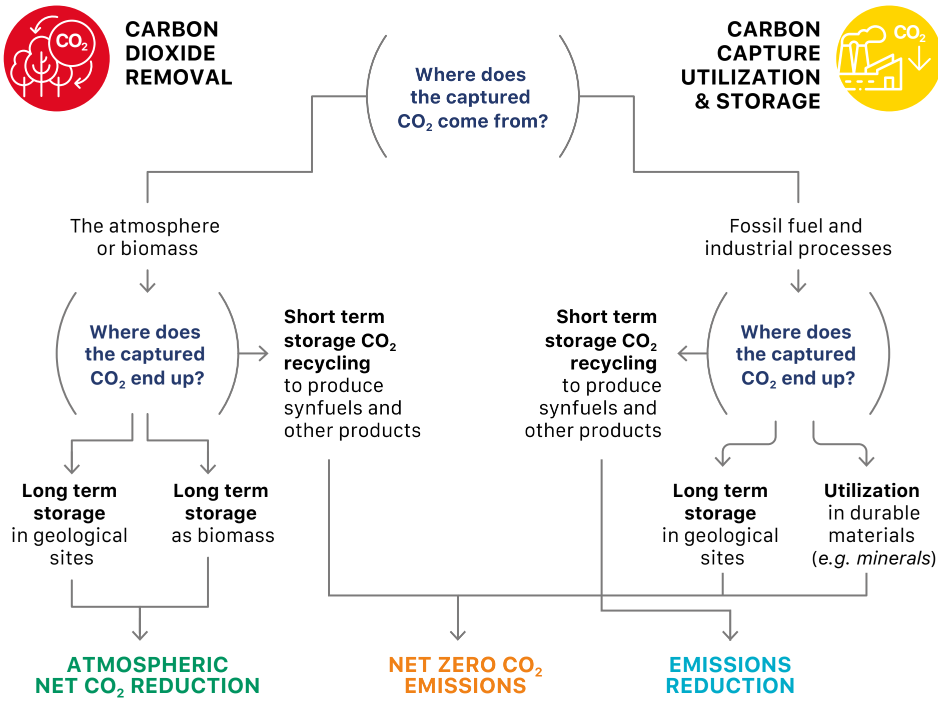
The crucial difference between the two is that CCUS captures CO_2 "newly" emitted by fossil fuel combustion or industrial processes, CDR subtracts CO_2 that is already present in the atmosphere. The different "origin" of the CO_2 captured is what affects the final CO_2 levels, i.e., CCUS can either achieve an emission reduction or net zero CO_2 emissions, whereas CDR can either achieve net zero CO_2 emissions or atmospheric CO_2 reduction.[3]

3 *Source: The European House - Ambrosetti on American University data, 2022.*

Figure 2

Impact on GHG levels of Carbon Dioxide Removal and Carbon Capture Utilization & Storage technologies

Source: The European House - Ambrosetti, 2022



There are three technological families available for the artificial capture of CO_2, namely post-combustion, pre-combustion, and oxy combustion, each with multiple capture methodologies, for a total of nine methodologies available. Besides polymeric membrane, which is a technology validated in lab (TRL 4), all methodologies have either an intermediate or high technology readiness level. The average demonstrated carbon capture efficiency of the capture methodologies is about 90%, with supercrytical CO_2 cycles presenting the highest capture efficiency (98%).[4]

4 *Source: The European House - Ambrosetti on IEA and US National energy technology laboratory data, 2022.*

Figure 3

Carbon capture methodologies, technology readiness level and capture efficiency

Source: The European House - Ambrosetti on IEA and US National energy technology laboratory data, 2022

Technology family	Capture methodology	TRL	Carbon capture efficiency (%)
Post-combustion	Physical absorption	9	85-90
	Chemical absorption	9	90-95
	Fluidized solid adsorption (Chemical Looping)	5	90-95
	Polymeric membrane	4	80-90
Pre-combustion	Physical absorption	9	85-90
	Chemical absorption	9	90-95
	Static solid adsorption (Pressure/Temperature Swing Adsorption)	9	90-95
Oxy combustion	Pure oxygen combustion	6	90-95
	Supercrytical CO_2 cycles	5	>98

The two projects are brought as examples for their scale and their ability to meet the needs of the multitude of stakeholders involved, coming from the most different fields: from governments, to Hard to Abate industries and power generation companies.

Hynet North West – UK Project partners

- The project envisages the decarbonisation of an energy-intensive industrial area in the Liverpool Bay
- By adapting current infrastructures and constructing a new **22 km** pipeline, storage operations in depleted hydrocarbon fields will start in **2025** with an initial capacity of 4.5 Mton/yr, with the possibility of expanding to **10 Mton/yr** by 2030
- In March 2021, the project received a funding commitment of **£33m** from UK Research and Innovation (UKRI) and a **£39m** of consortium partner contribution. The total estimated cost is **£900m**
- In October 2021, the project has been selected by the UK authorities between the two priority CCS projects
- in the Country and granted access to priority public funding (amount not specified)

Project partners

East Coast Cluster – UK

- The project is a collaboration between Zero Carbon Humber, Net Zero Teesside (the two industrial clusters) and Northern Endurance Partnership (for transportation and storage of CO_2), with the aim to remove **50%** of the UK's **industrial cluster** CO_2 emissions
- 7 partners are participating in the Zerocarbon Humber project, where over 17 Mton CO_2 are expected to be captured; instead, 8 partners are participating in the Net Zero Teesside project, where up to 10 Mton CO_2 are expected to be captured
- The project was selected to receive **government fundings** in January 2022
- The CO_2 collected from the two clusters will be transported to an offshore storage through a combined **248 km pipeline**

Project partners

Source: The European House Ambrosetti on Hynet North-West and East Coast Cluster data, 2022

There are currently 135 CCUS projects worldwide, 38 are located in Europe (28% of total): 43% of projects are currently in an advanced development phase, while only 20% are operational (CO_2 capture capacity from operational plants is 36.6 MTPA).

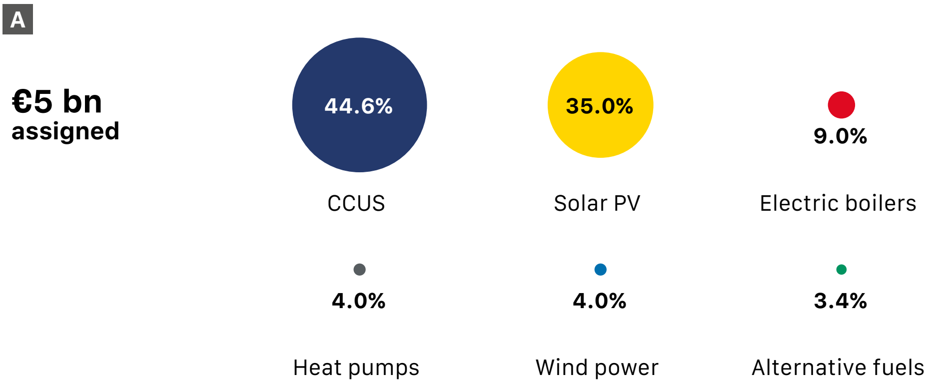
The European Green Deal considers CCUS a crucial technology to achieve the decarbonisation objectives. Notably**, 11 European National Energy and Climate Plans (NECP) contain explicit mention of CCUS as a measure to achieve their net zero emissions objectives, especially for the decarbonisation of Hard to Abate sectors** and dedicate parts of their National Resilience and Recovery Plans (NRRP) or other funds to develop national CCUS infrastructures. The key initiatives and investments are reported in figure 5. Among these, a special mention goes to the Dutch government, which has rated **CCUS as the most cost-effective technology** in its "Stimulation of Sustainable Energy Production and Climate Transition" Program. CCUS projects have received 44.6% of the total €5 billion assigned, as it is expected to absorb about 2.32 Mton CO_2 per annum – corresponding to 70% of the CO_2 absorbed by all projects.[5]

5 *Source: The European House - Ambrosetti on SDE++ data, 2022.*

Figure 4

Sustainable energy transition subsidy scheme (SDE++) 2020 budget allocation (% and billion of Euro) (A) and Technology efficiency: amount of CO_2 sequestered in 15 years per bn of investment (MtonCO_2 absorbed in 15 years/bn Euro) (B)

Source: The European House - Ambrosetti on SDE++ data, 2022



B

Technology efficiency: amount of CO_2 sequestered in 15 years per bn of investment
(MtonCO_2 absorbed in 15 years/bn Euro)

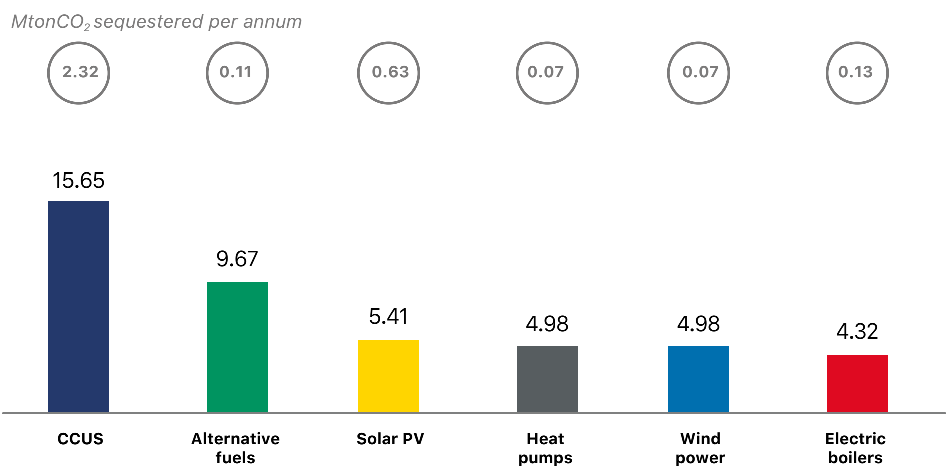


Figure 5

CCUS and CDR mentions and fundings in European Member States

Source: The European House - Ambrosetti on NECP and NRRP data, 2022

€1.85 bn to capture **0.4 Mtons CO_2/yr** from a cement factory in Norway. Development of a CO_2 transport and storage solution with a final capacity of 5 Mtons/yr

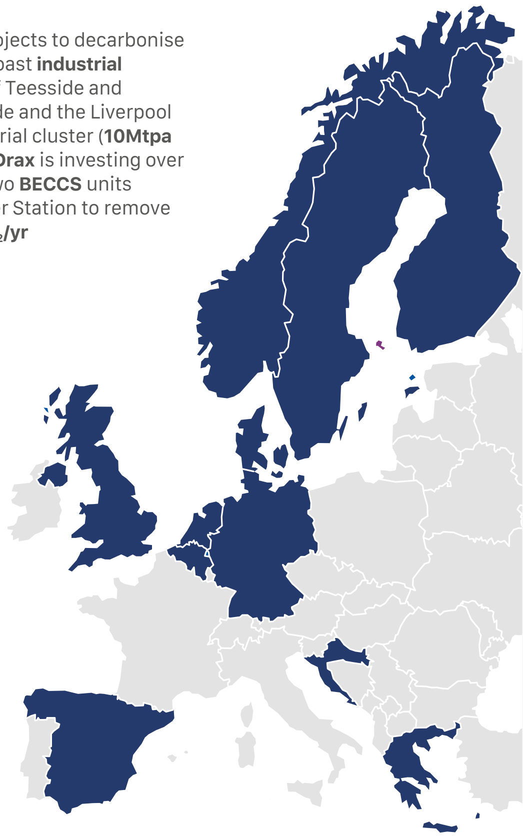
€27 mln to support the development and demonstration of **CO_2 storage** sites in depleted oil and gas fields in the Danish North Sea

A Finnish oil refinery was granted **€88 mln** by the European Commission for its Sustainable Hydrogen & Recovery of Carbon project

The Swedish government will subsidize **€37.9 mln** per **year**, over the period 2026-2040 to players investing in **bio-CCS** facilities

2 CCUS projects to decarbonise the East Coast **industrial clusters** of Teesside and Humberside and the Liverpool Bay industrial cluster (**10Mtpa** by 2030). **Drax** is investing over **£2 bn** in two **BECCS** units at its Power Station to remove **8 MtonCO_2/yr**

The Belgian NRRP allocated **€10 mln** to support the CCUS project **Antwerp@C, €50 mln** for the development of **low-carbon emission industry, €95 mln** to develop a network for **H_2 and CO_2 transport**



The Dutch NECP regards CCUS as an **inevitable transition technology** to reduce CO_2 emissions in sectors where **no cost-effective alternative is available** in the short term

Germany announced a **funding directive** for commercialising capture technologies and supporting CO_2 transport infrastructure options

The Spanish NECP proposes the integration of **CCUS technologies to reduce emissions**

€658 mln of the Croatian PNRR to develop innovative CCS projects, support the production of advanced biofuels and renewable hydrogen

The Greek NRRP destinates **€300 mln** to develop the **Prinos CCS project**, with CO_2 stored in the depleted offshore fields

Considering the second set of CO_2 capture options, i.e., CDR, four main technologies have been mapped. Bioenergies with CCS (BECCS), Direct Air CCS (DACCS) and biochar, which are engineered options, exploiting CCS technologies in the first two cases and biomass combustion through pyrolysis in the latter. Instead, afforestation and reforestation exploit the environment's natural ability to capture and store CO_2. Additional technologies were mapped, such as ocean fertilization, enhanced weathering, and blue carbon, but they have a lower implementation potential.

Figure 6

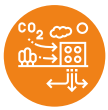
Carbon Dioxide Removal options

Source: The European House - Ambrosetti on IEA data, 2022

Engineered

Bioenergy with CCS (BECCS)

Capturing and storing the carbon in the process of extracting energy from biomasses



Direct Air Capture (DACCS)

CO_2 extraction directly from atmospheric air

Biochar

Pyrolysis or gasification of biomasses, the resulting char can be spread on arable fields, acting as a soil amendment technique

Natural

Afforestation and reforestation

Afforestation and reforestation to store CO_2 within permanent trees' biomasses

Underground CO_2 storage

CO_2 permanently stored in the soil

Environment's natural ability to capture and store CO_2

DACCS allows to capture CO_2 directly from the atmosphere. It can either exploit "liquid" or "solid" technologies: liquid DAC facilities pass air through chemical solutions that remove the CO_2. The system then reintegrates the chemicals in the process with high-temperature heat and returns the remaining air to the environment. Solid DAC facilities exploit solid sorbents that chemically bind in CO_2. When heated, filters release the CO_2, which is then captured for storage or use. Both technologies have an intermediate technology readiness level of 6 (it has been demonstrated in relevant environment).[6]

6 *Source: The European House - Ambrosetti on IEA data, 2022.*

BECCS involves the capture of atmospheric CO_2, which is stored within biomass. Basically, it exploits the ability of plants to separate atmospheric CO_2 and store it in the form of biomass. To "interrupt the biogenic cycle", BECCS removes the carbon present in the biomass in the form of CO_2. In order to implement BECCS, sustainable biomass is first grown and harvested, and atmospheric CO_2 is bound into biomass. Energy is then extracted from biomass through combustion, fermentation, pyrolysis or other conversion methods to produce electricity, heat, biofuels, etc. CO_2 emitted during this phase is absorbed with CCS technologies. BECCS has a technology readiness level of 9, meaning that the system was proven in operational environment (the manufacturing of key enabling technologies is competitive), given that it exploits CCS technologies.[7]

Like BECCS, **biochar also exploits the ability of plants to capture CO_2.** The main difference between the two technologies is that instead of removing carbon from biomass in the form of CO_2 (as in BECCS), it is retained in the form of biochar (vegetal coal). Additionally, biochar exploits the ability of the soil to retain carbon over the long term, while at the same time contributing to its quality. Biochar is a kind of natural coal (charcoal) created when biomass is sustainably harvested in crop residues, grass, trees, or other plants is collected and combusted at temperatures of 300–600°C without oxygen, through a pyrolysis process. The biochar with high concentration of carbon is then introduced into soils, where it sequesters CO_2 for hundreds of years and also works as a soil amendment.[8] Biochar has a readiness level of 8 (System complete and qualified), as it enhances naturally occurring processes.[9]

Afforestation and reforestation are nature-based solutions; reforestation is the process of planting trees where the number of trees has been decreasing due to deforestation or natural occurring events (e.g., fires), whereas afforestation occurs when new trees are planted, or seeds are sown in an area where there were no trees before. Through photosynthesis, forests capture CO_2 from the atmosphere and bind it into biomass. Both solutions have a technology readiness level of 9.[10]

7 *Ibid.*
8 *An amendment is any material added to a soil to enhance the effect of fertilizers by improving the physical properties of the treated soil, such as water retention, permeability, water infiltration, drainage, and aeration.*
9 *Ibid.*
10 *Ibid.*

Figure 7

Carbon Dioxide Removal methodologies, technology readiness level and estimated removal CO_2 potential (Gt/yr)

Source: The European House - Ambrosetti on IEA and US National energy technology laboratory data, 2022

Macro-categories	Technologies	TRL	Estimated CO_2 removal potential, Gt/yr (to be compared with costs)
BECCS	CCS technologies can be exploited thanks to similar CO_2 concentration levels	9	2.4-69.7
DACCS	Liquid	6	N.A.
	Solid	6	
Afforestation and reforestation	Enhancement of natural occurring processes	9	0.5-7.2
Biochar	Biomass combustion through pyrolisis	8	0.6-11.9

There are currently 20 BECCS pilot applications developed worldwide, 7 of which are in the USA and 10 in Europe. Drax power station in the UK, Project Langskip in Norway and Stockholm Exergi in Sweden, both part of the Northern Lights project, and the Lantmännen Agroetanol purification facility in Sweden are relevant commercial applications. Instead, there is one medium scale DACCS facility in Iceland and 17 small scale DAC facilities worldwide, of which 15 are in Europe. The two most representative DACCS cases are project ORCA in Iceland and 1PointFive DAC in Texas, USA.

ORCA and Mammoth – Iceland

- In september **2021**, ORCA started operations in Iceland: it is the first large-scale DAC plant operated by **Climeworks** and **CarbFix**
- The facility consists of **eight collector containers**, with an annual capture capacity of **500 tons each**; such containers capture CO_2 from the atmosphere and blends it with CO_2 captured from geothermal fluids for underground storage in basalt rock formations
- The CO_2 is **permanently stored** thanks to a **mineralization process** that turns it into rock within 2/3 years
- The plant will capture **4,000 tons CO_2/yr**, making ORCA the largest DAC plant removing CO_2 from the atmosphere
- In **June 2022**, the companies announced the groundbreaking of the second, newest and largest DACS, **Mammoth.** This plant will have a capacity of **36,000 tons CO_2/yr** when fully operational
- The two companies are planning to launch other plants with multimegaton capacity by 2030 and gigaton capacity by 2050

Project partners

Source: The European House Ambrosetti on Climeworks and Carbfix data, 2022

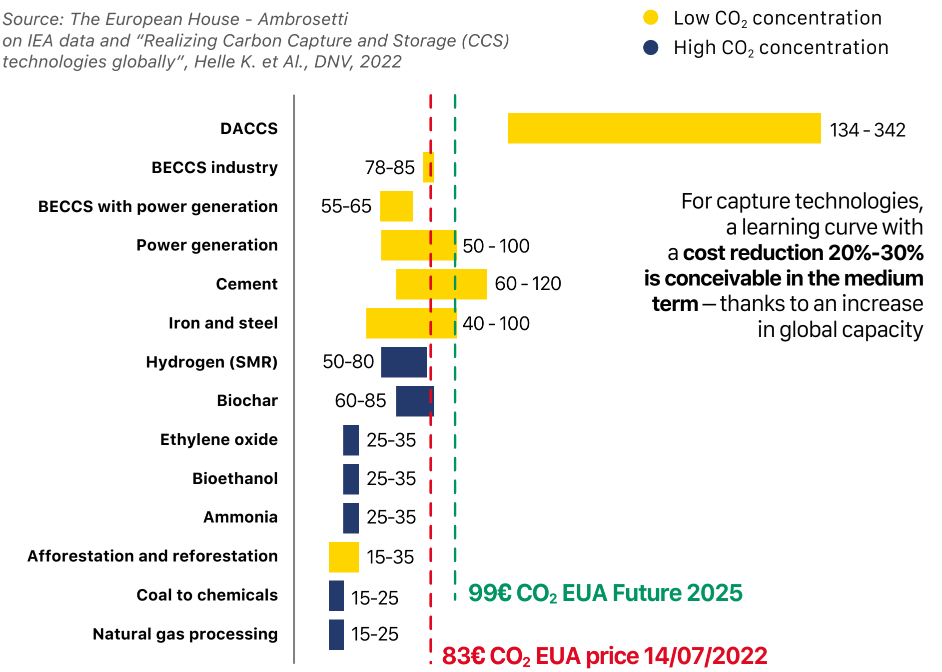
Costs, storage and safety of CCUS and CDR technologies

The cost of carbon capture largely depends on the CO_2 concentration levels and is indirectly related to it: the higher the CO_2 concentration, the lower the cost. Given that CO_2 concentration in the atmosphere is lower than the concentration in most applications, it is not surprising that DACCS is the most expensive technology. Anyhow, in most cases the current cost is lower than the cost of CO_2 on allowance markets (the current price is 83€ EUA[11] and the average European annual carbon price was 72€ per ton of CO_2 in 2021). For capture technologies, a learning curve with a cost reduction of 20%-30% is conceivable in the medium term, thanks to an increase in global capacity.[12]

Figure 8

Levelised cost of CO_2 capture by sector and initial CO_2 concentration, (USD/ton CO_2 captured), 2019

Source: The European House - Ambrosetti on IEA data and "Realizing Carbon Capture and Storage (CCS) technologies globally", Helle K. et Al., DNV, 2022



11 *EUA is the European Union Allowance, the tradable unit under the Emissions Trading Scheme (EU ETS), giving the right to emit one ton of CO_2.*
12 *Source: The European House - Ambrosetti on IEA and DNV data, 2022.*

Total global geological long-term storage capacity has been estimated between 8,000 Gt and 55,000 Gt by the IEA. Considering the current annual CO_2 emission (34 Gtons), the capacity is equal to at least 235 years of global emissions. The two most common underground storage solutions are depleted oil and gas fields and deep saline formations. Depleted fields are reservoirs in the sub-surface sand or rock formation where oil or gas were once naturally stored and were later extracted. The empty fields can be used to store CO_2. Deep saline formations are sedimentary basins where mineral collected and solidified over millions of years, creating several layers. Some layers – aquifers – are made of porous and permeable rocks charged with water. Deeper aquifers can be used for CO_2 storage.[13]

Notably, public opinion is quite concerned about safety issues associated to CO_2 storage, with fears ranging from CO_2 leakage, to lack of effectiveness, environmental impact, seismic activities, destruction of facilities and land loss to infrastructures. All these fears represent a barrier to full-scale CCS implementation and undermine its potential positive impact. For this reason, multiple scientific studies have addressed these concerns and most of them investigates the potential CO_2 leakage. Among these, British scientific study published on Nature Communications have demonstrated that CO_2 leakage in well managed facilities is less than 2% over 10,000 years. The authors presented a numerical program that calculates CO_2 storage leakage to the atmosphere over a 10,000 years span, by combining quantitative estimates of surface CO_2 leakage and of geological subsurface CO_2 retention. Their results show that **well-regulated storage has a 50% probability that leakage remains below 0.0008% per year, and over 98% of the injected CO_2 is maintained in the geological storage over 10,000 years.**[14]

Key message #6

Hydrogen should be exploited as a Carbon Neutral energy carrier with great potential for decarbonising end-uses when not in competition for access to renewable electric energy.

The European House - Ambrosetti has identified 17 technological options grouped in six macro-categories available to produce hydrogen. The

13 *Source: The European House - Ambrosetti on IEA data, 2022.*
14 *Source: "Estimating geological CO_2 storage security to deliver on climate mitigation", Alcalde J. et Al., Nature Comminucations, (2018), 2022.*

technologies with the highest technology readiness level (9) are those pertaining to the gas reforming and solid fuel gasification macro-category. Additionally, two technologies exploiting electrolysis (alkaline and polymer electrolyte membrane) and biomass pyrolysis have a technology readiness level of 9. Overall, technologies pertaining to the photo-chemical macro-category have the lowest readiness level. The efficiency of the 17 technologies is positively related to the readiness level.

Figure 9

Hydrogen production technology, sources, readiness level and efficiency levels (%)

Source: The European House - Ambrosetti on IEA and US National energy technology laboratory data, 2022

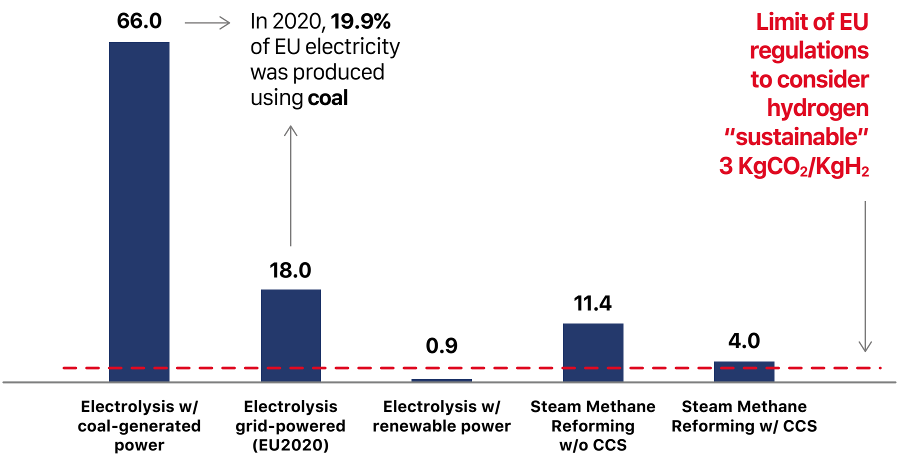
Macro-categories	Technologies	Sources	TRL	Efficiency (%)
Gas reforming	Steam Methane Reforming	Methane	9	74-85
	Autothermal Reforming		9	60-75
	Partial Oxidation		9	60-75
Solid fuel gasification	Gasification of coal	Coal	9	74-85
Electrolysis	Alkaline electrolysis	Electricity + Water	9	63-70
	Polymer electrolyte membrane		9	56-60
	Microbial Electrolysis		3	N.A.
	Solid oxide electrolyser cells		7	74-84
Pyrolisis	Methane pyrolysis	Methane	6	45
	Biomass pyrolysis	Biomass	9	75
Photo-chemical	Photo-electrochemical	Water + Solar Energy	2	0.5-12
	Photosynthesis	Organic plant + Sunlight	3	<5
	Photofermentation	Bacteria + Sunlight	3	<1
	Photofermentation from Microalgae	Microalgae + Sunlight	3	1
	Bio-photolysis	Biomass	3	<1
	Dark fermentation	Microorganisms	5	60-70
Chemical	Chemical Looping with CCUS	Calcinated iron ore + biomass pyrolysis gas	4	NA

To be Carbon Neutral and achieve net zero emissions, some of hydrogen production technologies must be coupled with CCUS and/or CDR technologies given that, under a Life Cycle Approach (LCA), there are no technologies that offer fully decarbonised hydrogen. For instance, electrolysis conducted using coal-generated power is the most emitting, as the production of each kg of hydrogen entails 66 kg of CO_2 emitted. This is far above the European regulations, according to which hydrogen is sustainable if the CO_2 emitted is at most 3 kg per each kg of hydrogen produced.[15]

Figure 10

Hydrogen's Life Cycle Assessment emissions according to different technologies (Kg CO_2/KgH_2), 2020

Source: The European House - Ambrosetti on Paper «Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions», Oni et Al., Energy Conversion and Management (2022), 2022



15 *Source: «Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions», Oni et Al., Energy Conversion and Management (2022), 2022.*

More specifically, each singular technology requires key measures to produce Carbon Neutral hydrogen:

- Steam reforming and solid fuel gasification require CCS and CDR technologies or usage of bioenergies in input;
- Electrolysis must rely on electricity generated by renewable energy sources and should be coupled with CDR;
- Pyrolysis should use and store black-carbon residues[16] (in solid state) and exploit CDR for the remaining emissions;
- Photo-chemical technologies rely directly on natural energy sources (solar energy) and therefore do not need to be paired with any key measure to achieve carbon neutrality.

Hydrogen from natural gas steam reforming without CCUS is the most accessible Carbon Neutral option today. Coupling it with CCUS only leads to a slight increase in final costs. Instead, the cost of hydrogen from electrolysis performed with renewables is today almost three times higher than the steam reforming case, but it is expected to decrease by 65.2% in 2050, when it will reach a similar level to hydrogen from natural gas.[17]

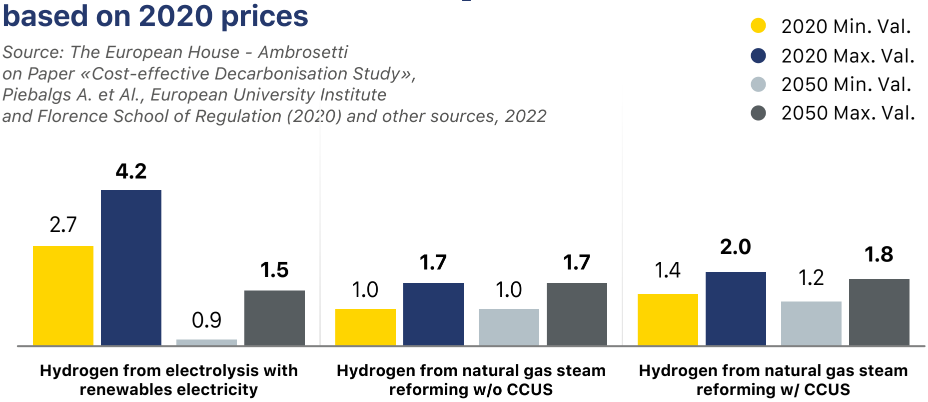
There is a consensus that **green hydrogen is the way forward to achieve the decarbonisation objectives in the long term, but at the same time it is not possible to pursue it today** (besides applications such as storage) **due to the scarcity of renewable resources**. It is necessary to provide a bridge that allows for a market uptake already in the short term, enabling access to technologies and hydrogen in a safe and cost-effective manner.

16 *Black carbon is generated from the incomplete combustion of fossil fuels, wood, and other fuels.*
17 *Source: The European House - Ambrosetti on Paper «Cost-effective Decarbonisation Study», Piebalgs A. et Al., European University Institute and Florence School of Regulation (2020) and other sources, 2022.*

Figure 11

Hydrogen's costs according to different technologies (€/KgH_2), based on 2020 prices

Source: The European House - Ambrosetti on Paper «Cost-effective Decarbonisation Study», Piebalgs A. et Al., European University Institute and Florence School of Regulation (2020) and other sources, 2022



In Europe, about 11.5 Mtons of hydrogen was produced in 2020, of which 11.2 Mtons were fossil-based (97.7%). If fossil-based hydrogen was generated from renewable electricity, an additional capacity of 514.6 TWh would be required – equal to an 18% increase with respects to total electricity generation in the European Union in 2020, and an 47% increase with respects to renewable electricity generated in the European Union in 2020.[18]

By 2030, Repower EU foresees the production of 20 Mtons of hydrogen, of which 84% from electrolysis: to produce 16.8 Mtons of decarbonised hydrogen (84% of the total forecasted), it will be necessary to use 769.4 TWh of electricity – a 22% increase with respects to the 2030 forecasted European electricity generation, and a 34% increase with respects to the 2030 forecasted European renewable electricity generation. **An issue of strong competition on green electricity emerges, but the use of renewable electricity for hydrogen production is only convenient if it is not in competition with other uses.** As a matter of fact, in the medium term, the production of hydrogen with electrolysis minimizes the decarbonisation potential of electric renewable energy sources.[19] It has been estimated that 1 kWh of electricity from renewable energy sources could either:

- Substitute fossil sources in electricity generation, leading to a 350-

18 *Source: The European House - Ambrosetti on Hydrogen Europe, IEA, Italgas and European Commission data, 2022.*

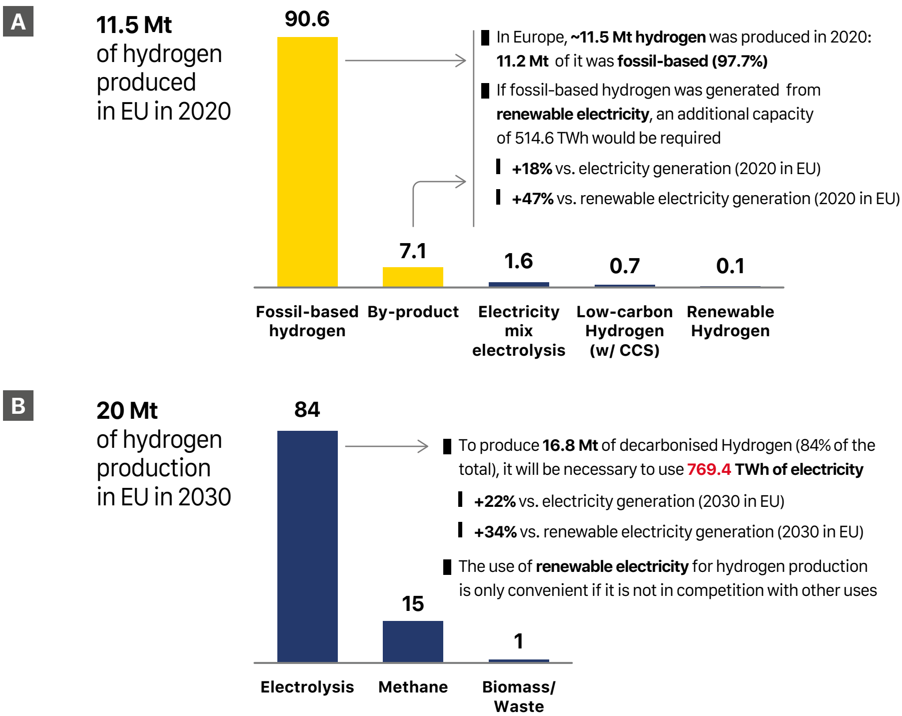
19 *Source: The European House - Ambrosetti on plan "RePowerEu", European Commission and report «World Energy Outlook», IEA, 2022.*

700 g CO_2 saved (depending on whether replacing gas or coal-fired generation);
- Replace hydrogen produced from fossil sources with hydrogen from electrolysis, leading to 94 g saved if hydrogen is produced from natural gas steam reforming with CCUS, or 249 g saved if hydrogen is produced from steam reforming without CCUS.

Figure 12

Source of Hydrogen production in EU27 (%), 2020 (A) and 2030 (B)

Source: The European House - Ambrosetti on plan "RePowerEu", European Commission and report «World Energy Outlook», IEA, 2022



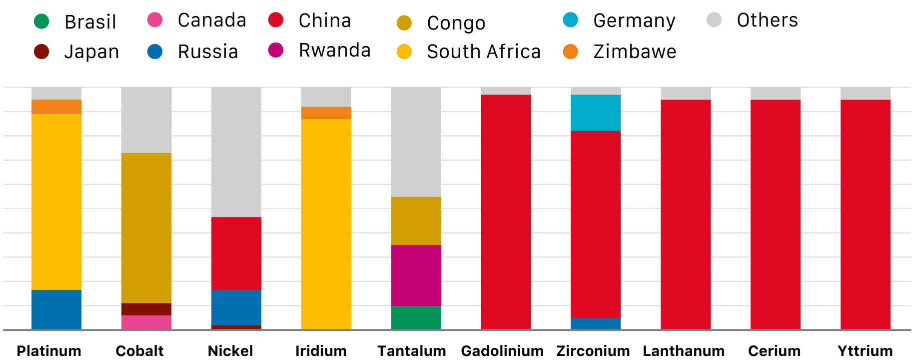
One last, crucial point to consider is the origin of relevant components required to produce electrolysis technologies, introducing a dependency issue: **Germany is the only European country of origin of one of the ten key metals, as it detains 15% of global mining of zirconium.**[20]

20 *Source: The European House - Ambrosetti on IRENA data, 2022.*

Figure 13

Global mining supply of key metals for electrolysers (%), 2020

Source: The European House - Ambrosetti on IRENA data, 2022



Key message #7

Biofuels, whose production is not in competition with food, can be a Carbon Neutral solution to replace traditional fuels while minimizing the necessary changes in consumption systems and supply chains.

Biofuels are a special kind of renewable energy derived from recently living organic materials, known as biomass, and the CO_2 emitted by the use of biofuels is part of the biogenic carbon cycle with a neutral impact. Anyway, under a Life Cycle Assessment perspective, also emission for the biofuels production shall be considered. **To achieve carbon neutrality, it is necessary to leverage on CCUS (at the production stage) and/or CDR offsets afterwards.**

Only biofuels derived from residuals, non-edible oils, agricultural and municipal waste, algae, discarder animal fats and glycerin[21] – hence, **all sources not in competition with food chains are considered in the scope of this study.** Biofuels derived from agricultural crops and oilseeds that could be used as human feed are not considered as a decarbonisation le-

21 *Glycerin is a natural compound derived from animal fats or vegetable oils.*

vers. Additionally, **only sources cultivated in marginal lands are included in the study**, i.e., land unsuitable for agricultural cultivation for human use, such as polluted and drought-affected land, etc.[22]

Nowadays, **there are five technological options already available to produce four kinds of biofuel, which only emit biogenic renewable CO_2 and can be readily integrated in transport systems and other infrastructures.** Hydrotreating, anaerobic digestion and pyrolysis have a technology readiness level of 9, whereas gasification has a readiness level of 7. Fischer-Tropsch synthesis (FTS) and Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK) have a readiness level comprised between 5 and 9. This last technology has different readiness levels, based on the way it is performed, for instance gasification and Fischer-Tropsch has a readiness level of 7 (Technology demonstrated in operational environment), but when associated to hydrogen enhancement the TRL drops to 5 (Technology validated in relevant environment).[23]

Figure 14

Biofuels production technology, description, technology readiness level and biofuel produced

Source: The European House - Ambrosetti on IEA and US National energy technology laboratory data, 2022

Technology	Description	TRL	Biofuel
Hydrotreating	They process vegetable/algal oils and animal fats via chemical processes treatments	9	Biofuels (HVO) and SAF
Anaerobic digestion	It can process organic waste fraction, industrial wastes, sewage and manure sludge including energy crops and crop residues	9	Biomethane
Gasification	It can produce gaseous and liquid fuel from wastes, forestry and agricultural residues	7	Gas and liquid fuels
Pyrolysis		9	
Fischer-Tropsch synthesis (FTS) and Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK)	It can be integrated at the thermochemical pathway with the aim to convert syngas	5-9	Drop-in fuel and green jet fuel

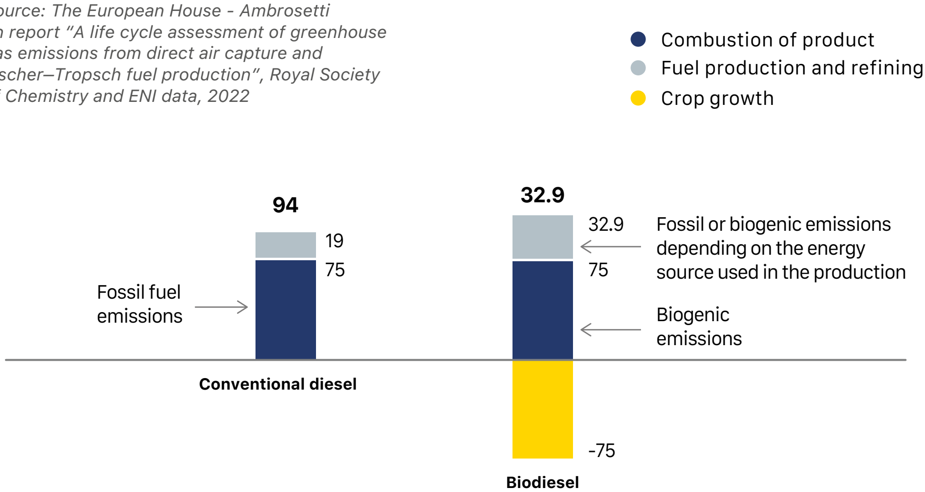
22 *Source: The European House - Ambrosetti on IEA data, 2022.*
23 *Ibid.*

Overall, a study published by the Royal Society of Chemistry has demonstrated that switching from conventional diesel to biodiesel is associated to a 65% emission reduction. The CO_2 emitted in the use of biofuels is part of the biogenic carbon cycle with a neutral impact. Anyway, under a Life Cycle Assessment perspective, also emission for the biofuels production shall be considered. To achieve carbon neutrality, it is necessary to leverage on CCUS (at the production stage) and/or CDR offsets. The main downside of biofuels is the high production cost, especially if compared to traditional fossil fuels. **To foster the diffusion of biofuels, it is therefore necessary to address the high production cost level issues.**[24]

Figure 15

Carbon intensity of conventional diesel and biodiesel production (g CO_2/MJ diesel), 2020

Source: The European House - Ambrosetti on report "A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production", Royal Society of Chemistry and ENI data, 2022



Raw materials for biofuels production are generated from two main sources: wastes and residues and agriculture energy crop not in competition with food. **In Europe, there is a great potential to implement circular economy models to produce biofuels: each year, more than 34.9 million tons of waste from multiple sources are available, but they are currently unexploited.**

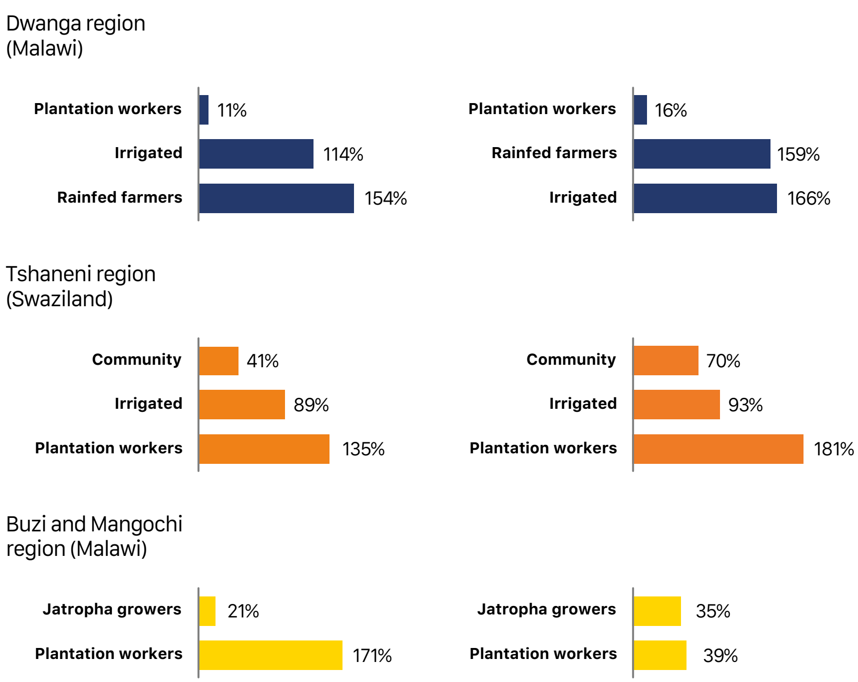
24 *Source: The European House - Ambrosetti on report "A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production", Liu C. et Al., Royal Society of Chemistry (2020) and ENI data, 2022.*

To ensure sustainability, agriculture and energy crops should be harvested on marginal land, which has little or no agricultural value, and is characterized by physical isolation (like being far from any available road), no water, severe slope or industrial pollution. **Africa is the world's first area for marginal lands (784 million hectares) that can be exploited for energy crops not in competition with food, while bringing important socio-economic benefits to local African communities in terms of increased disposable income and expenditure levels.** At the same time, reducing income poverty with improvements on health, education and living standards.[25]

Figure 16

Differences in income (left) and expenditure (right) between diverse producers and a control group with low or high level of involvement in biofuels production (percentage value), 2021

Source: The European House - Ambrosetti on report "Fuelling rural development? The impact of biofuel feedstock production in Southern Africa on household income and expenditures", South Africa University, University of Oxford and Stockholm Environment Institute, 2022



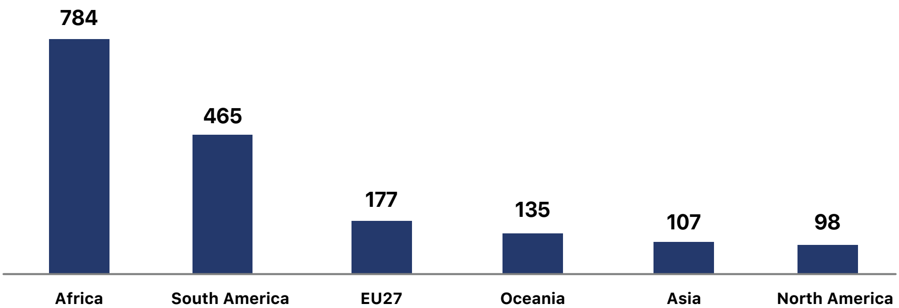
25 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

In the European Union, there are 177 million hectares of marginal land available, of which 34% is suitable for biofuels production (60 million hectares). Notably, oilseed crops have the potential to "bring back" marginal land, making it useful for food crops after some years of harvesting.[26]

Figure 17

Global marginal lands (million hectares), 2022

Source: The European House - Ambrosetti on report "Global marginal land availability of Jatropha curcas L.-based biodiesel development" Hao M. et Al., Journal of Cleaner Production (2022), 2022



Key message #8

Synthetic fuels can be a Carbon Neutral solution that can replace traditional fuels while minimising the necessary changes in consumption systems for specific Hard to Abate sectors (e.g., aviation) due to the overall low energy efficiency.

Another solution to replace traditional fuels is synthetic fuels, which are Carbon Neutral and require minimal adaptation in consumption systems for specific Hard to Abate sectors (e.g., aviation), due to the overall low energy efficiency. **Synthetic fuels are produced from the mix of hydrogen and CO_2, leveraging on well-known technologies** such as methanization, Fischer-Tropsch and hydrocraking and methanol synthesis and methanol to gasoline. **All these technologies individually have high ma-**

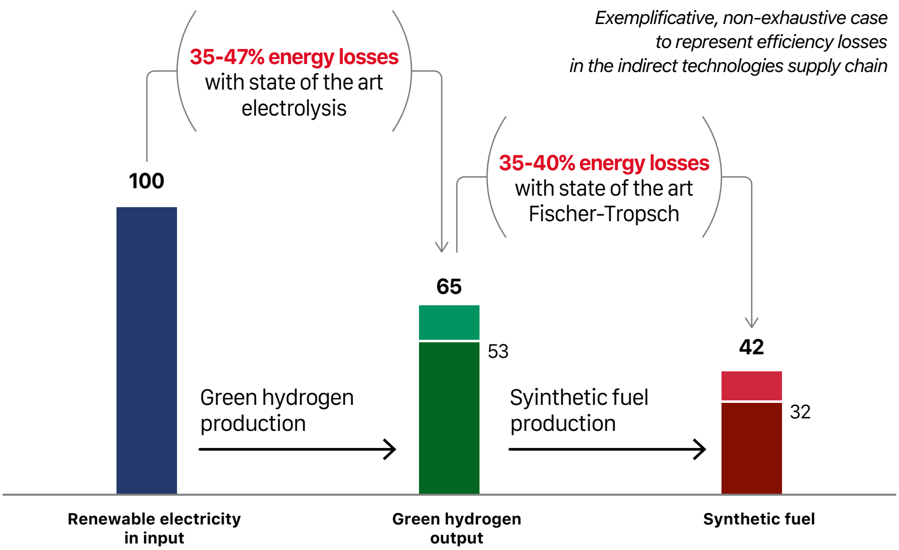
26 *Source: The European House - Ambrosetti on report "Global marginal land availability of Jatropha curcas L.-based biodiesel development" Hao M. et Al., Journal of Cleaner Production (2022), 2022.*

turity, but there is still a need of value chain integration to compete with other alternatives. Overall, synthetic fuels offer multiple advantages, but one major downside that needs to be addressed: the supply chain is associated to efficiency losses at each transformation stage, leading to higher costs.[27]

Figure 18

Technology efficiency losses in the production of green hydrogen and synthetic fuel from renewable electricity, (%, TWh of renewable electricity = 100) - Light and dark colours indicate value ranges

Source: The European House - Ambrosetti on various data, 2022



Key message #9

Discontinuity in the decarbonisation process will be generated by some breakthrough technologies, the development of which is accelerating thanks to new models of open innovation.

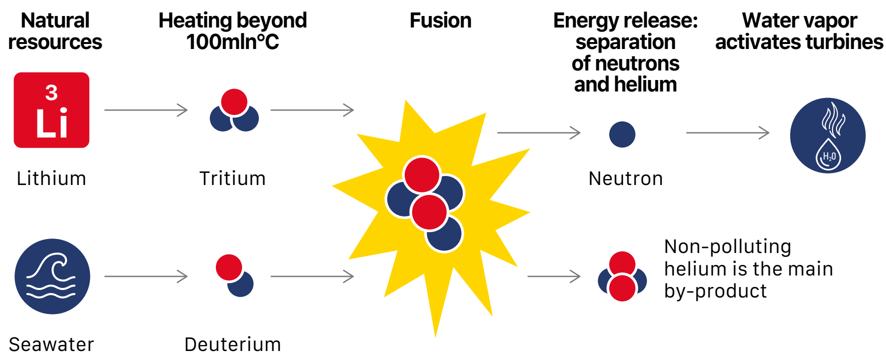
27 *Source: The European House - Ambrosetti on various data, 2022.*

Nuclear fusion is the reaction happening in the sun and other stars: it could provide a clean, virtually limitless source of energy to complement renewables by providing electricity during peaks and throughs. It could provide clean industrial heat to energy-intensive industries, and it can generate hydrogen as replacement for natural gas. Differently from nuclear fission, nuclear fusion energy uses easily attainable, clean and virtually inexhaustible materials (such as seawater), and releases four times the energy produced with nuclear fission at equal mass. At a power density that is 10 million times greater than fossil fuels, only half a bathtub of seawater will produce as much energy as 40 train cars of coal.[28]

Figure 19

Nuclear fusion process breakdown

Source: The European House - Ambrosetti on Fusion Industry Association data, 2022



There have been major technological breakthroughs that enable this technology to be envisaged in the coming decades, making it crucial for **Europe and its member states to ensure a favorable environment for research and experiments in this field, which could be a game changer to achieve Net Zero Emissions by 2050**: it is necessary to invest in R&D to maintain a technology leadership in this field.

Worldwide, there are 33 companies investing in the development of commercial nuclear fusion, supported by 36 other affiliate companies, mostly active in the USA and Europe. These companies are part of the Fu-

28 *Source: The European House - Ambrosetti on Fusion Industry Association data, 2022.*

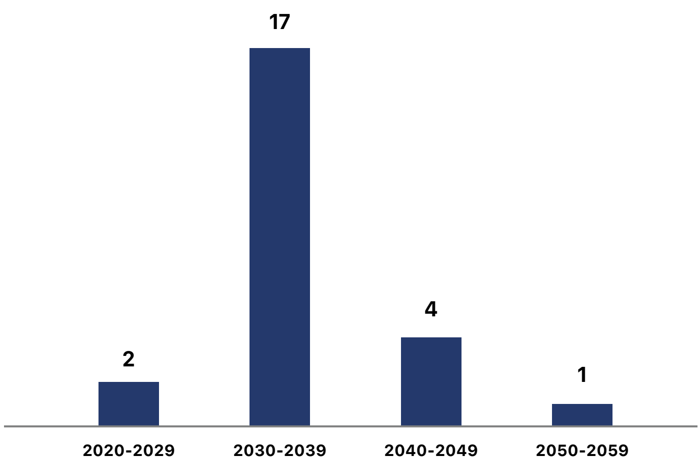
sion Industry Association, which conducts a yearly survey to assess the state-of-the-art technologies, developments and investments in nuclear fusion. **As of 2021, 70% of fusion companies expect fusion to be commercial in the 2030s,** a positive outlook motivated by recent historical results:

- At the European level, In February 2022, the **JET project experiments produced 59 megajoules of energy in 5 seconds** (11 megawatts of power);
- In the UK, Tokamak Energy achieved important milestones in early 2022: **the spherical Tokamak ST40 touched a plasma temperature of 100 million degrees Celsius**, the threshold required for nuclear fusion;
- In September 2021, **the MIT CFS generated a magnetic field of 20 Tesla in just two weeks**, enabling a temperature suitable for the nuclear fusion process.[29]

Figure 20

Perception of the time horizon for implementing nuclear fusion plants

Source: The European House - Ambrosetti on Fusion Industry Association data, 2022



29 *Ibid.*

Chapter 3

Zero Carbon Technology Roadmap

3.1 Introduction

This chapter describes the analyses carried out to estimate the CO_2 emission reduction impacts enabled by the four key technologies for decarbonisation – Carbon Capture Utilization & Storage and Carbon Dioxide Removal, hydrogen, biofuels and synthetic fuels – as applied to the Hard to Abate, Heavy Duty transportation and power generation industries.

The impact of the decarbonisation technologies – so-called decarbonisation levers – and their potential contribution to emissions' reduction have been assessed by The European House - Ambrosetti thanks to a deep literature review of academic and managerial papers, and thanks to stakeholder engagement activities. More than 30 experts and/or stakeholders were involved in Working Tables or one-to-one interviews.

In the first part of the chapter, key contextual elements are presented and then the methodology behind the model to estimate emission reduction is presented. In the following section, key elements characterizing each decarbonisation levers for each sector are described. Then, the application of the model to different industrial sector and relative impacts are presented.

3.2 Simulation of emissions impacts: structure, assumptions and results of the model

Key message #10

The extensive application of Carbon Capture Utilization & Storage (CCUS), Carbon Dioxide Removal (CDR), hydrogen, biofuels and synthetic fuels technologies is indispensable to achieve full decarbonisation of the Hard to Abate, Heavy Duty transport and fossil fuel power generation by 2050.

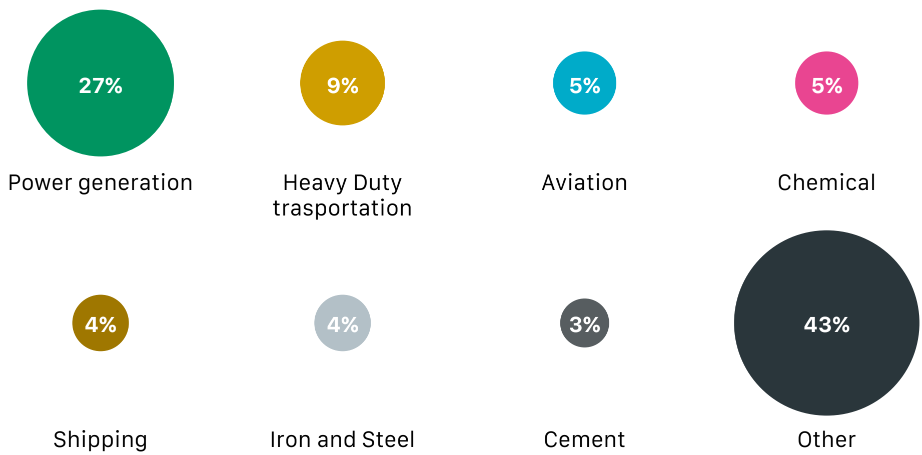
The decarbonisation scenarios developed by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) show that renewables and electrification will play central role to achieve the decarbonisation objectives, hence, to go from 33.9 Gton of CO_2eq emitted globally in 2020, to 21.1 Gton in 2030 and, finally, to net zero emissions in 2050: together, they account for 43% of total emission reduction. Anyhow, they have to be paired with other mitigating measures to achieve net zero emissions, such as energy efficiency, behavioural change and other "complementary" technologies, namely Carbon Capture Utilization & Storage (CCUS) and Carbon Dioxide Removal (CDR), Hydrogen, Biofuels and Synthetic fuels – these **technologies should be exploited synergically** with all the other above-mentioned options.

Heavy industry and Heavy Duty transport are together responsible for nearly one-third of global CO_2 emissions. At the European level, Hard to Abate sectors accounted for 1.89 Gton CO_2e in 2019, 57% of total European emissions. Given that this percentage is expected to double under business-as-usual scenarios, these sectors have a vital role in halting and reducing global greenhouse gas (GHG) emissions to achieve net zero emissions by 2050. Furthermore, Hard to Abate sectors are an integral part of the industrialized society, and the growth in global population has led to a constant increase in demand, leading to a highly efficient but fossil-fuel dependent production and transportation system, whereby the use of fossil energy and fossil feedstock is deeply rooted in the production process and transportation.[1]

Figure 1

Hard to Abate sectors emissions with respects to total European emissions (%, total European GHG emissions=100), 2020

Source: The European House - Ambrosetti on Eurostat data, 2022



The European House - Ambrosetti has therefore developed a model to forecast the decarbonisation impact of each "alternative" technology on the Hard to Abate industrial sectors, on Heavy Duty transport and on Power Generation from fossil fuels, taking into account the difficulties in the decarbonisation of these sectors:

- **The cement, iron and steel and chemical sectors rely on fossil fuels for 81% of final energy consumption**, and the latest IEA scenarios include **a 22% share of power generated by fossil fuels in 2050**, requiring the diffusion of decarbonised technologies. Furthermore, on average **52% of the emissions are generated from industrial processes** (this figure rises above 63% in the cement sector), making it crucial to foster the deployment of Carbon Capture & Storage/Carbon Dioxide Removal, hydrogen and Zero Carbon fuels to reach net zero emissions;

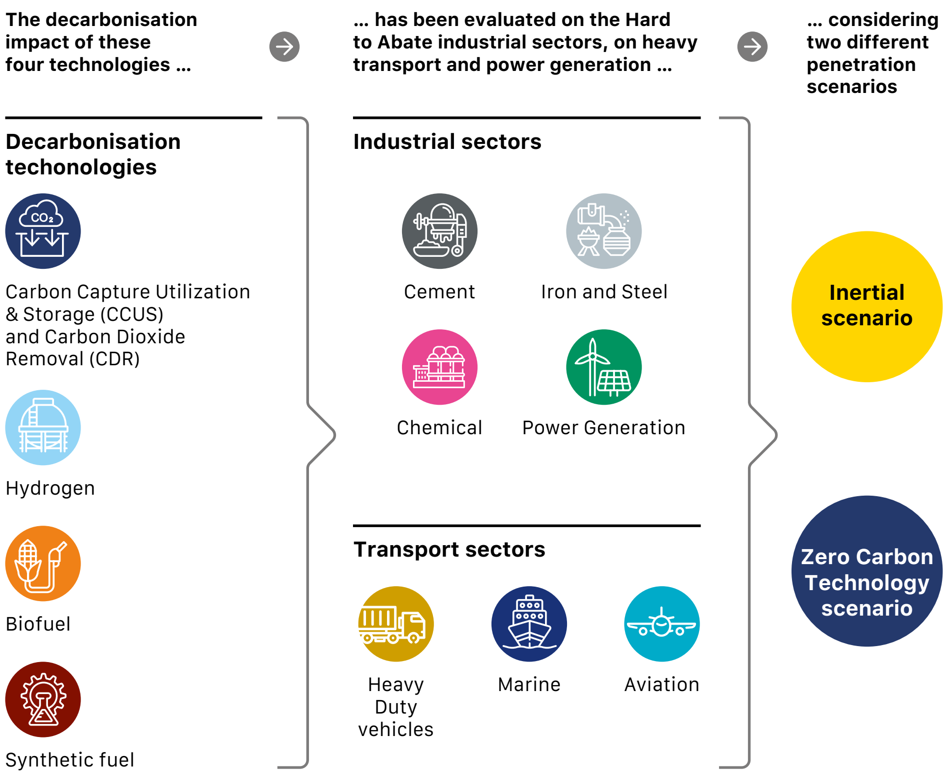
1 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

- **Transports modes rely on fossil fuels for more than 90% of final consumption**, **electrification is a long-term challenge** in road transport, and it is not an option for aviation. It is therefore necessary to foster the sector's decarbonisation with alternative options;
- **In power generation, solid and liquid fossil fuels still account for almost 20% of energy production, while natural gas accounts for over 23%**, and they will be required to ensure energy system adequacy and flexibility.[2]

Figure 2

Framework of the model to estimate impacts on CO_2 reduction

Source: The European House - Ambrosetti, 2022



2 *Ibid.*

The model presents two potential decarbonisation scenarios in each sector:

- The **Inertial Scenario** takes into consideration a **reduction of CO_2 emissions leveraging only on existing technology deployment trends and policies** and excluding any acceleration in their diffusion;
- The **Zero Carbon Technology Scenario takes into consideration a series of recommendations and insights coming from deep dive interviews, working table discussions and analyses of existing literature**. Specifically, this Scenario accounts for:
  - Use of **biofuels** to accelerate the transition from traditional fuels;
  - Full exploitation of **Carbon Neutral hydrogen**, whatever the source of it;
  - Exploitation of **CCUS** thanks to the development of dedicated infrastructure and regulations;
  - Use of **CDR** to address the remaining atmospheric CO_2.

The model assumptions of each technology are summarized in the following figure, but the key difference between the two scenarios is based on the fact that the **Zero Carbon Technology Scenario relies on a technology neutrality principle based on the ability to abate CO_2 along the value chain.**

Figure 3

Decarbonisation model assumptions

Source: The European House - Ambrosetti proprietary model, 2022.

SCENARIOS ASSUMPTIONS

	INERTIAL SCENARIO
CARBON NEUTRAL BIOFUELS AND SYNTETIC FUELS	Persistence of the tank-to-wheel principle in accounting for CO_2 emissions
	Maintaining existing limitations to the scope of sources for the production of advanced biofuel from waste, residues and non-food competing crops
CARBON NEUTRAL HYDROGEN	Only hydrogen from electric renewable energy recognized as Carbon Neutral
	Slowdown in market uptake due to the limited availability and higher initial cost of hydrogen from electrolysis
CARBON CAPTURE & STORAGE **CARBON DIOXIDE REMOVAL**	Limited technologies recognition in the energy and climate strategies of Member States to 2030 and 2050
	Lack of a clear regulatory framework both at national and European level
	Lack of public support for plant construction and national/European-wide infrastructure
	Limited possibility to account for CO_2 offsetting through engineered (BECCS and DACCS) and natural solutions (afforestation/reforestation and biochar)

	ZERO CARBON TECHNOLOGY SCENARIO
CO_2 Life Cycle Assessment	Use of Carbon Neutral biofuels to accelerate the transition from traditional fossil fuels following a LCA of emitted CO_2
Advanced biofuel scope	Broadening the definition of advanced biofuels to all waste, residues and crops not competing with food
CO_2 Life Cycle Assessment	Hydrogen from fossil fuel with CCUS and CDR recognized as Carbon Neutral following a LCA
Market uptake	Accelerated market uptake thanks to wide availability and lower initial cost of Carbon Neutral hydrogen from fossil fuel
Recognition in national climate strategies	Widely recognised technologies in the energy and climate strategies of Member States to 2030 and 2050
Regulatory framework	Development of a clear and shared European regulatory framework to enhance common infrastructure among Member States
Public support	Definition of public support mechanisms for the construction of infrastructures and plants that award grants on the basis of economic efficiency in abating emissions vs. other decarbonisation technologies
CO_2 accounting	Possibility of accounting for CO_2 offsetting through engineered (BECCS and DACCS) and natural solutions (afforestation/reforestation and biochar)

The model is based on a set of five variables that are used to evaluate the potential diffusion of each technology in different sectors:

- **Percentage of addressable direct emissions:** this variable considers the share of CO_2 reduction that can be achieved thanks to the analysed technological levers;
- **Degree of maturity**: it measures the Technological Readiness Level (TRL) of each technology to assess the market potential and diffusion, and its relative time span;
- **Economic feasibility**: it refers to the cost, CAPEX and OPEX, that must be covered to exploit the technology analysed;
- **Plant readiness**: it evaluates the necessity to update facility infrastructures in order to exploit the technology considered;
- **System readiness**: it measures all the other factors (e.g. source availability, infrastructure readiness, regulatory framework, public acceptance, etc.) that need to be taken into account when evaluating the potential diffusion of each technology.

In the next part of the chapter, the analyses for the Hard to Abate, heavy transport and power generation industries are presented. The aim of these sections is to describe the main technology options and their impacts in terms of decarbonisation of the sectors considered according to the two scenarios described above (Inertial Scenario and Zero Carbon Technology Scenario).

The following analyses present, for each sector, an overview of the emission sources and their evolution over time. Then, a schematic table covering all the main decarbonisation levers and key elements to consider for the potential application and feasibility in the sectors is presented. Finally, for each sector, the proprietary model for the assessment of CO_2 reduction fostered by the decarbonisation levers is presented.

The impact of the decarbonisation levers and their potential contribution to emission reduction have been assessed by The European House - Ambrosetti following an **intense activity of literature review of academic and managerial papers, the stakeholder engagement activities** (Working Tables that involved 30 stakeholders and one-to-one interviews with External experts) and the **discussion with top-experts within the Working Groups**.

Figure 4

Stakeholders involved in the Hard to Abate and Transports Working Tables

Sectorial Analysis: Hard to Abate industry

The first area analysed takes into consideration Hard to Abate industries, namely cement, iron and steel and chemical. As previously mentioned, the decarbonisation of these industries poses challenges related to the very nature of the processes, e.g., the need to achieve extremely high operating temperatures that are difficult to achieve using renewable electricity sources, or the existence of emission caused by chemical reactions that cannot be avoided. Given these elements, it is crucial to define all the possible and alternative solutions that can foster and promote the decarbonisation of the Hard to Abate industrial sectors.

Cement

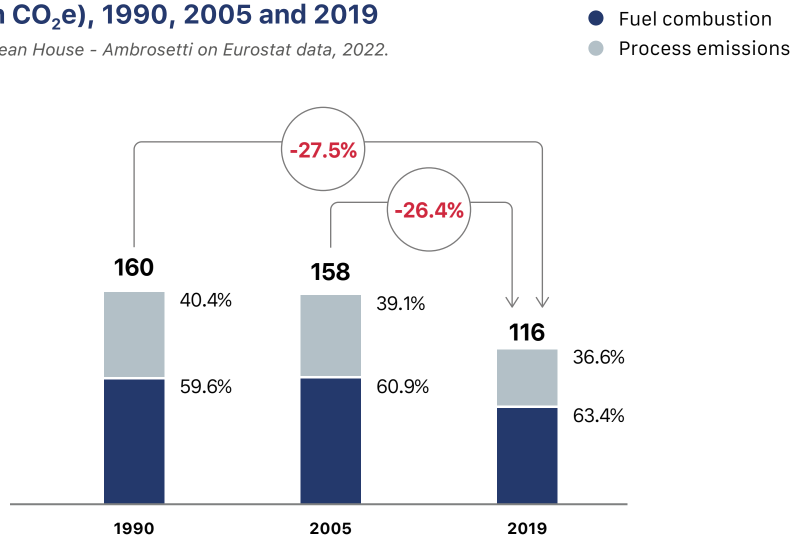
In the past 30 years, global GHG emissions from cement production have increased by 65.2%, going from 0.8 Gton CO_2e in 1990 to 2.3 Gton CO_2e in 2019, with industrial processes accounting for 65% of total emissions. **The European cement sector** followed a different trend, as **GHG emissions have decreased** by 27.5% since 1990 (from 160 to 116 Mton CO_2e), with industrial processes being the most emitting part.[3]

3 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

Figure 5

Process and fuel combustion GHG emissions in the cement production sector in Europe (% and Mton CO_2e), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022.



On average, the cement sector alone accounts for about **3.2% of total GHG emissions in the European Union**. As of 2019, Spain is the country where the cement sector weighs the most over national emissions (4.7%). In Italy, cement emissions were 3.2% of national emissions (in line with the average European level), whereas in France the figure was 2.7%, and in Germany it was 2.5%. Over time, cement emissions decreased in all countries. Since 1990, the biggest reduction was observed in Italy, where emissions decreased by 49.3%. The second largest emission reduction was observed in France (-37.6%), followed by Spain (-28.7%), and Germany (-19.9%).[4]

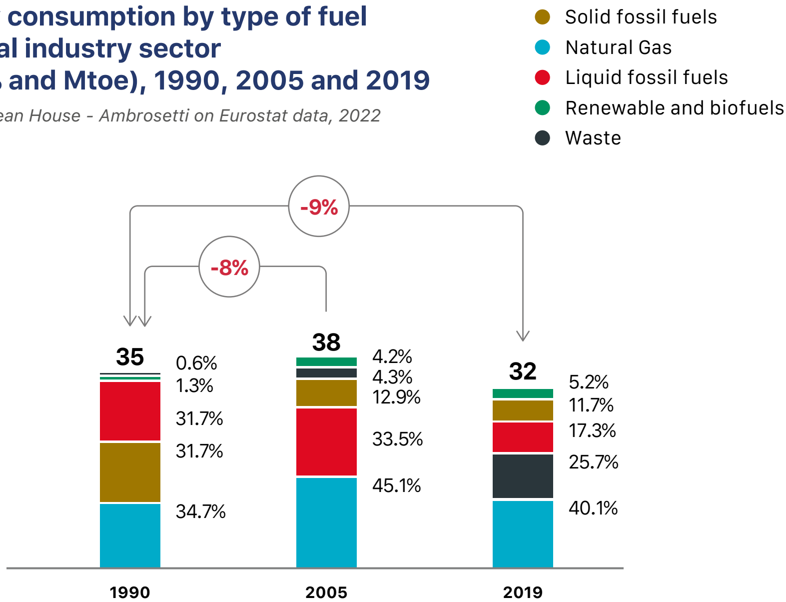
Since 1990, final energy consumption in the mineral industry sector[5] (which comprises the cement sector) **has decreased by 9%** in the European Union, going from 35 Mtoe in 1990 to 32 Mtoe in 2019. Natural gas was the main source in 2019 (40.1%). Notably, the share of solid and liquid fossil fuels over final consumption has decreased by 20.1 p.p. and 14.4 p.p. between 1990 and 2019.[6]

4 *Ibid.*
5 *Note: the final energy consumption by source is only available at the aggregate level i.e., mineral industry. Given that the cement sector represents a relevant share of this sector, the whole sectoral consumption are considered a good proxy for cement consumption.*
6 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

Figure 6

Final energy consumption by type of fuel in the mineral industry sector in Europe (% and Mtoe), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



For the cement industry, the analysis has identified six decarbonisation levers:

- **Energy efficiency** – Considering that most emissions come from the industrial process and the high temperatures required, the range to implement energy efficiency measures is limited and maturity is high, but the possibility of integration into plants if there is an economic benefit shall be investigated;[7]
- **Renewable electrification** – Using electricity to provide process heat could contribute to decarbonising the sector if the electricity provided is 100% fossil fuel free. The cement industry is exploring several technologies to electrify cement production, including generating the heat via plasma generators and microwave energy, which have yet to be developed beyond the laboratory (TRL 3).[8] The construction of a pilot plant that uses plasma technology is currently being investigated. An

7 *Source: elaboration The European House - Ambrosetti on Press Release "Vattenfall and Cementa take the next step towards a climate neutral cement" (2019), Report "Elaborating the decarbonisation roadmap", Climate Action Tracker (2020), Report "Decarbonisation pathways for the EU cement sector", New Climate Institute (2020) and Report "The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete", Global Cement and Concrete Association (2021), 2022.*

8 *Source: elaboration The European House - Ambrosetti on Report "Deep decarbonisation of industry: The cement sector", European Commission and Joint Research Centre (JRC), 2022.*

important possible benefit of electrified heating systems is the much higher concentration of CO_2 in the flue gases than with combustion heating, from an estimated 25% CO_2 concentration to close to 100%. This would allow easier capture and purification of CO_2 from process emissions;[9]

- **Carbon Neutral fuels** – Currently, the fuels used to provide the necessary process heat are a mix of fossil fuels (mainly petcoke, coal and oil), waste fuels and biomass, while bioenergies usage accounts for 6% of the total fuel mix in the European cement sector. The co-processing of fuels (use of alternative fuels, such as waste and biomass) currently represents nearly half of all fuels used in the EU cement industry, with some cement plants reaching occasional substitution rates of 100%. While alternative fuels could provide 100% of the thermal energy, full substitution of fossil fuels with truly sustainable biomass is technically challenging due to the lower calorific value of most organic materials;[10]
- **Hydrogen** – Combusting hydrogen as a fuel can reach the high temperatures required in the cement manufacturing process but has not yet been tested. Since the combustion of hydrogen and the heat transfer (by radiation) in the kiln differ significantly from fuels currently used, extensive research would be required on modifications to cement kilns. Cement production using a mixture of hydrogen and biomass fuels is currently at an early stage of investigation (TRL 2);[11]
- **Carbon Capture Utilization & Storage and Carbon Dioxide Removal** – To fully decarbonise the sector, process emissions from the clinker-making process need to be addressed, regardless of the heat source. Part of the solution will need to be CO_2 capture applied to both the combustion and process emissions or combining a zero-CO_2 heat source with the capture of concentrated process emissions;[12]
- **Feedstock change** – Clinker can be partially substituted by so-called supplementary cementitious materials, such as fly ash from coal power plants and blast furnace slag from steelmaking. Due to the reduced clinker ratio, less energy is required for clinker-burning and some of the process emissions inherent to clinker-making are avoided.[13]

9 *Source: elaboration The European House - Ambrosetti on Press Release "Vattenfall and Cementa take the next step towards a climate neutral cement" (2019) and Paper "CemZero – A Feasibility Study Evaluating Ways to Reach Sustainable Cement Production via the Use of Electricity", Wilhelmsson, Bodil, et al. (2018), 2022.*

10 *Source: elaboration The European House - Ambrosetti on Paper "Use of Alternative Fuels in Cement Manufacture: Analysis of Fuel Characteristics and Feasibility for Use in the Chinese Cement Sector", Murray, A and Price, L., Berkeley National Laboratory (2008), 2022.*

11 *Source: elaboration The European House - Ambrosetti on Press Release "Vattenfall and Cementa take the next step towards a climate neutral cement" (2019) and Report "Deep decarbonisation of industry: The cement sector", European Commission and Joint Research Centre (JRC), 2022.*

12 *Ibid.*

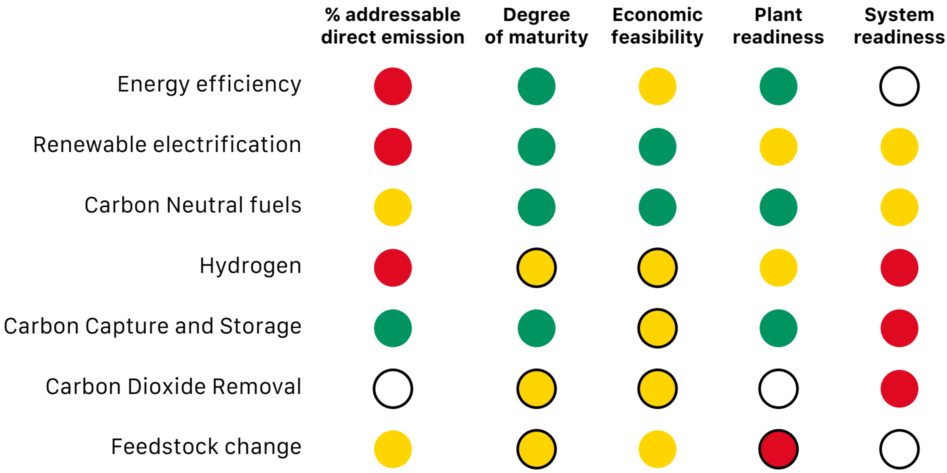
13 *Source: elaboration The European House - Ambrosetti on Report "Deep decarbonisation of industry: The cement sector", European Commission and Joint Research Centre (JRC), 2022.*

Figure 7

Decarbonisation levers for the cement industry

Legend: The colour of the circle represents the level of advancement of each technology (green, if high; yellow, if intermediate; red, if low; white, if not applicable).
The outline of the circle represents the dynamic view (blue outline indicates an expectation of strong improvement for the coming years)

Source: elaboration The European House - Ambrosetti, 2022



According to the model developed by The European House - Ambrosetti:

- In the **Inertial Scenario, the combination of the decarbonisation technological levers will allow to reduce the impact of CO_2 emissions up to 17% at 2030 and up to 47% in 2050;**
- In the **Zero Carbon Technology Scenario**, promoting more comprehensive deployment of various decarbonisation technologies, it will be possible to decrease up to **24% the sector's emissions by 2030 and 81% by 2050.**[14]

In both scenarios, **Carbon Capture Utilization & Storage is the most relevant technological option to promote the decarbonisation of the cement industry** – in 2050, it accounts for 20% CO_2 reduction in the Inertial Scenario and 58% in the Zero Carbon Technology Scenario.

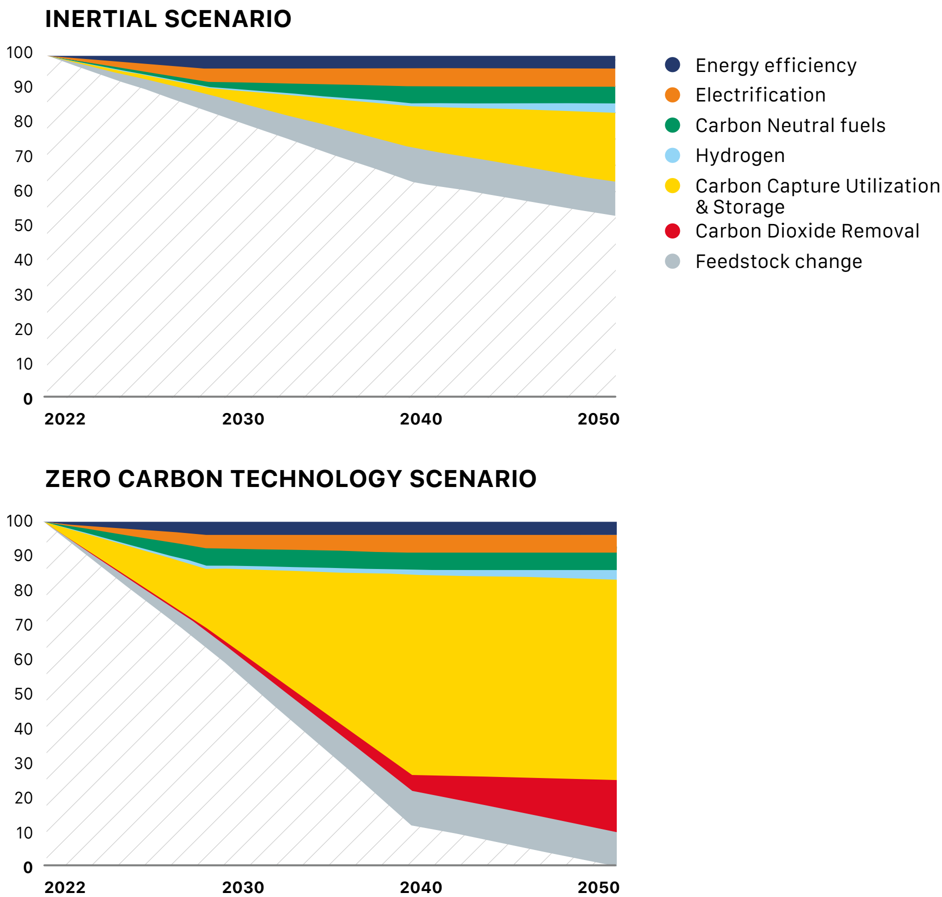
14 *Source: The European House - Ambrosetti on data from proprietary models, 2022.*

Only in the Zero Carbon Technology Scenario, Carbon Dioxide Removal is included, fostering a 15% CO_2 reduction in 2050.

Figure 8

CO_2 emissions reduction in the cement industry considering different technologies, in Europe (%), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



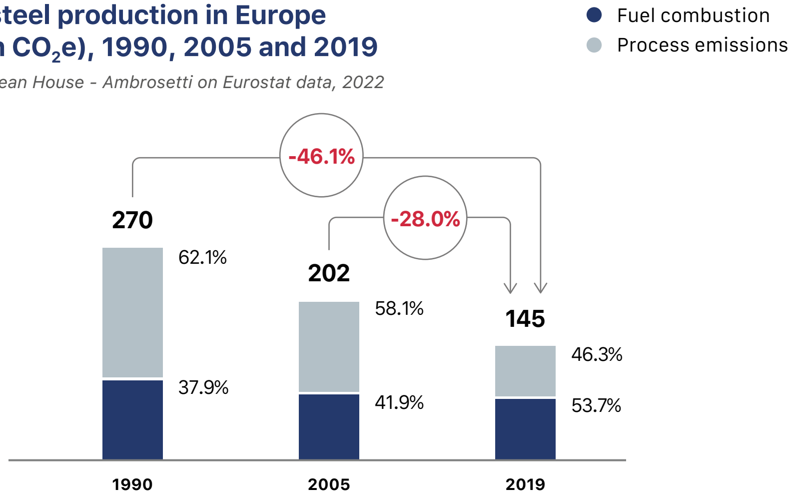
Iron and Steel

In the past thirty years, **GHG emissions from iron and steel production have increased by 46.2% worldwide** going from 1.4 Gton CO_2e in 1990 to 2.6 Gton CO_2e emitted in 2019, with energy-related fuel combustion being the most emitting part (88.5%). At the **European level, GHG emissions from the production of iron and steel have decreased by 46.1%**, with fuel combustion being the most emitting part in 2019 (53.7%).[15]

Figure 9

Process and fuel combustion GHG emission in iron and steel production in Europe (% and Mton CO_2e), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



On average, **the iron and steel sector alone accounted for 4% of total GHG emissions in the European Union in 2019**. Germany is the country where the iron and steel sector weighs the most over national emissions (6.7%), followed by France (3.8%), Italy (2.7%) and Spain (2.2%). Since 1990, emissions decreased in all analysed countries: the largest reduction was observed in Italy (-60.5%), followed by Spain (-42.3%), France (-32.6%) and Germany (-8.2%).[16]

Since 1990, **final energy consumption in the iron and steel industry sector have decreased by 59.9%** in the European Union, going from 37 Mtoe consumed in 1990 to 15 Mtoe in 2019. Natural gas was the main source in 2019 (78.3%). Notably, the share of solid and liquid fossil fuels over

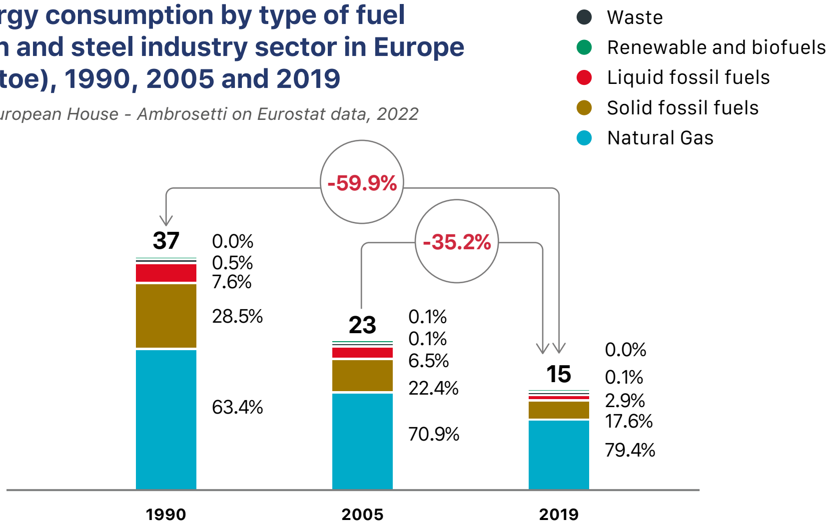
15 *Source: The European House - Ambrosetti on Eurostat data, 2022.*
16 *Ibid.*

final consumption has decreased by 10 p.p. and 4.6 p.p. between 1990 and 2019.[17]

Figure 10

Final energy consumption by type of fuel in the iron and steel industry sector in Europe (% and Mtoe), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



For the iron and steel industry, the analyses have identified five main decarbonisation levers:

- **Energy efficiency** – The iron and steel industry's potential for decarbonisation through process efficiency alone is limited since current iron and steel-making processes have been efficiently operated (from an industry standpoint) close to their thermodynamic limits;[18]
- **Renewable electrification** – This solution would allow to lower energy consumption, and it is technically feasible to decarbonise the iron and steel industry but is limited in market share to recycled steel capacity;[19]
- **Biomasses** – Biomass, especially solid biofuels, provides a promising option for both low-carbon heat and possible low-carbon coking feedstock for use in primary production.[20] Biomass could replace fossil-based reducing agents and it has the potential to decrease CO_2

17 *Ibid.*
18 *Source: elaboration The European House - Ambrosetti on Paper "Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options", Kim J. et al. (2022) and Paper "Evaluation of reactive absorption and adsorption systems for post-combustion CO_2 capture applied to iron and steel industry", Appl. Therm. Eng. (2016), 2022.*
19 *Source: elaboration The European House - Ambrosetti on Paper "Low-carbon production of iron and steel: Technology options, economic assessment, and policy", Fan Z. and Friedman S. (2021), 2022.*
20 *Ibid.*

emissions up to 50% in the integrated steelmaking process. Biochar can be used in the sintering process, and charcoal is a promising substitute in blast furnaces;[21]

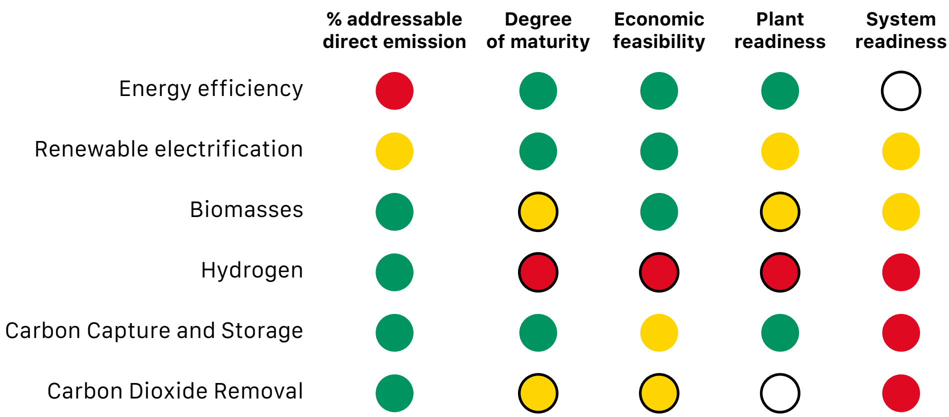
- **Hydrogen** – Hydrogen would be effective for CO_2 mitigation in various iron and steel processes, such as BF (blast furnace), DRI (direct reduced iron), smelting reduction, and ancillary procedures. Hydrogen could also be used directly as a reducing agent in the steel-making process and therefore has excellent potential for CO_2 reduction;[22]
- **Carbon Capture Utilization & Storage and Carbon Dioxide Removal** – Carbon Capture, Utilization & Storage (CCUS) technology is one of the key options to mitigate carbon emissions and hence could be helpful for the decarbonisation of the iron and steel industry.[23]

Figure 11

Decarbonisation levers for the iron and steel industry

Legend: The colour of the circle represents the level of advancement of each technology (green, if high; yellow, if intermediate; red, if low; white, if not applicable).
The outline of the circle represents the dynamic view (blue outline indicates an expectation of strong improvement for the coming years)

Source: elaboration The European House - Ambrosetti, 2022.



21 *Source: elaboration The European House - Ambrosetti on Paper "Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options", Kim J. et al. (2022), 2022.*

22 *Source: elaboration The European House - Ambrosetti on Paper "Low-carbon production of iron and steel: Technology options, economic assessment, and policy", Fan Z. and Friedman S. (2021) and Paper "Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options", Kim J. et al. (2022), 2022.*

23 *Source: elaboration The European House - Ambrosetti on Paper "Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products", Muslemani H. et al. (2021) and on Paper "Low-carbon production of iron and steel: Technology options, economic assessment, and policy", Fan Z. and Friedman S. (2021), 2022.*

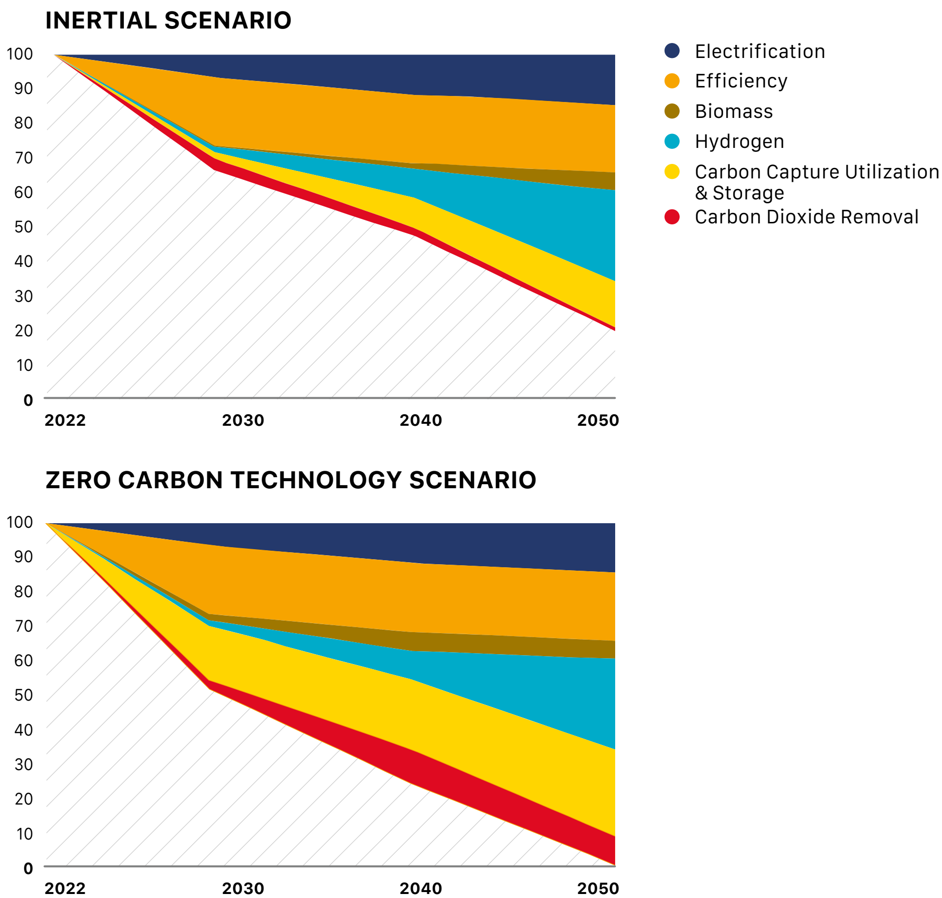
For iron and steel industry the model estimates a potential **CO_2 reduction of 34% in 2030 that can reach 81% in 2050 in the Inertial Scenario**. In contrast, in the **Zero Carbon Technology Scenario**, the greater deployment of different technology options may promote faster decarbonisation of the sector, **up to 49% in 2030 and 100% in 2050**.

Again, CO_2 sequestration and capture technologies – Carbon Capture Utilization & Storage and Carbon Dioxide Removal – are the real differentiators between the two scenarios.

Figure 12

CO_2 emissions reduction in the iron and steel industry considering different technologies, in Europe (%), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



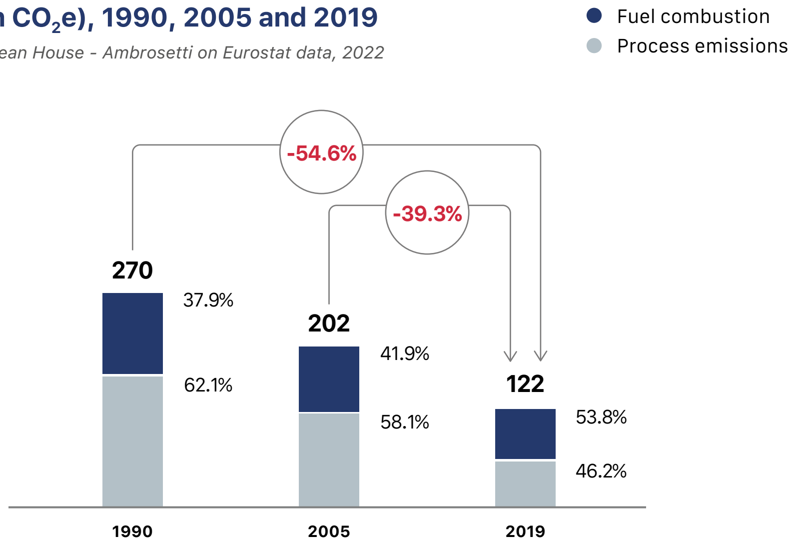
Chemical

In the past thirty years, **GHG emissions from the chemical sector have increased by 21.4% worldwide** going from 1.1 Gton CO_2e in 1990 to 1.4 Gton CO_2e emitted in 2019, with energy-related fuel combustion being the most emitting part (85.7%). **At the European level, GHG emissions from the chemical sector have decreased by 54.6%** (from 270 to 122 Mton CO_2e), with fuel combustion being the most emitting part in 2019 (53.8%).[24]

Figure 13

Process and fuel combustion GHG emission in the chemical sector in Europe (% and Mton CO_2e), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



On average, **the chemical sector alone accounted for 3.4% of total GHG emissions in the European Union in 2019**. Spain is the country where the chemical sector weighs the most over national emissions (4.3%), followed by France (4.1%) and Italy (2.7%). For Germany, only process emission data is available, and it weighs 0.8% over national emissions. Since 1990, emissions from the chemical sectors have decreased in all four countries, especially in Germany (-78%), followed by France (-65.2%), Italy (-64.3%), and Spain (-3%).[25]

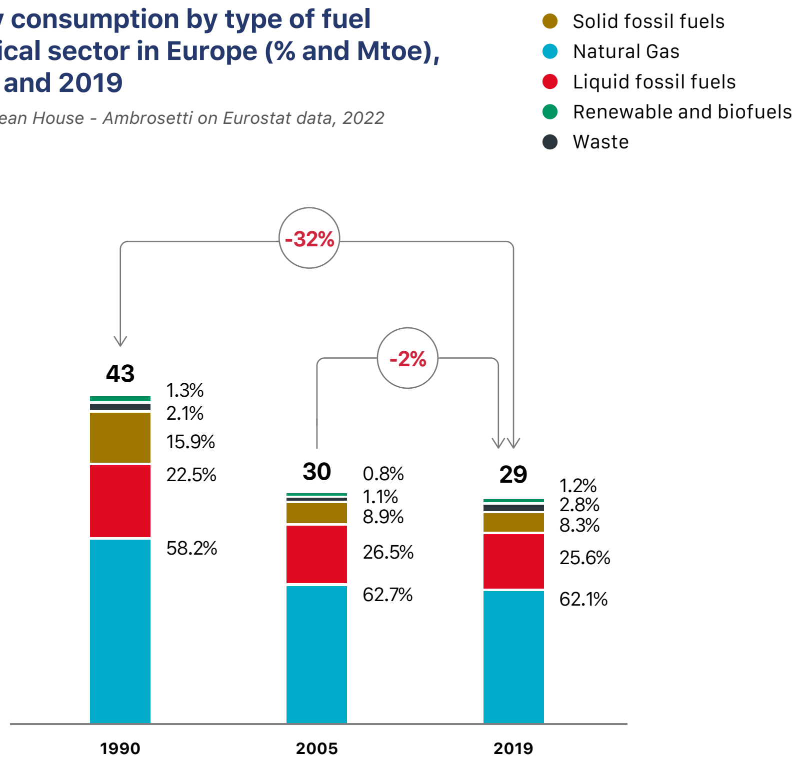
24 *Source: The European House - Ambrosetti on Eurostat data, 2022.*
25 *Ibid.*

Since 1990, final energy consumption in the chemical sector have decreased by 32% in the European Union, going from 43 Mtoe consumed in 1990 to 29 Mtoe in 2019. Natural gas was the main source in 2019 (62.1%). Notably, the share of solid fossil fuels over final consumption has decreased by 7.6 p.p., whereas the share of liquid fuels has increased by 3.1 p.p. between 1990 and 2019.[26]

Figure 14

Final energy consumption by type of fuel in the chemical sector in Europe (% and Mtoe), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



26 *Ibid.*

In the chemical industry, the analysis has identified six technological levers for decarbonisation:

- **Energy efficiency** – The leverage of energy efficiency can be used on the different components of plants, fostering the spread of best practices and frontier technologies to reduce energy demand. The energy efficiency levers is considered an important element to foster decarbonisation of the industry;[27]
- **Renewable electrification** – The electrification of processes and the introduction of new catalytic processes can be key elements in facilitating the decarbonisation of the sector. However, the adoption of such tools requires a radical rethinking of many of the plants with consequent capital costs and long payback periods;[28]
- **Biofuels and bio-feedstock** – Various biomass feedstocks can replace fossil fuels for process heat generation. Moreover, bio-feedstock will be viable source of substitution but some processes and end products will require a re-thinking;[29]
- **Carbon Capture Utilization & Storage and Carbon Dioxide Removal** – The carbon sequestration route offers the possibility of using existing technologies and infrastructures, without the need of a complete reshaping of the chemical industry while permanently removing CO_2 from the atmosphere, hence representing a key element not only to achieve net zero CO_2 emissions, but also to achieve net-negative CO_2 emissions;[30]
- **Recycled plastic** – Mechanical and chemical recycling techniques could have a role in marginally reducing carbon footprint of the chemical industry. Anyhow the former requires improvements in sorting capacity and resource management, while the latter needs technological innovations to expand the amount of plastics polymers handled;[31]
- **H_2-based chemical** – Low-CO_2 hydrogen and derivate products will play a systemic role in the decarbonisation of the chemical industry. Hydrogen could be used as sustainable fuel, and as sustainable feedstock for the chemical industry.[32]

27 *Source: elaboration The European House - Ambrosetti on Article "Zero-Emission Pathway for the Global Chemical and Petrochemical Sector", Deger Saygin and Dolf Gielen, International Renewable Energy Agency (IRENA), Innovation and Technology Centre (IITC) (2021), 2022.*

28 *Ibid.*

29 *Source: elaboration The European House - Ambrosetti on Paper "Green feedstock for the chemical industry – ambition and reality", Cefic and Report "Bio-Based Chemicals", IEA (2021), 2022.*

30 *Source: elaboration The European House - Ambrosetti on Report "The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero- CO_2 Emissions Chemical Industry", Industrial & Engineering Chemistry Research (2020), 2022.*

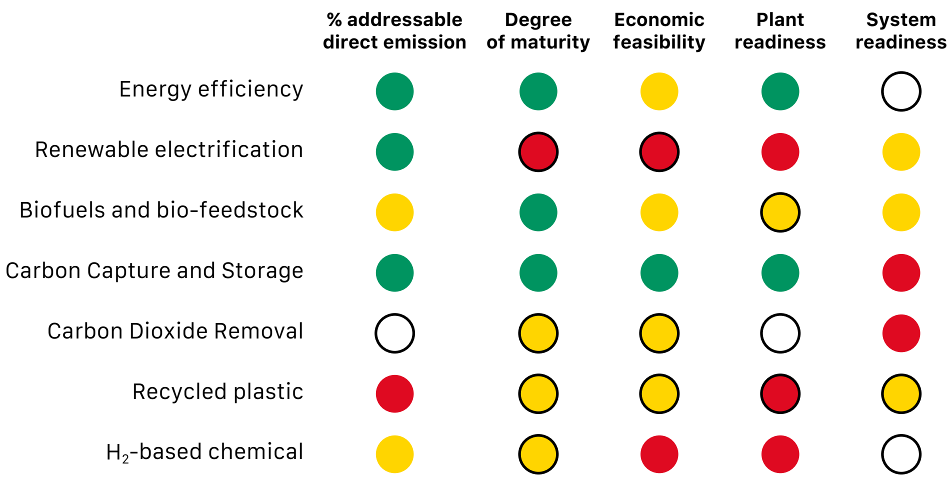
31 *Source: elaboration The European House - Ambrosetti on Report "Chemical Recycling: Greenhouse gas emission reduction potential of an emerging waste management route", Cefic (2020) and*

32 *Source: elaboration The European House - Ambrosetti on Report "HYDROGEN ROADMAP EUROPE", Fuel Cell and Hydrogen Joint Undertaking (2019), Results of the Round Tables "Clean Hydrogen in Industrial Applications", European Clean Hydrogen Alliance (2021) and Report "Green Hydrogen a Guide to Policy Making", IRENA (2020), 2022.*

Figure 15

Decarbonisation levers for the chemical industry

Legend: The colour of the circle represents the level of advancement of each technology (green, if high; yellow, if intermediate; red, if low; white, if not applicable).
The outline of the circle represents the dynamic view (blue outline indicates an expectation of strong improvement for the coming years)



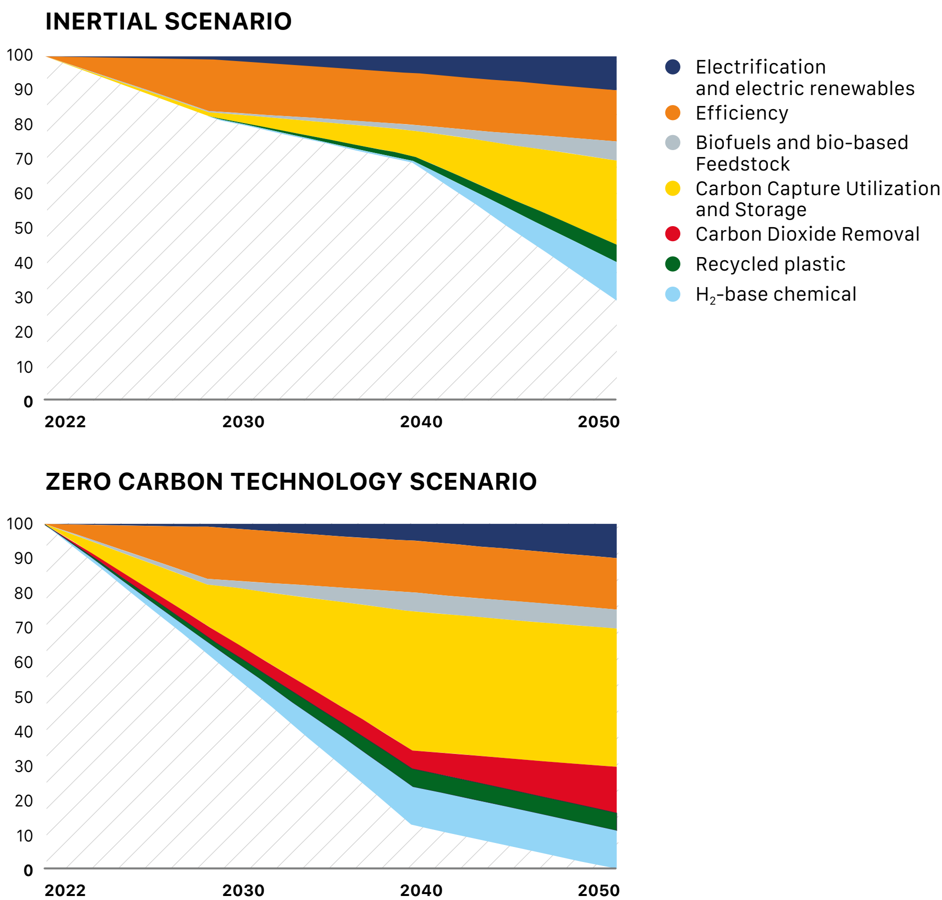
In the **Inertial Scenario, chemical industry is expected to reach an 18% reduction of its CO_2 emissions by 2030 which can reach 71% in 2050.**

By leveraging on a greater deployment of the technologies considered in the previous scenario and assuming the presence of Carbon Dioxide Removal solutions, in the **Zero Carbon Technology Scenario, the chemical sector can achieve 38% decarbonisation by 2030 and 100% by 2050.**

Figure 16

CO_2 emissions reduction in the chemical industry considering different technologies, in Europe (%), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



Sectorial Analysis: heavy transport

In this second section, the focus of the analysis shifts towards heavy and long-haul transport modes, analysing Heavy Duty vehicles,[33] Marine and Aviation transports. For these sectors, the decarbonisation is challenging, given that they can rely only marginally on electric powertrain (e.g., for short distance routes).

Heavy Duty vehicles

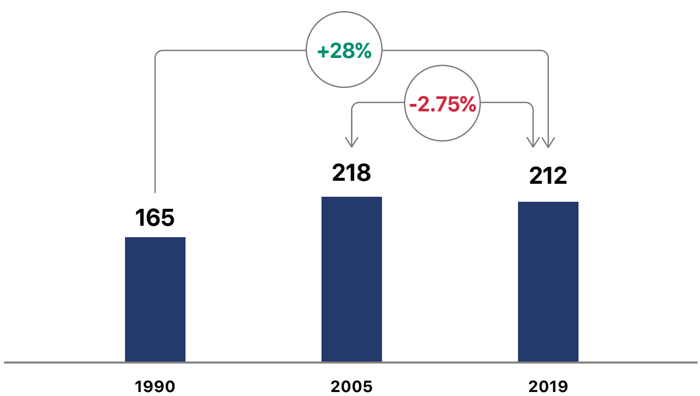
At the European level, **emissions generated by Heavy Duty trucks and buses have increased by 28%** between 1990 and 2019, going from 165 Mton CO_2e emitted in 1990, to 212 Mton CO_2e in 2019. Notably, a 2.75% reduction was observed since the 2005 level (218 Mton CO_2e).[34]

On average, Heavy Duty vehicles alone accounted for 26.7% of total road transport emissions in the European Union in 2019. Germany is the country where Heavy Duty transport weighs the most over national road transport emissions (29%), followed by France (26%), Spain (23.3%) and Italy (18%).[35]

Figure 17

GHG Emissions by fuel combustion in Heavy Duty trucks and buses in Europe, (Mton CO_2e) 1990, 2005 and 2019

Source: The European House Ambrosetti on Eurostat data, 2022



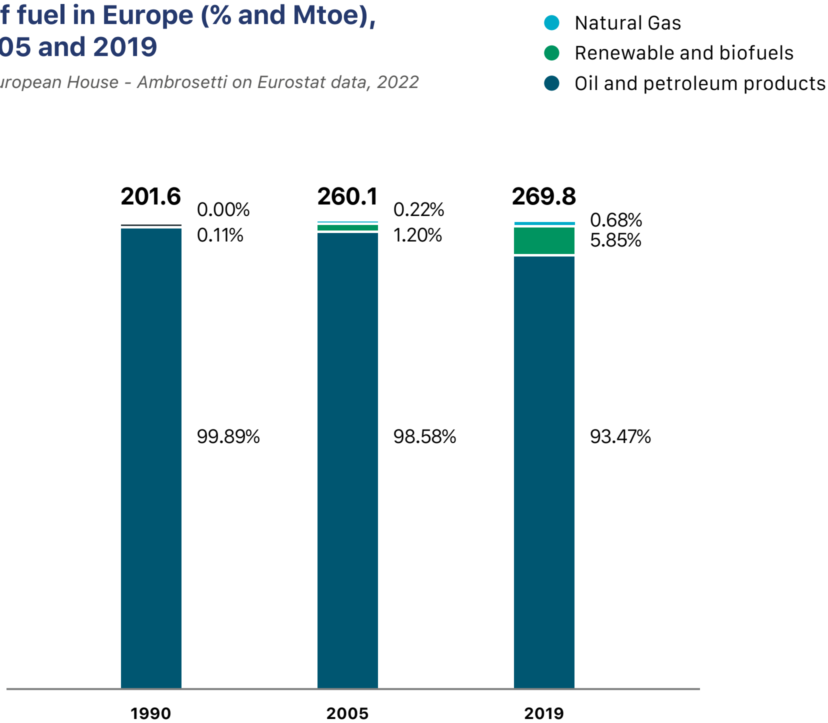
33 *Heavy Duty vehicles include trucks that weight more than 3.5 tons or buses and coaches with more than 8 seats.*
34 *Source: The European House - Ambrosetti on Eurostat data, 2022.*
35 *Ibid.*

Since 1990, **road transports fuel consumption**[36] **has increased by 34% in the European Union**, going from 201.6 Mtoe in 1990 to 269.8 Mtoe in 2019. Oil and petroleum products were the main source in 2019 (93.47%), while renewables and biofuels represented 5.85% of fuel consumption, and natural gas accounted for 0.68%. Notably, the share of oil and petroleum products over final consumption has decreased by 6.42 percentage points between 1990 and 2019, whereas the share of renewables and biofuels increased by 5.85 percentage points, and the share of natural gas increased by 0.57 percentage points.[37]

Figure 18

Road transport consumption by type of fuel in Europe (% and Mtoe), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



36 *Data on Heavy Duty trucks and buses fuel consumption by type of source is not available, hence the aggregate road consumption are considered as a proxy to get a glance on the evolution of the fuel mix.*
37 *Ibid.*

In the Heavy Duty vehicles sector the main decarbonisation levers are related to:

- **Internal Combustion Engine LNG / CNG** – Natural gas as a fuel for Heavy Duty vehicles has a potential to reduce CO_2 emissions from transport. Moreover, blending it with renewable gas can contribute to accelerate transport decarbonisation;[38]
- **Synthetic Fuels** – Synthetic fuels can be already used in vehicles without requiring a significant change in the propulsion system. Synthetic fuels derived from CO_2 represent a bridge in the energy transition, helping to accelerate towards net zero emissions;[39]
- **Biofuels** – Biofuels can also be used without requiring major modifications to the propulsion system. Biofuels could have an even larger contribution to emissions reduction in the future, depending on commercial developments and their availability in the EU. Advanced Biofuels, once commercially available, could enable emissions reduction in this sector (up to 90%);[40]
- **Battery Technologies (BEV)** – Electric motorizations will only be available on short-medium distance routes and in cases with a definable route so that charging stops can be managed. The deployment of fast-charging technologies may encourage the spread of electric motorizations. In addition, Heavy Duty electric vehicles will have to discount the weight and space occupied by the battery pack that can drastically lower the payload available up to 30%;[41]
- **Fuel Cell Electric Vehicles (FCEV)** – Hydrogen-powered vehicles can overcome the issues of range limitation of BEV vehicles, as well as decreasing charging time (10 to 15 minutes are required depending on the size of the tank). Moreover, FCEVs offer the same high torque that comes with battery electric vehicles, but at lower weight. To enable the full deployment of this type of vehicle, it is necessary to create the refuel infrastructure and develop new platforms for the vehicles;[42]
- **Electric Road System (ERS)** – The creation of electric road system could play a relevant role in fostering the diffusion of electric power-

38 *Source: elaboration The European House - Ambrosetti on Article "Technology-neutral approach to transport decarbonisation", Natural & bio Gas Vehicle Association, 2022.*

39 *Source: elaboration The European House - Ambrosetti on Paper "Synthetic Fuels in a Transport Transition: Fuels to Prevent a Transport Underclass", Front. Energy Res. (2021) and Report "Synthetic Transport Fuels, Policy Briefing", The Royal Society (2019), 2022.*

40 *Source: elaboration The European House - Ambrosetti on Paper "Accelerating to zero Speeding up the decarbonisation of Heavy Duty vehicles in the EU", Stockholm Environment Institute (2021) and Paper "Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake", Energy Strategy Reviews (2021), 2022.*

41 *Source: elaboration The European House - Ambrosetti on Article "The feasibility of heavy battery electric trucks", Nykvist, B. and Olsson, O. (2021), Paper "Technical and Business Aspects of Battery Electric Trucks— A Systematic Review", Future Transportation (2022) and Paper "The long haul towards decarbonising road freight – A global assessment to 2050", Mulholland E. et al. (2018), 2022.*

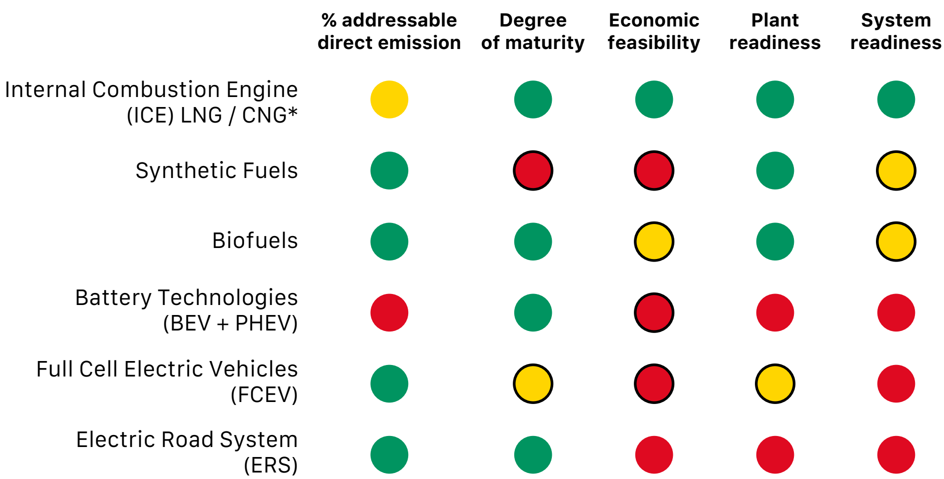
42 *Source: elaboration The European House - Ambrosetti on Article "Hydrogen Fuel Cell trucks can decarbonise heavy transport", Energypost.eu (2019) and Paper "Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California", Forrest K. et al. (202o), 2022.*

train with positive results in terms of CO_2 reduction. The ERS solution is still in a primordial phase where research and development (R&D), coupled with financial support, is needed. In addition, aspects of energy access need to be managed and economic models need to be identified to amortize costs.[43]

Figure 19

Decarbonisation levers for Heavy Duty transport

Legend: The colour of the circle represents the level of advancement of each technology (green, if high; yellow, if intermediate; red, if low; white, if not applicable).
The outline of the circle represents the dynamic view (blue outline indicates an expectation of strong improvement for the coming years)
*20%-25% emission reduction on single Heavy Duty Vehicle



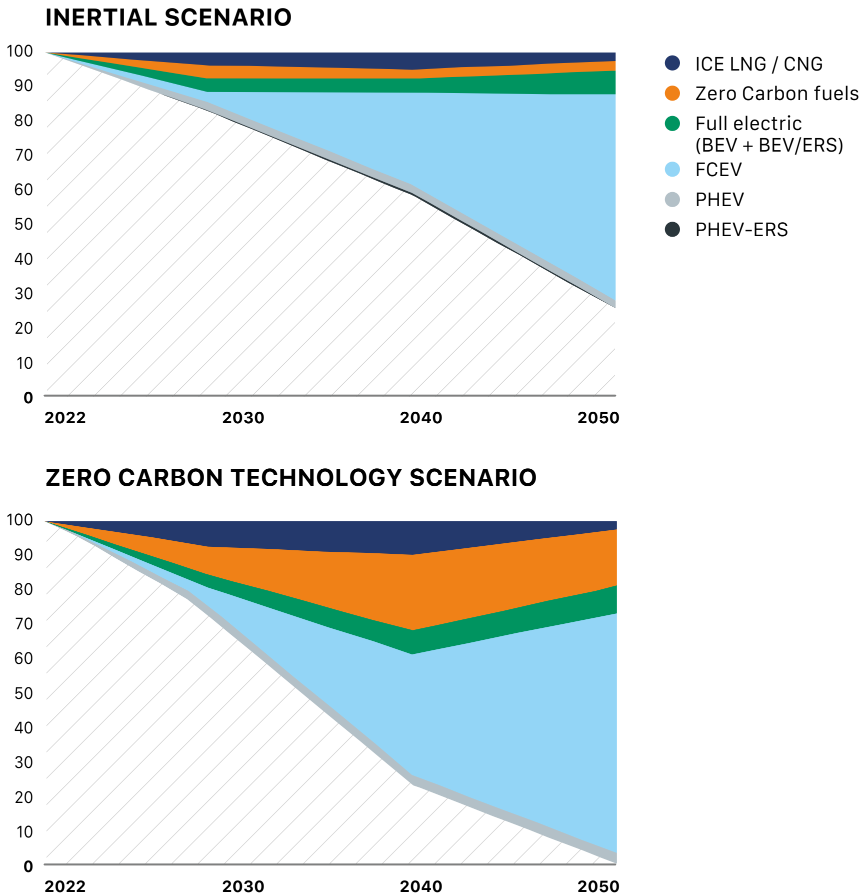
For Heavy Duty vehicles, in the **Inertial Scenario, the model estimates a potential reduction up to 18% of CO_2 emissions in 2030 and 75% in 2050.** In the **Zero Carbon Technology Scenario**, a more relevant increase in the diffusion of Zero Carbon fuels and hydrogen is expected with respect to the Inertial Scenario, fostering a **reduction of 28% CO_2 emissions in 2030 and 100% in 2050**.

43 *Source: elaboration The European House - Ambrosetti on Report "Research & Innovation Platform for Electric Road Systems", RISE Research Institutes of Sweden (2021), 2022.*

Figure 20

CO_2 emissions reduction in Heavy Duty vehicles considering different technologies, in Europe (%), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



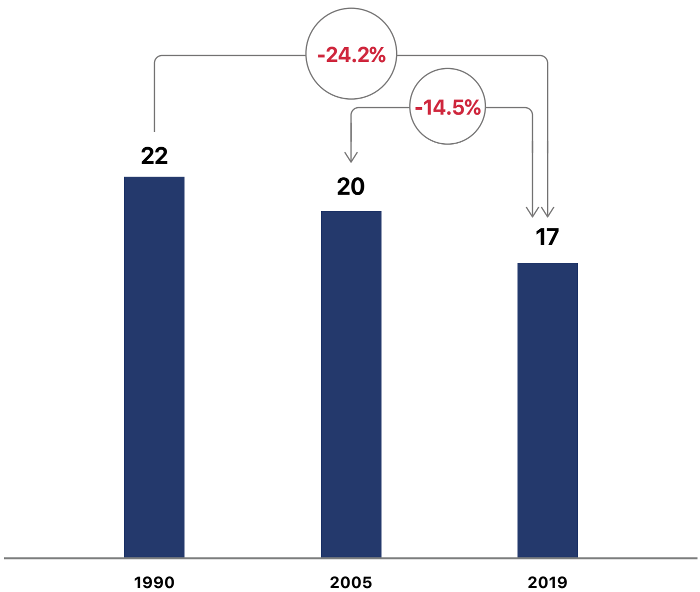
Marine

At the European level, **emissions generated by domestic navigation**[44] **have decreased by 24.2% between 1990 and 2019**, going from 22 Mton CO_2e emitted in 1990, to 17 Mton CO_2e in 2019. On average, domestic navigation alone accounted for 2% of total transport emissions in the European Union in 2019. Italy is the country where domestic navigation weighs the most over national transport emissions (4.2%), followed by Spain (3.6%), France (1%), and Germany (0.95%).[45]

Figure 21

GHG Emissions by fuel combustion in maritime transport in Europe, (Mton CO_2e) 1990, 2005 and 2019

Source: The European House Ambrosetti on Eurostat data, 2022



44 *Domestic navigation covers maritime or inlands shipping of all flags not engaged in international navigation. The domestic/international split is determined based on port of departure and arrival and not by the flag or nationality of the ship.*

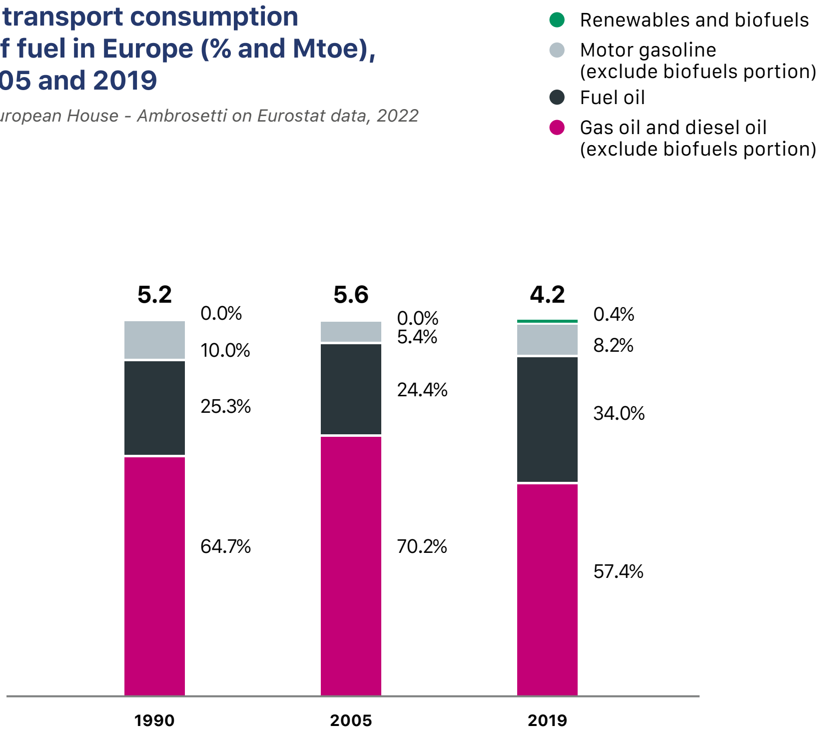
45 *Source: The European House - Ambrosetti on Eurostat data, 2022.*

Since 1990, **maritime transports fuel consumption**[46] **has decreased by 18.5%** in the European Union, going from 5.2 Mtoe consumed in 1990 to 4.2 Mtoe in 2019. Gas oil and diesel oil were the main source in 2019 (57.4%), together with fuel oil (34%) and motor gasoline (8.2%), they represent the fossil fuel share of final consumption: overall fossil fuels cover 99.6% of demand. Over time, the fuel mix has remained pretty much constant, the share of fuel oil has increased by 8.7 percentage points, at the expense of gas oil and diesel oil and motor gasoline, which decreased by 7.3 and 1.8 percentage points, respectively. The contribution of renewables and biofuels has only increased by 0.4 percentage points.[47]

Figure 22

Maritime transport consumption by type of fuel in Europe (% and Mtoe), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



46 *Domestic navigation covers maritime or inlands shipping of all flags not engaged in international navigation. The domestic/international split is determined based on port of departure and arrival and not by the flag or nationality of the ship.*
47 *Ibid.*

In the marine sectors, the Strategic Study has identified four main decarbonisation levers:

- **Liquid Natural Gas** – The use of LNG results in CO_2 emissions at combustion that are lower than traditional oil-derived bunker fuels usually burned in ship engines. LNG poses some challenges due to the required modifications to ship engines. LNG is considered a possible solution to foster the transition to Carbon Neutral fuels and Zero Carbon fuels;[48]
- **Electricity from the grid** – the use of electric power for vessels could be a functional solution to reduce emissions. There are still challenges related to the technical development of the solution and the retrofitting possibility of vessels in use. A final consideration must be addressed considering the business model: costs are still high. Propulsion can come from electric motors, which are relatively cheap, however, combined with the cost of batteries and their housing on ships, it can be an expensive option;[49]
- **Biofuels and synthetic fuels (Carbon Neutral fuels)** – Alternative fuels may have the potential to lower or have net zero emissions when used for ship propulsion. Their use is possible without changing the propulsion systems of ships. Alternative fuels can also be used as "drop-in" fuels (such as biodiesel) but are only applied on an experimental basis. Such carriers still need development from a technological standpoint and cost reduction;[50]
- **Hydrogen** – A key advantage of hydrogen over other fuel alternatives is the relative ease of retrofitting existing ships with hydrogen fuel cells. Hydrogen, even in liquid forms, is less energy-dense than bunker fuel, meaning that hydrogen fuel cells will take up more volume on cargo ships, causing an efficiency and opportunity cost of lost cargo. Fuel cells are an efficient way of producing low-carbon electricity and they are a key technology to unlock the use of future alternative fuels. This is because fuel cells may provide a suitable solution, since they are fuel-efficient and are associated to few hazardous emissions. Hydrogen has a very high Lower Heating Value (LHV), about three times bigger than traditional marine fuels. The Higher Heating Value (HHV) is 141.8 MJ/kg. Hydrogen combustion allows for the attainment of the most heat energy per 1 kg of mass.[51]

48 *Source: elaboration The European House - Ambrosetti on Report "The Role of LNG in the Transition Toward Low- and Zero Carbon Shipping", World Bank (2021), 2022*

49 *Source: elaboration The European House - Ambrosetti on Paper "Decarbonisation in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals", George Mallouppas and Elias Ar. Yfantis (2021), 2022.*

50 *Source: elaboration The European House - Ambrosetti on Paper "Decarbonisation in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals", George Mallouppas and Elias Ar. Yfantis (2021) and Paper "The Maritime Sector and Its Problematic Decarbonisation: A Systematic Review of the Contribution of Alternative Fuels", Vinicius Andrade dos Santos et al. (2022), 2022.*

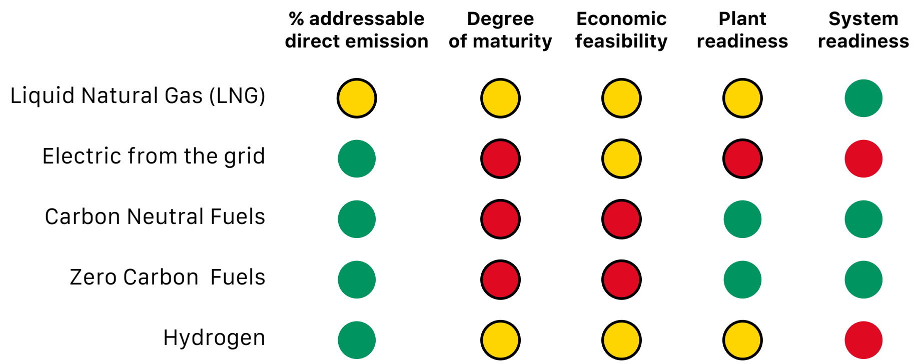
51 *Source: elaboration The European House – Ambrosetti on Paper "Decarbonisation in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals", George Mallouppas and Elias Ar. Yfantis (2021), Article "Decarbonisation of Marine Fuels - The Future of Shipping", Jerzy Herdzik (2021), 2022.*

Figure 23

Decarbonisation levers for Marine transport. Carbon Neutral fuels include biofuels and synfuels. Zero Carbon fuels include hydrogen and other products

Legend: The colour of the circle represents the level of advancement of each technology (green, if high; yellow, if intermediate; red, if low; white, if not applicable).
The outline of the circle represents the dynamic view (blue outline indicates an expectation of strong improvement for the coming years)

Source: elaboration The European House - Ambrosetti, 2022

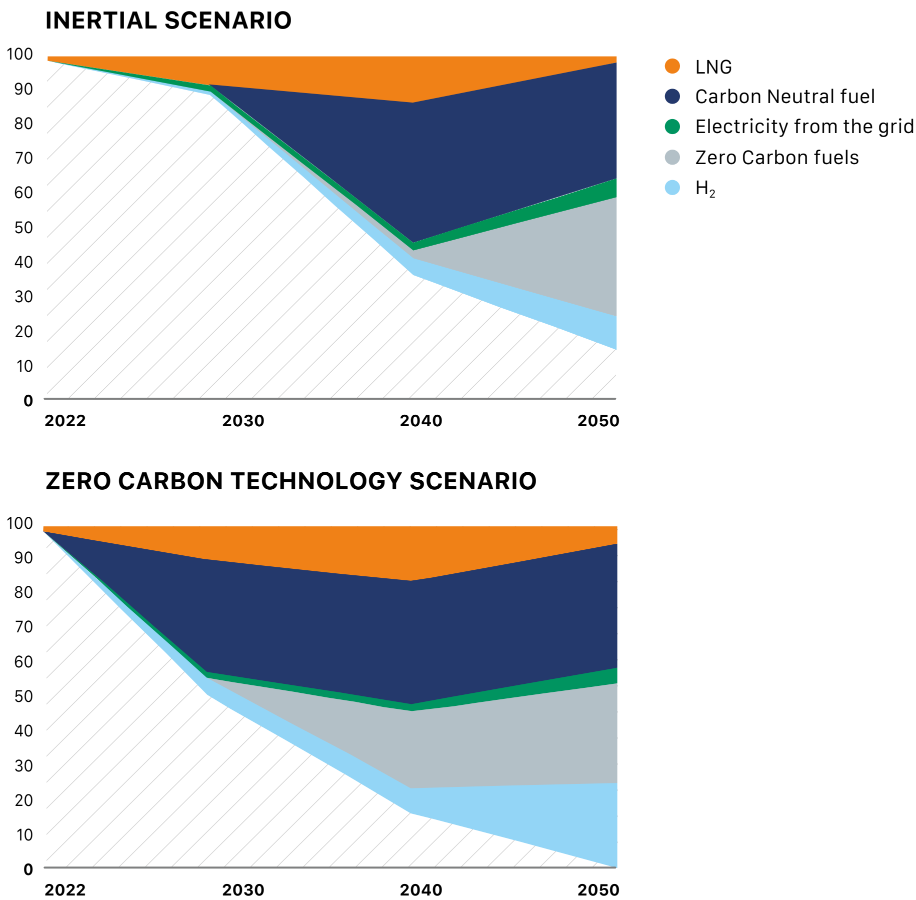


The decarbonisation levers identified for maritime transportation can contribute to the **11% CO_2 reduction in 2030 and 86% in 2050 in the Inertial Scenario.** In the **Zero Carbon Technology Scenario**, the contribution of the technology set can foster a higher CO_2 reduction, up to **50% in 2030 and 100% in 2050**.

Figure 24

CO_2 emissions reduction in Maritime transport considering different technologies, in Europe (%), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



Aviation

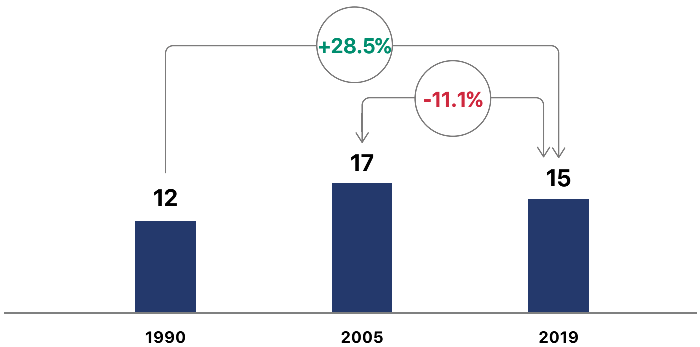
In Europe, **emissions generated by domestic aviation**[52] **have increased by 25.8%** between 1990 and 2019, going from 12 Mton CO_2e emitted in 1990, to 15 Mton CO_2e in 2019. Notably, the sectoral emissions decreased by 11.1% since 2005 levels.[53]

On average, domestic aviation alone accounted for 1.8% of total transport emissions in the European Union in 2019. France is the country where domestic aviation weighs the most over national transport emissions (3.8 %), followed by Spain (3.4%), Italy (2.3%), and Germany (1.4%).[54]

Figure 25

GHG Emissions by fuel combustion in aviation in Europe, (Mton CO_2e) 1990, 2005 and 2019

Source: The European House Ambrosetti on Eurostat data, 2022



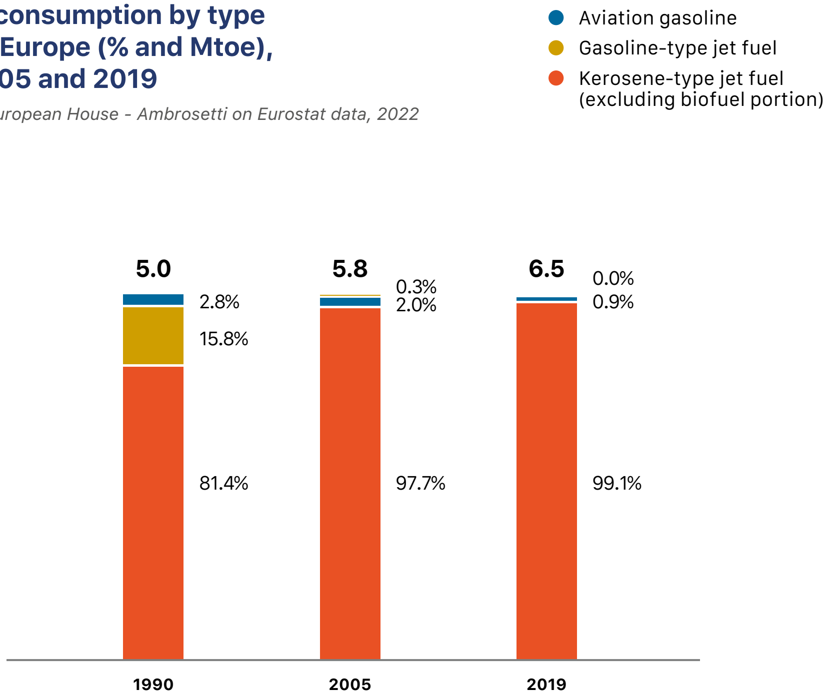
Since 1990, **aviation fuel consumption**[55] **has increased by 30.3%** in the European Union, going from 5 Mtoe consumed in 1990 to 6.5 Mtoe in 2019. Kerosene-type jet fuel was the main source in 2019 (99.1%). Over time, kerosene-type jet fuel has increased at the expense of gasoline-type jet fuel: the contribution of the former has increased by 17.7 percentage point, whereas the contribution of the latter has decreased by 15.8 percentage points.[56]

52 *Domestic aviation includes all those passenger and cargo flights within a specific country's boundaries.*
53 *Source: The European House - Ambrosetti on Eurostat data, 2022.*
54 *Ibid.*
55 *Data on heavy duty trucks and buses fuel consumption by type of source is not available, hence the aggregate road consumption are considered as a proxy to get a glance on the evolution of the fuel mix.*
56 *Ibid.*

Figure 26

Aviation consumption by type of fuel in Europe (% and Mtoe), 1990, 2005 and 2019

Source: The European House - Ambrosetti on Eurostat data, 2022



In the perimeter of this Strategic Study, the considered decarbonisation levers for aviation industry are three:

- **Carbon Dioxide Removal** – Long-haul aviation creates residual emissions that are hard to mitigate, as tackling these emissions requires meaningful actions to reduce fossil fuel use as well as permanently remove and store excess CO_2;[57]
- **Biofuels and syntetic fuels (Carbon Neutral fuels)** – also known as Sustainable Aviation Fuels (SAF) is a liquid fuel currently used in commercial aviation which reduces CO_2 emissions by up to 80%. It can be produced from several sources including waste oil and fats, green and municipal waste and non-food crops. It can also be produced synthetically via a process that captures carbon directly from the air. It is "sustainable" because the raw feedstock does not compete with food crops or water supplies. While fossil fuels add to the overall level of CO_2

57 *Source: elaboration The European House - Ambrosetti on Report "Decarbonizing long-haul aviation requires permanent solutions with real climate benefits", Climatework Foundations (2020) and Report "Aviation, decarbonisation and climate change", House of Commons Library UK (2021), 2022.*

by emitting carbon that had been previously locked away, SAF recycles the CO_2 which has been absorbed by the biomass used in the feedstock during its life;[58]

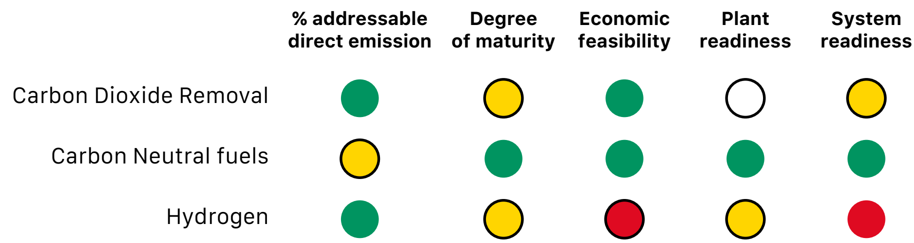
- **Hydrogen** – H_2 propulsion could significantly reduce climate impact. Hydrogen eliminates CO_2 emissions in flight and can be produced carbon-free. Industry experts project that important advancements are possible within five to ten years. Assuming these technical developments, H_2 propulsion is best suited for commuter, regional, short-range, and medium-range aircraft. Long-range aircraft require new designs for hydrogen. H_2 is technically feasible but less suitable for evolutionary long-range aircraft designs from an economic perspective. Refuelling infrastructure is a manageable challenge in early ramp-up years but will require significant coordination.

Figure 27

Decarbonisation levers for aviation

Legend: The colour of the circle represents the level of advancement of each technology (green, if high; yellow, if intermediate; red, if low; white, if not applicable).
The outline of the circle represents the dynamic view (blue outline indicates an expectation of strong improvement for the coming years)

Source: elaboration The European House - Ambrosetti, 2022



Overall, in the aviation industry, the application of the decarbonisation levers will foster a **8.1% CO_2 reduction in the Inertial Scenario (2030) that will reach 82.6% in 2050**.

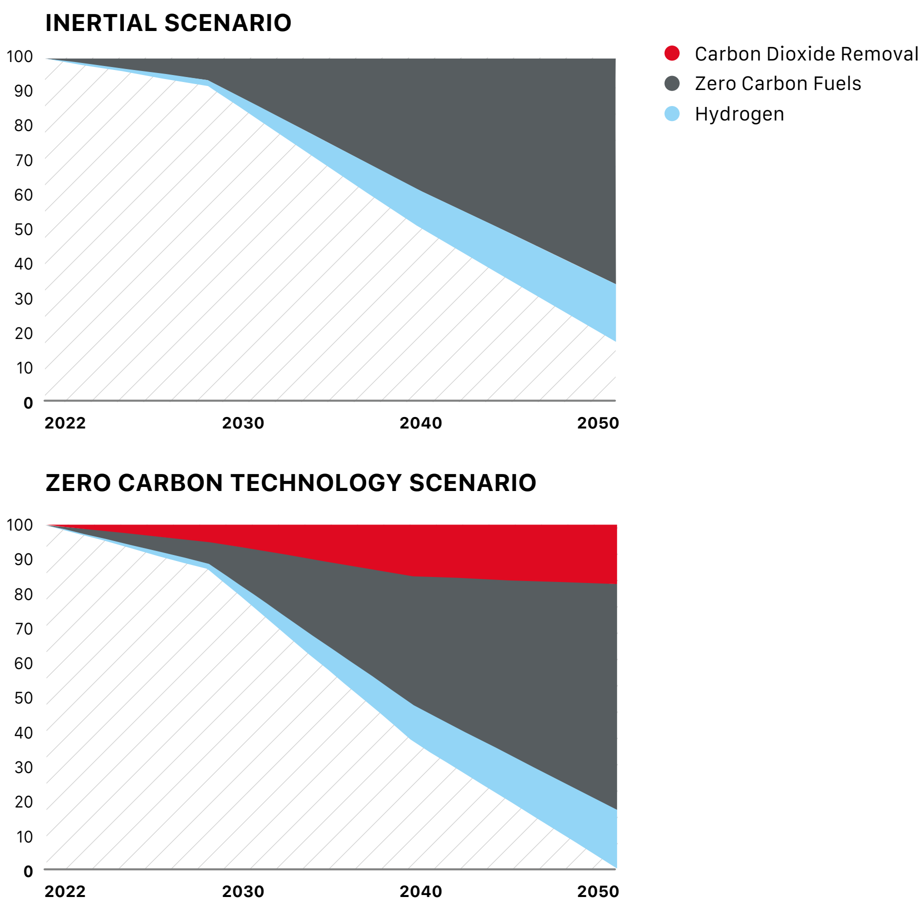
58 *Source: elaboration The European House - Ambrosetti on Report "Net zero 2050: sustainable aviation fuels", IATA (2022) and Paper "Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C", : M. Sharmina, O. Y. Edelenbosch, C. Wilson, R. Freeman, D. E. H. J. Gernaat, P. Gilbert, A. Larkin, E. W. Littleton, M. Traut, D. P. van Vuuren, N. E. Vaughan, F. R. Wood & C. Le Quéré (2021), 2022.*

In the **Zero Carbon Technology Scenario**, the adoption of Carbon Dioxide Removal (CDR) techniques, combined with other Sustainable Aviation Fuel and Hydrogen, will allow to reach a **13% reduction of CO_2 emissions in 2030 and 100% reduction in 2050.**

Figure 28

CO_2 emissions reduction in aviation considering different technologies, in Europe (%), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



Sectorial Analysis: Power generation

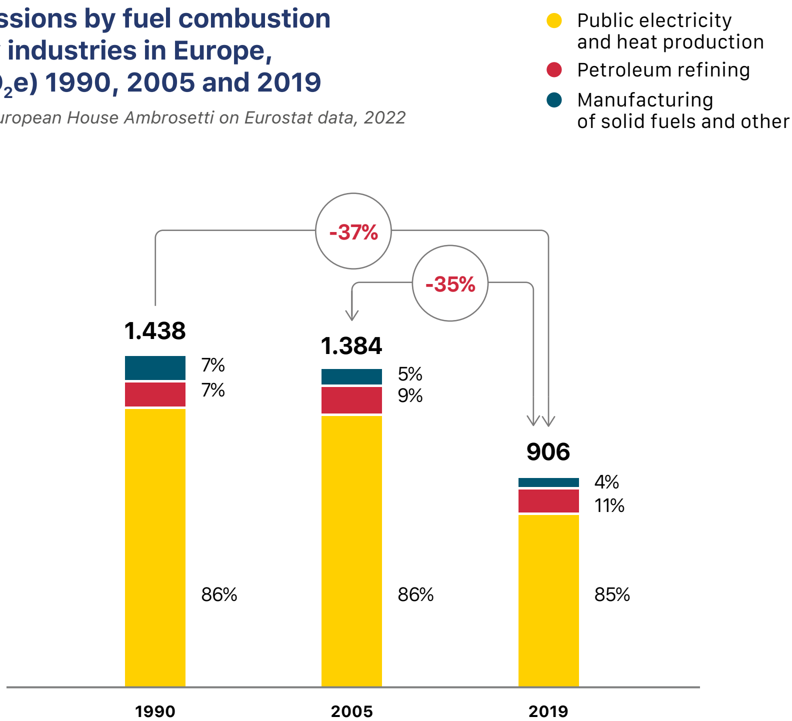
In Europe, **emissions generated by energy industries have decreased by 37%** between 1990 and 2019, going from 1,438 Mton CO_2e emitted in 1990, to 906 Mton CO_2e in 2019. There are three main components that generate emissions in this sector, namely public electricity and heat production, petroleum refining and manufacturing of solid fuels. Over time, electricity and heat production has always been the most emitting component, accounting for about 85% of total sectoral emissions in all three years considered.[59]

On average, energy industries alone accounted for 25% of total European emissions in 2019. Out of the countries analysed in Germany energy industries weigh the most over national emissions (31%), followed by Italy (22%), Spain (18%), and France (9.6%).[60]

Figure 29

GHG Emissions by fuel combustion in energy industries in Europe, (Mton CO_2e) 1990, 2005 and 2019

Source: The European House Ambrosetti on Eurostat data, 2022

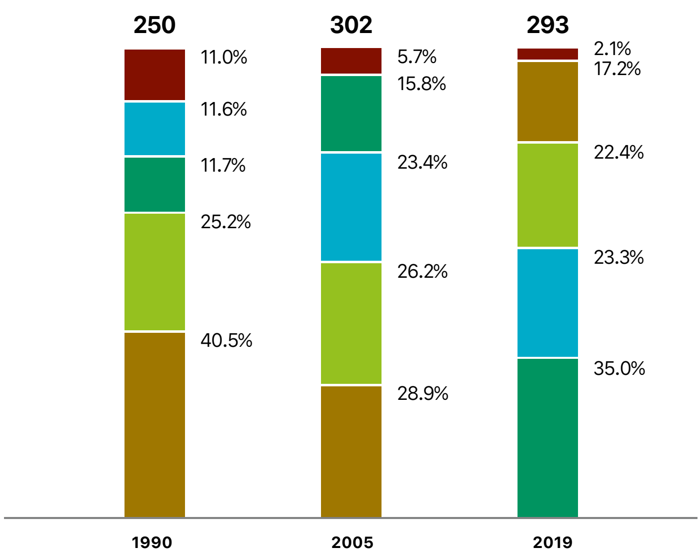


59 *Source: The European House - Ambrosetti on Eurostat data, 2022.*
60 *Ibid.*

In the last 30 years, **there has been a significant shift in the share of sources due to the growth of renewables and biofuels**, whose contribution increased by 23.3 percentage points between 1990 and 2019. Together with renewables, natural gas is the only source whose contribution increased over time (11.7 percentage points). Instead, the overall contribution of solid and liquid fossil fuels went from 65.7% in 1990 to 39.7% in 2019, a 26 percentage points reduction. Lastly, nuclear heat's contribution has decreased by 2.7 percentage points.

Figure 30

Gross production of public electricity and heat, in Europe (% and Mtoe generated, totals = 100%), 1990, 2005 and 2019



Emission reduction in power generation industry will be promoted mainly by the diffusion of renewable sources of energy and, in the long term, by the diffusion of nuclear technologies (in particular, the Study refers to nuclear fusion – more details in the fourth chapter).

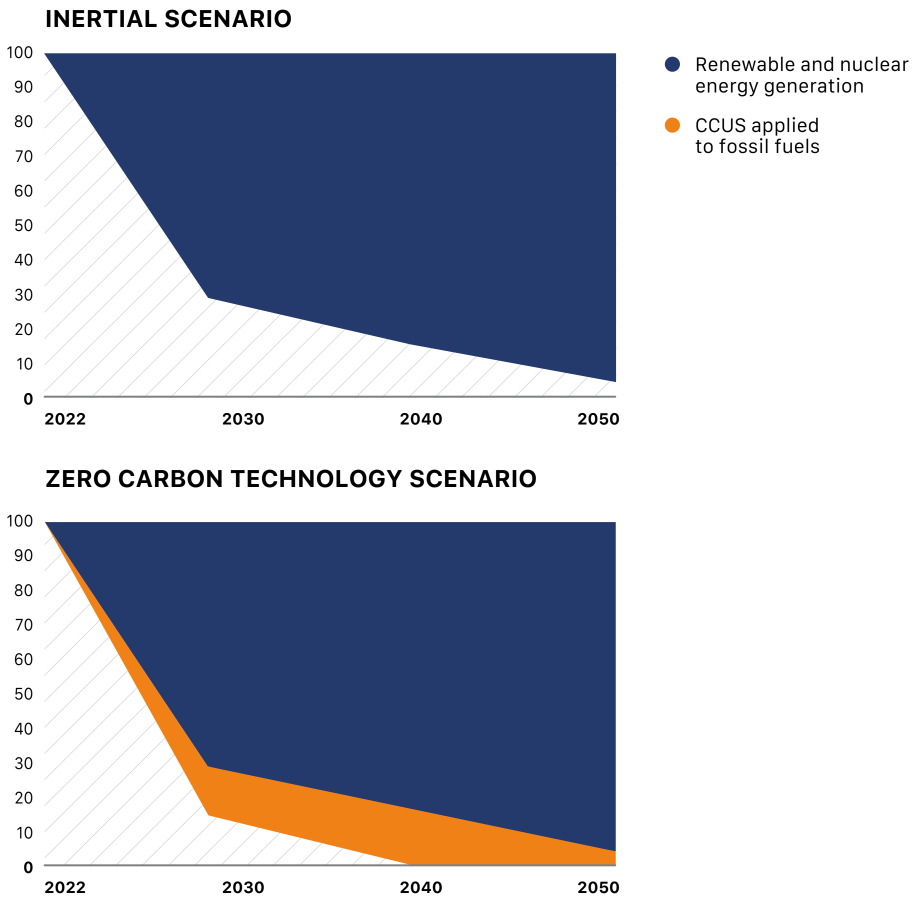
It will be possible to reach a **reduction of CO_2 emission of 71% in 2030 and 96% in 2050** just relying on the above-mentioned technologies (**In-**

ertial Scenario). Instead, in the **Zero Carbon Technology Scenario**, the inclusion of Carbon Capture Utilization & Storage (CCUS) technology will allow to **achieve a 85% CO_2 emissions reduction in 2030 and a complete decarbonisation (-100% CO_2 emissions) in 2050.**

Figure 31

CO_2 emissions reduction in the power generation industry considering different technologies, in Europe (%), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



Summary view of impacts generated in terms of CO_2 reduction

In this section of the Strategic Study, cumulative results of the two scenarios are presented. In the analysis, results are presented for two crucial, target years — 2030 and 2050 — and the role of the decarbonisation technologies mentioned in the above analyses is highlighted.

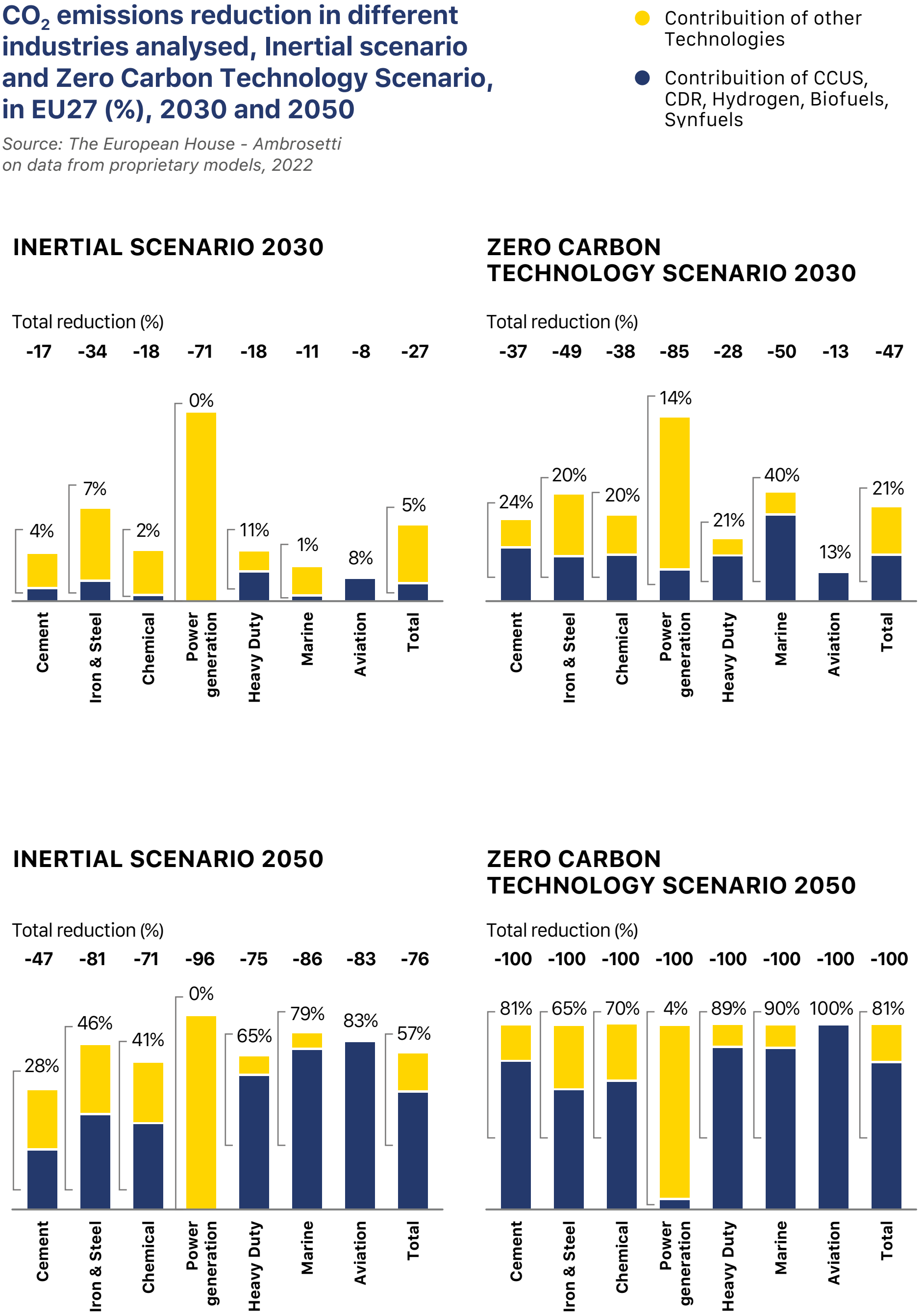
In 2030, **the Inertial Scenario foresees an overall reduction of CO_2 emissions of 27% that could reach 47% in the Zero Carbon Technology Scenario**. By 2030, the **role of decarbonisation technologies is 5% in the Inertial Scenario, and 21% in the Zero Carbon Technology Scenario**. Considering the most advanced scenario (Zero Carbon Technology Scenario), cement, Heavy Duty transport, marine and aviation are the sectors where the technology set has a key role in fostering decarbonisation.

In 2050, it will be possible to reach a 76% CO_2 emission reduction in the Inertial Scenario, that increases to 100% in the Zero Carbon Technology Scenario. In both scenarios, the decarbonisation technologies identified in the study play a key role.

Figure 32

CO_2 emissions reduction in different industries analysed, Inertial scenario and Zero Carbon Technology Scenario, in EU27 (%), 2030 and 2050

Source: The European House - Ambrosetti on data from proprietary models, 2022

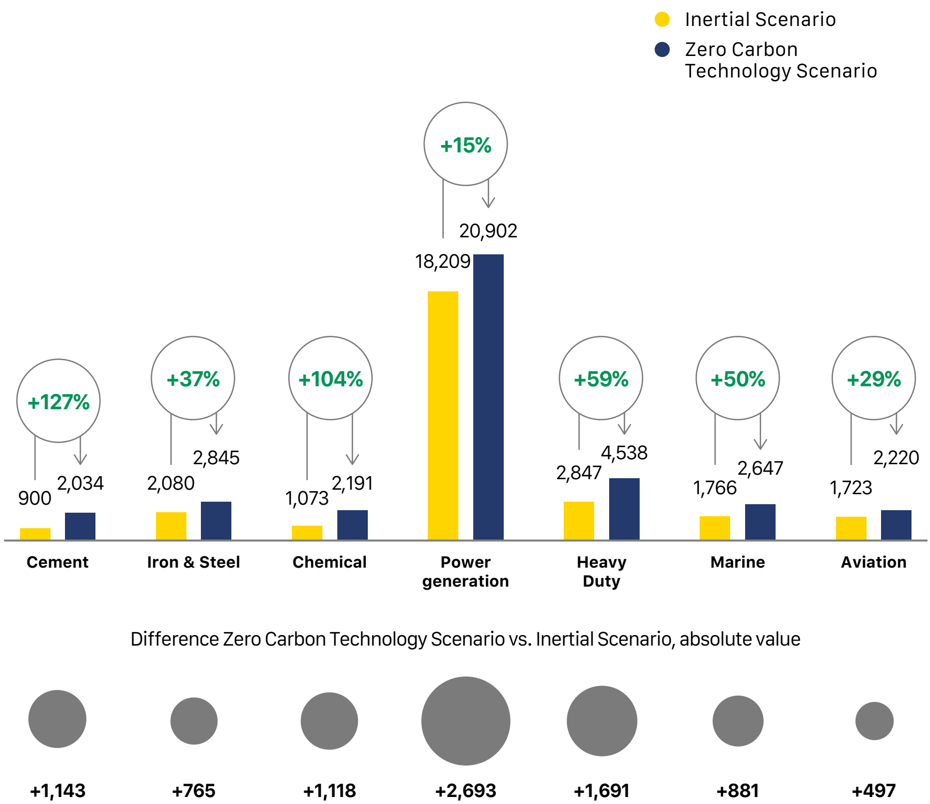


The cumulative difference between the two Scenarios is 8.8 Gton CO_2 (+31% reduction in the Zero Carbon Technology Scenario vs. Inertial Scenario). Considering 2020 emissions, this is equivalent to 6 years of total emissions of the considered sectors and 2.5 years of total emissions of the entire EU27. The biggest difference is observed in the cement sector, where the Zero Carbon Technology Scenario is 127% higher than the Inertial Scenario.

Figure 33

CO_2 emissions reduction in different industries analysed considering all technologies available, Inertial Scenario and Zero Carbon Technology Scenario, in EU27 (Mton), 2022-2050

Source: The European House - Ambrosetti on data from proprietary models, 2022



Chapter 4
Energy innovation governance

4.1 Introduction

This chapter is dedicated to the analysis of the impacts of investments in decarbonisation technologies across Europe on Gross Domestic Product (GDP) and employment. These impacts are estimated with an econometric proprietary model developed by The European House - Ambrosetti.

The second part of the chapter, is devoted to the policy proposals made by the Advisory Committee at the end of the analysis process undertaken during the development of the Study, taking into account the evidence emerged during the stakeholder engagement activities. These proposals cover nine aspects that need to be carefully considered to promote effective decarbonisation of different industrial sectors at the European level. The proposals are intended as a tool to foster discussion and reasoning about decarbonisation opportunities that can be enabled right away by leveraging all available technologies.

4.2 The econometric model to estimate impacts on GDP and employment

In this section, impacts on Gross Domestic Product (GDP) and employment are presented.

The European House - Ambrosetti developed an econometric model, based on a proprietary database, and conducted a series of scenario simulations to estimate the benefits of deploying key technologies for decarbonisation in the different sectors analysed.

As previously mentioned in chapter three, the analyses on CO_2 reduction were carried out considering two reference scenarios – Inertial and Zero Carbon Technology – that differ in the degree of diffusion and penetration of key technologies for decarbonisation. The proprietary model to estimate the economic and employment impact was built by The European House - Ambrosetti considering investment multipliers of the sectors impacted by the diffusion of the considered techologies in the sector analysed. Given the scope of this Strategic Study, all factors are analysed at the European level.

The direct economic impact related to the need to enable the market deployment of decarbonisation technologies was calculated - for instance, considering the additional cost of retrofitting facilities, conversion and retrofitting costs of transport means, and so on.

Positive impacts are also related to the provision of new energy commodities and to the development phase of decarbonisation technologies and related enabling, supporting infrastructure, considering the induced employment activated along supply chains at the European level, along with skills enhancement.

Overall, the **application of the four recommended technologies in the seven analysed sectors** has the following impact on value added and employment: according to the model, it will generate **more than € 2,700 billion of value added cumulated between 2023-2050 and about 1.7 million employees in EU27 by 2050, considering the direct, indirect and induced impacts.**

Figure 1

Main results of the econometric model

Source: The European House - Ambrosetti on data from proprietary models, 2022

	VALUE ADDED (€ BN)			EMPLOYMENT (FULL TIME EQUIVALENT)	
	In 2030	In 2050	Cumulated 2023-2050	2030	2050
Direct Impact	€ 13.6 Bn	€ 56.9 Bn	€ 855.7 Bn	117,332	532,004
Indirect Impact	€ 30.4 Bn	€ 120.8 Bn	€ 1,847.1 Bn	258,460	1,105,052
Induced Impact	€ 0.6 Bn	€ 3.3 Bn	€ 46.7 Bn	5,728	34,787
Total	**€ 44.6 Bn**	**€ 181.0 Bn**	**€ 2,749.5 Bn**	**381,520**	**1,671,843**

4.3 The proposals for energy innovation governance

Analyses and stakeholder engagement activities carried out by The European House - Ambrosetti have shed light several factors to focus on, in order to maximise opportunities for decarbonisation and technology deployment.

In this sense, nine policy proposals were formulated with the aim of supporting the regulator and supply chain actors in creating the conditions necessary to achieve decarbonisation goals in the coming years.

Policy proposal #1: **Carbon Capture Utilization & Storage (CCUS)**

European institutions recognize the relevance and potential contribution of CCUS to achieve the targets set forth by the Green Deal. Therefore, they have envisaged several funding mechanisms for R&D and demonstration projects. For instance, the Innovation Fund dedicates over €25 billion over ten years to foster breakthrough technologies in multiple fields, including CCUS. Connecting Europe Facility promotes cross-border CO_2 transport networks. The Just Transition Fund supports those areas facing socio-economic challenges associated to the transition towards climate neutrality, by providing funding for CCUS technologies. Lastly, Horizon Europe supports research, small-scale demonstration and pilot projects related to CCUS.[1]

With regards to policy initiatives and legislation, the **Directive 2009/31/EC on the geological storage of CO_2** (also known as the "CCS Directive") **provides the legal framework for the safe geological storage of CO_2.** The Commission and competent authorities in Member States collaborate to ensure the implementation of CCS by adopting Commission Opinions on storage permits and distributing guidance documents. Additionally, the Strategic Energy Technology Plan TWG9[2] identifies Research and Innova-

1 *Source: The European House - Ambrosetti on European Commission data, 2022.*
2 *The Integrated Strategic Energy Technology Plan identifies 10 key actions to accelerate the energy system transformation and the realisation of the European Union's objective to become the global leader in the development and use of renewable energy.*

tion priorities for CCUS in six key areas, namely full-scale projects, clusters and infrastructure, CO_2 capture, CO_2 storage, CO_2 utilization and CO_2 modelling. This framework is a guideline for Member States, companies, and research institutes to develop and bring to the market CCUS technologies faster and in a cost-competitive way. Lastly, the Commission is exploring the possibility to develop an EU certification system for carbon removals. On 15 December 2021, it published the Communication "Sustainable Carbon Cycles", which indicates an action plan to create sustainable solutions to boost carbon removal technologies.[3]

Policy Proposal #1

- **Envisage the development of a regulatory framework for CCUS** according to a single European market logic, providing the creation of infrastructures with access for all Member States
- Foster the **inclusion of CCUS in the energy and climate planning** of all EU Member States

In the upcoming years, it will be necessary to expand CCUS, market in industry. The first crucial step to empower regulatory and markets uses of carbon certificates is to ameliorate their monitoring, reporting and verification. **Investments in industrial projects in carbon removals must be incentivized with the creation of a robust certification and accounting framework.** The Commission recognizes this need and therefore will put forward a regulatory framework for the certification of carbon removals by the end of 2022, in an aim to safeguard the transparent identification of industrial solutions that unequivocally remove carbon from the atmosphere.[4]

3 *Ibid.*
4 *Ibid.*

Policy proposal #2: **Carbon Dioxide Removal (CDR)**

The European Parliament has frequently called for the implementation of emissions reductions and CDR measures. As a matter of fact, **the European Commission's strategic long-term vision includes CO_2 removal techniques based on Carbon Capture and Storage**, especially those combined with Direct Air Capture and Storage (DACCS) or Bioenergies Carbon Capture and Storage (BECCS) to achieve climate neutrality.[5]

Under the current European policy framework, **the most relevant legislation concerning CDR technologies is Regulation 2018/841, which leaves out DACCS and BECCS and focuses solely on nature-based CDR solutions.** This regulation extends emissions and removals-related accounting obligations to all types of land use from 2021 (except wetlands, which will be included from 2026), therefore obligating Member States to ensure that LULUCF[6] emissions do not exceed removals over 2021-2030. Member States with net emissions can buy removals from other Member States or use emissions allocations under the Effort Sharing Regulation (ESR). In the Commission's vision, BECCS and DACCS are instead dependent on CCS development. Bioenergy production is regulated in the Renewable Energy Directive 2018/2001, reviewed in 2021. There is currently no specific EU legislation regarding Direct Air Capture.[7]

Concerning EU support for research and innovation on CDR, Horizon 2020 and Horizon Europe fund relevant projects to assess the impact of CDR technologies on emission mitigation; among these, the most relevant is NEGEM.[8] Additionally, the Innovation Fund has allocated €10 billion over the 2020-2030 period to commercially demonstrate low-carbon technologies including CDR.[9]

5 *Source: The European House - Ambrosetti on European Commission and European Parliament data, 2022.*

6 *The LULUCF (Land Use, Land Use Change and Forestry) sector is used to report the CO_2 flows between different terrestrial reservoirs (biomass, soils, etc.) and the atmosphere that take place on the managed surfaces of a territory. It can thus constitute a net source or a net sink of CO_2.*

7 *Source: The European House - Ambrosetti on European Commission data, 2022.*

8 *The NEGEM project is a Research and Innovation Action funded by the EU Horizon 2020 Programme, to assess the realistic potential of Negative Emission Technologies and Practices (NETPs) and their contribution to climate neutrality.*

9 *Ibid.*

Policy Proposal #2

- Put in place a **policy mechanism that allows to account for negative emissions**, currently not possible under the EU Emissions Trading System (ETS)
- Introduce a **financing mechanism to de-risk industrial investments** in large-scale **CDR** demonstration facilities

In order to fully exploit the enormous potential of CDR technologies in the long run, it is necessary to incentivize investments in this field as soon as possible. For instance, by **including emission offsets performed with BECCS and DACCS besides natural CDR solutions, and by including both natural and engineered CDR solutions in the EU Emissions Trading System**, Member States would be incentivized to invest in engineered CDR projects. Clearly, the legislative aspect must be coupled with financing measures to incentivize the creation of BECCS and DACCS plants: there is a general consensus that a major downside of these technologies is the high capital costs requirements, but also the currently elevated operating costs – which are decreasing in CO_2 concentration levels, making DACCS the costliest CCS application due to relatively low CO_2 concentration in the atmosphere. One possibility is to **specifically designate a portion of CCS fundings** (contained in the Innovation Fund, Connecting Europe Facility, Just Transition Fund and Horizon Europe) **to DACCS and BECCS projects**,[10] or by creating ad-hoc fundings schemes for BECCS and DACCS projects exploiting the **Carbon Contracts for Difference framework.**[11]

10 *Ibid.*
11 *CCfDs are funding mechanisms that enable Governments to guarantee investors a fixed price to reward CO_2 emission reductions above its current price levels in the EU Emissions Trading System (ETS). These fundings have the potential to boost the deployment of breakthrough Green Deal technologies, by kickstarting the value chains with a first generation of strategic technologies, to be paired with the development of other market and demand pool policies to scale up decarbonisation technologies.*

Policy proposal #3: **Hydrogen**

Today, **the vast majority of the hydrogen produced (97.7%) is based on fossil fuels**.[12] Therefore, it is not considered as a sustainable energy vector, being excluded from all incentives for the production and realization of infrastructures. As demonstrated in previous chapters of this Strategic Study, **it is possible to decarbonise fossil-based hydrogen by applying Carbon Capture Utilization & Storage (CCUS) technologies**.

In the recent "REPowerEU", the European Commission outlined plans to produce ten million tonnes of green hydrogen within the EU by 2030 and import a further ten million by the same deadline. Moreover, the European Commission has defined renewable hydrogen and its derivatives as "produced in an electrolyser that uses renewable electricity". According to a newly published public consultation on the long-awaited Delegated Acts, the green power used to make "fully renewable" hydrogen must be sourced from dedicated new capacity, or from curtailed renewable energy or from green electricity purchased from the grid via strictly regulated power purchase agreements.[13] **The new definition of sustainable hydrogen will halt the diffusion of this energy vector and the creation of needed infrastructure** (production, storage, transport, distribution).

Moreover, to promote the creation of industrial value chain, the European Commission is fostering the creation of the so-called "Hydrogen Valley" across Europe. In particular, in May 2022, the "H2 Valleys S3 Partnership" has been presented during the Hyvolution 2022 conference in Paris. The key objectives of the Partnership are the following:

- Develop the technological readiness and the commercial availability of Fuell Cell and Hydrogen (FCH) applications;
- Overcome the lack of access to information and expertise in the field hydrogen;
- Facilitate match-making and co-investment between European regions;
- Strengthen the value chain for FCH technologies via interregional cooperation;
- Contribute to the decarbonisation of the EU's economy;
- "Green" the production of hydrogen;
- Be an active stakeholder on EU policy making on hydrogen.[14]

12 *Source: elaboration The European House - Ambrosetti on Hydrogen Europe, IEA, Italgas and European Commission data, 2022.*

13 *Source: elaboration The European House - Ambrosetti on Article "Proposed stringent EU rules on green hydrogen 'would put the brakes on development'", Recharge, 2022.*

14 *Source: elaboration The European House - Ambrosetti on "Smart Specialisation Platform – Hydrogen Valleys", European Commission, 2022.*

Even though this partnership could be considered a first step to harmonize the line of action in the creation and in the operation of Hydrogen Valleys across Europe, an effective policy to regulate these initiatives is still missing.

Policy Proposal #3

- **Recognize as sustainable the hydrogen generated from fossil fuel with CCUS when demonstrated that there are no unabated or uncompensated emissions under a life cycle assessment**. This will make it possible to sustain the conversion of current gray hydrogen plants and support the diffusion of hydrogen fuelled technologies in the short-term, facilitating the future uptake of hydrogen from electrolysis
- Promote the diffusion of a **European policy reference standard** to be applied in all Member States to provide **technical** and **regulatory** clarity for companies involved in hydrogen valley and other implementation projects

In order to foster the diffusion and the creation of the industrial value chain, **the Advisory Board considers necessary the recognition as "sustainable hydrogen" of hydrogen generated from fossil fuel with CCUS** when demonstrated that there are no unabated or uncompensated emissions under a life cycle assessment. In this way, it will be possible **to accelerate the creation of a market – demand and supply – of hydrogen products and the reduction of prices for hydrogen vector**. These aspects are key for the development of hydrogen produced by renewables that will be reasonable only when there won't be a competition for electricity energy from renewable. This will for sure facilitate the market uptake of hydrogen solution activating a **virtuous circle between demand & supply of Carbon Neutral cheap hydrogen**.

Policy Proposal #4: **Biofuels**

Since 2016, the European Commission strives to formulate a renewable energy management plan. That year saw the launch of the "Clean Energy for all Europeans", where a first legislative proposal for the recast of the Renewable Energy Directive (RED) was included. In December 2018, the revised Renewable Energy Directive 2018/2001/EU (RED II) entered into force.

In the revised Directive, the overall EU target for Renewable Energy Sources consumption by 2030 has been raised to 32%. The RED II also defines a series of sustainability and GHG emission criteria that bioliquids used in transport must comply with to be counted towards an overall 14% target and to be eligible for financial support by public authorities.

Within the 14% transport sub-target, there is a dedicated target for advanced biofuels produced from feedstocks listed in Part A of Annex IX. **The contribution of advanced biofuels and biogas produced from the feedstock listed in Part A of Annex IX as a share of final consumption of energy in the transport sector shall be at least 0.2 % in 2022, at least 1 % in 2025 and at least 3.5 % in 2030.**[15]

Policy Proposal #4

- Ensure that all the feedstocks sourced from **wastes, residues and crops, not in competition with food and feed chains, are considered sustainable** to produce Carbon Neutral biofuels when demonstrated that there are no emissions other than biogenic ones

More specifically, **it will be important to recognise as "Sustainable feedstock" all feedstocks** (Low ILUC[16] energy crops, Waste & Residues, etc.) **that enable the production of biofuels with low environmental impact and that do not compete with the agri-food supply chain**. In this sense, it will be necessary to improve the formulation of the RED II in order to recognise this specification to all feedstocks included in Part A of Annex II.

15 *Source: elaboration The European House - Ambrosetti on "Renewable Energy – Recast to 2030 (RED II)", European Commission, 2022.*
16 *Low ILUC (Indirect Land Use Change) biofuels are defined as those produced from feedstocks that avoid displacement of food and feed crops through improved agricultural practices or through cultivation of areas not previously used for crop production.*

Policy proposal #5: **Technology Neutrality**

As demonstrated in the first chapter of the present Strategic Study, **at the current rate, Europe will miss the "Fit for 55" target by 2030 for reduction of gas emission and increase of renewable consumption, reaching -55% CO_2 reduction only in 2050 and, consequently, missing the Net Zero Target in that year**.

Therefore, it is clear that Europe will need to change pace in order to reach climate neutral goals in line with the Paris Agreement. To do so, the Strategic Study endorses the view that a key task for policymakers is to establish a regulatory framework that sets incentives for innovation while also enabling the effective and efficient decarbonisation of the overall economy.[17]

In current policy debates, business leaders, academics, and policymakers often cite **"Technological Neutrality" as an important criterion that should inspire the design of regulatory instruments**.

The principle of technological neutrality dictates that policymakers should not "pick winners" in the competition between alternative technologies, rather, **market mechanisms should determine which technologies achieve broad adoption**, for this will **ensure the most cost-effective solutions.**[18] This is a very simple principle that should be applied to foster market efficiency and **technology diversification** and competition.

In this light, **only the objective should be stated by the policy, not the way to achieve results**. Technologies cannot be used as a political flag, they should not be considered a political issue. The risk is that differently, following a technology driven approach, it will be impossible to reach the target simply because **the market is not put in a position to be proactive and to invest on a broad innovation.** And this should be reflected in the way public **subsidies** are allocated: only based on the potential to reduce CO_2 over expenditure. To this end, it is also essential to introduce **objective emission measurement models** based on a life cycle approach.

In this sense, the adoption of a "Technology Neutral" approach will allow to foster research and development, the industrialization and the diffusion of all possible technical solutions to reach the Net Zero target in 2050.

17 *Source: elaboration The European House - Ambrosetti on Paper "Technological Neutrality: A Critical Assessment", Helmholtz Centre for Environmental Research (2020), 2022.*
18 *Ibid.*

Policy Proposal #5

- To incentivize investments in decarbonisation infrastructures and technologies, resources should be allocated according to the **economic efficiency to abate CO_2**, evaluating the potential in comparison with other alternative technologies and according to a **Technology Neutrality principle**

The adoption of a "Technology Neutral" approach will allow the development of different solution to respond to climate challenges. Then, it will be important to define a mechanism to incentivise the development of those technologies that have the highest decarbonisation potential and economic feasibility.

Policy proposal #6: **Hard to Abate industries and fossil fuel power generation**

Decarbonisation is a crucial driver of change for society and businesses, with a remarkable impact on current business practices and models. **Innovative business models are therefore necessary to exploit new business challenges** and opportunities brough about by the decarbonisation objectives.[19]

In March 2020, the European Commissions has laid the foundations of the European Industrial Strategy, a plan to support the twin transition and increase the competitiveness of the EU industry globally. Notably, the Commission aims for **climate-neutral competitiveness**, therefore posing the twofold challenge to lower emissions while keeping industry competitive, and eventually positioning it to exploit the huge potential of global market for low-emission technologies and services.[20]

In its New Industrial Strategy (updated in 2021), the European Commission stated its intent to develop a **European approach for Carbon Contracts for Difference** (CCfDs) to encourage the development and deployment of low-carbon technologies in energy-intensive industries. The plan is to propose a European approach to CCfDs by including them in a revised ETS Directive. Additionally, the Commission is considering com-

19 *Source: elaboration The European House - Ambrosetti on Paper "How to fight climate change with innovative business models", BMI Lab (2021), 2022.*
20 *Source: The European House - Ambrosetti on European Industrial Strategy data, 2022.*

plementing other forms of support to develop decarbonised technologies in heavy industries under the Innovation Fund.[21]

In May 2022, The European Commission published its plan to dedicate CCfD subsidies to support the switch of hydrogen production in industrial processes from natural gas to renewables, and the consequent transition to hydrogen-based production processes in Hard to Abate industries, such as the iron and steel sector.[22]

Green Public Procurement (GPP) is another powerful instrument to incentivize the decarbonisation of heavy industries, by accounting for the **carbon footprint of products and services in the award of public contracts.** Knowing that the lower the footprint, the more likely they are going to be awarded a public contract, companies are incentivized to achieve substantial emission reduction – for instance, through climate-friendly material choices, material-efficient product design, and optimization in manufacturing, construction, and logistics. Notably, the emissions reduction potential is associated to different stages of the supply chain, therefore enhancing integration, for instance through collaborative contracting and alliances can allow for the implementation of projects with larger mitigation potential.[23]

Policy Proposal #6

- Introduce a **Carbon Contracts for Difference** model that encourages the investments in Zero Carbon technologies by reducing the risks in the investment phase, in a similar way as done to incentivize the diffusion of electric renewable energies

To incentivise virtuous Open Innovation mechanisms, the European Commission should broaden the spectrum of CCfD, under two points of view: first, **CCfD should be specifically targeted to Hard to Abate sectors**; second, although CCfD to produce green hydrogen are a good starting point, **more decarbonised technologies should be taken into consideration.** Lastly, GPP schemes should be incentivized both at the Union and State level.

21 *Ibid.*
22 *Source: The European House - Ambrosetti on European Commission data, 2022.*
23 *Source: elaboration The European House - Ambrosetti on Paper "Industrial Innovation: Pathways to deep decarbonisation of Industry", ICF (2020), 2022.*

Policy proposal#7: **Heavy Transport**

The Green Deal adopted by the European Commission sets a clear objective: by 2050, transport emissions will have to be reduced by 90%, compared to 1990 levels. To this end, the transition from the use of fossil fuels for mobility to the use of alternative fuels needs to be accelerated.

The European Commission decided on a new regulation concerning targets to reduce carbon dioxide emissions in transport sector. The assessment to calculate emissions takes into consideration only tailpipe emissions, according to the principle "**Tank-to-Wheel**". This calculation method particularly rewards electric vehicles (EVs) since their **emissions are zero during the use phase** but are all concentrated in the power generation phase.[24]

In the future, **GHG emissions from generation of electricity or other alternative fuels should also be considered.** In this sense, the "Well-to-Wheel" approach should be contemplated to quantify the impact of transportation fuels.

As more and more alternative drivetrains and fuels are used whose impact on the environment does not occur – or it is very limited – during driving of the vehicle, fuel production emissions and energy consumption for fuel production also must be assessed.[25]

By applying the "Well-to-Wheel" principle, it will be possible to recognise the status of "Carbon Neutral fuel" to biofuels and hydrogen (even if based on fossil fuels) when it is demonstrated that CO_2 emissions are captured, or compensated. This fact will act as incentive for investments, accelerating the diffusion of alternative fuels.

Finally, cost side must be accounted. Today, alternative fuels have a higher price than traditional fuels: for example, Hydrotreated Vegetable Oil has a range price of 90-150 €/MWh vs. traditional fossil fuel 35-50 €/MWh. It is necessary to create incentives to foster the demand of alternative fuels to reach CO_2 reduction target in transport.

24 *Source: elaboration The European House - Ambrosetti on Paper "Well-to-the-Wheel Analysis", Renewable and Sustainable Energy Reviews (2022), 2022.*

25 *Source: elaboration The European House - Ambrosetti on Paper "Environmental impacts of hydrogen use in vehicles", Compendium of Hydrogen Energy, Volume 4: Hydrogen Use, Safety and the Hydrogen Economy, Woodhead Publishing Series in Energy, 2022.*

Policy Proposal #7

- **Moving beyond the "tank-to-well" emissions calculation** approach and promoting a "**well-to-wheel**" Life-Cycle Assessment (LCA) approach in assessing overall fuel emissions
- Recognize, in the European taxonomy, the status of "carbon neutral fuels" to **biofuels** and **hydrogen** produced from fossil sources in **combination with CO_2 Capture technologies**
- Foster the **creation of infrastructure**, such as refilling stations, required for a massive deployment of alternative fuels on roads, ports and airports and introduce **fiscal policies to reduce the price gap with traditional fuels**

A policy action is needed to revise the emission calculation approach in order to promote an overall assessment method that accounts for all the emissions related to the production, transport and utilization of a fuel (Well-to-Wheel). With the same action, it will be possible to update the European taxonomy to accept the status of "Carbon Neutral fuels" to new alternative vectors, such as biofuels and hydrogen.

In order to foster demand and enable the diffusion of Carbon Neutral fuels, it will be necessary to **support the creation of infrastructures** and to adapt existing one, covering also the price gap versus traditional fuels. These actions can be achieved by putting in place a mechanism to support investment and provide incentives for fuel purchases.

Policy proposal #8:
Fostering Research and Innovation

Public-private partnerships in energy industries at the European level are part of the Energy Research and Innovation Program promoted by the European Commission. The partnership has the objective **to improve the link between research and societal growth as well as bridge the gap between project results and markets**. In the EU, Public-private partnerships take the form of Joint Undertakings (JUs), Contractual public-private partnerships (cPPPs) or European Technology and Innovation Platforms (ETIPs).[26]

- JUs allow the EU to pool Union-wide resources to tackle the biggest challenges in innovative research fields, support competitiveness to deliver high quality jobs, and encourage private investment in research and innovation in the energy sector. Some examples are: Biobased Industries Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking.[27]
- cPPPs enable interested industries and the EU to partner in the context of a 7-year strategic roadmap. The EU contributes financially with €7.1 billion drawn from Horizon 2020, and industrial partners increase investments in research and innovation and work on pioneering technologies to guarantee the competitive edge of the European industry. Some examples include European Green Vehicle Initiative and Sustainable Process Industry through Resource and Energy Efficiency.[28]
- ETIPs are industry-led communities that develop and implement the Strategic Energy and Technology Plan priorities. Each ETIP promotes the market uptake of key low-carbon energy technologies by combining skills, funding, and research facilities. Some examples include ETIP bioenergy and ETIP Zero Emission Fossil Fuel and Power.[29]

26 *Source: The European House - Ambrosetti on European Commission data, 2022.*
27 *Ibid.*
28 *Ibid.*
29 *Ibid.*

Policy Proposal #8

- Foster the **leadership in research and development of frontier technologies** that will potentially be disruptive in decarbonisation processes, such as nuclear fusion
- Ensure **policy support** (regulatory framework, incentives, …) **to promote the creation of public-private partnerships** between academia, research centres, industries and public authority to accelerate the developments of such technologies

The public-private partnerships currently in place are an excellent starting point to build upon. **The scope of the projects should be broadened to include more frontier technologies and key industries** in an aim to exploit potential spill over effects. Additionally, this type of cooperation should be encouraged at the state and local level in an aim to **include even smaller, marginal industries and research centres and foster open innovation**. Lastly, states should also provide aids to further incentivize participation in this type of projects.

Policy Proposal #9: **Nuclear Fusion**

European fusion laboratories and companies collaborate through a consortium called **EUROfusion**[30] in an aim to pursue the objectives set forth by the long-term strategy set out in the European research roadmap for the deployment of fusion energy. The consortium has received a €679 million contribution from Horizon 2020 – Euratom Research and Training Programme.[31] The Euratom budget is €1.38 billion for the period 1 January 2021 to 31 December 2025:[32]

- €583 million for indirect actions by multi-partner consortia in fusion research and development;
- €266 million for indirect actions by multi-partner consortia in nuclear fission, safety and radiation protection;
- €532 million for direct actions undertaken by the Joint Research Centre.[33]

Additionally, multiple European companies are participating in ITER, a unique project to build the **world's biggest fusion machine**. The project creates job opportunities and economic growth while supporting the European leadership in global fusion research, by fostering innovation and international collaborations. Although ITER is a purely experimental device, **it will advance fusion energy technology** for a greener and more sustainable energy mix, by providing the necessary scheme for the construction of future commercial fusion plants.[34]

It has to be considered that ITER is a **large-scale plant** with an approach that cannot be down-scaled to smaller modules. It requires a huge infrastructure to deliver energy, whereas small scale projects cannot rely on lot of space nor high investments. In this light it is important to **put attention also on smaller scale projects that can industrialize a modular technology**. The big advantage is the faster time to market.

30 *EUROfusion is the European Consortium for the Development of Fusion Energy.*
31 *Euratom Research and Training Programme (2021-2027) is a complementary funding programme to Horizon Europe which covers nuclear research and innovation.*
32 *In line with the Euratom Treaty, the programme will run for 5 years, from 2021 to 2025, to be extended in 2025 by 2 years in order to be aligned with the EU's long term budget 2021-2027.*
33 *Source: The European House - Ambrosetti on Euratom data, 2022.*
34 *Source: The European House - Ambrosetti on European Commission data, 2022.*

Policy Proposal #9

- Provide **clarity on the overall regulatory regime** for fusion energy facilities, considering all the differences with respect to nuclear fission technology
- Ensure regulators have the **technical capability** to regulate fusion energy facilities effectively
- **Maximise public confidence** in the regulatory framework for fusion, envisioning occasions for public debate and discussion
- Create a **platform mechanism through which innovation projects and financial investors** can be brought together

The European research roadmap to fusion energy enables commercial electricity generation from fusion as a long-term solution for clean energy, but **the commercial exploitation of fusion electricity will require national regulatory frameworks** to ensure safety and assess licensing applications to build and operate fusion power plants. Unlike fission power plants, there is still no specific legal framework to regulate fusion power plants.[35]

While there are some common safety aspects between fusion and fission, there are structural differences. A **fission-based regulation could be overly conservative in tackling fission safety issues** that do not occur in nuclear fusion. Instead, the potential for offsite radioactive release from fusion power stations could require different regulations from current fusion experimental facilities. Among other attributes for a fusion regulatory framework, flexibility and adaptability are highly recommended to accommodate the high uncertainty associated with the current and future technology development. The framework must also be transparent regarding regulatory control and licensing to facilitate political and **public acceptance of fusion power plants**. Additional work could focus on the promotion of cross-border regulatory cooperation.[36]

35 *Source: elaboration The European House - Ambrosetti on Paper "Exploring Regulatory Options for Fusion Power Plants", European Commission Directorate-General for Research and Innovation (2022), 2022.*
36 *Ibid.*

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