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Review

Analysis of the Status of Research and Innovation Actions on Electrofuels under Horizon 2020

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Abstract: Europe stated the ambitious target of becoming carbon neutral by 2050 to combat climate change and meet the requirements imposed by the Paris Agreement, and renewable energy has proved to be a promising solution for the decarbonization of many sectors. Nonetheless, their aleatory nature leads to grid unbalances due to the difference between supply and demand. Storage solutions are needed, and electrofuels become a key factor in this context: they are fuels produced from electricity, which leads to carbon-neutral fuels if it originates from renewable sources. These can constitute a key solution to store the surplus energy and to decarbonize the so-called hard-to-abate sectors. Electrofuel production technologies have not yet been fully developed, and, in this context, extensive study of the state-of-the-art of existing projects can be very useful for researchers and developers. This work researches the European projects funded by the Horizon 2020 Programme regarding electrofuel production. The projects were analyzed in-depth using specific features, and the results were presented.

Keywords: Horizon 2020 Framework Programme; Power-to-X; European research projects; energy storage; smart energy systems; flexibility; optimization

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1. Introduction

The need to find a solution to environmental problems caused by the current use of fossil fuels is a central issue in research and innovation activities. The ambitious European objectives for the mitigation of global warming set out a drastic reduction in greenhouse gas (GHG) emissions in the next decades in order to reach a net-zero carbon economy by 2050. In order to achieve these targets, radical changes in the current energy sector must be performed [1]. The urgency to replace fossil fuel-based energy is at the forefront of the energy transition, and the use of renewable energy sources is seen as the most promising solution due to the limitless and clean energy supply they offer [2]. Nonetheless, there are many uncertainties on how to carry out this transition, and one of the main problems related to the use of renewable energies is their intermittency. Indeed, when dealing with clean energies such as wind and solar, it is well known that their fluctuating and intermittent nature must be balanced for electrical grid stability purposes. Consequently, long-term and large-capacity electricity storage is required, as well as reserve production capacity [2]. In addition, it was observed that the exploitation of renewable energy sources such as wind, solar, sustainable biomass and hydropower have successful results in decarbonizing the power sector [3], with very promising effects, but there are some sectors, the so-called hard-to-abate, that cannot be electrified, and their decarbonization presents particular challenges.

In this context, new fuel technologies, such as electrofuels, can play a key role. Electrofuels are fuels produced from electricity. The idea is to store the electrical energy within the molecular structure of gaseous or liquid fuels, and if they are produced using renewable electricity, carbon-neutral fuels are obtained [4]. The electrofuels can be used as energy storage and transformed back to electricity directly in fuel cells, or they can be used in combustion systems similarly to conventional fuels. Their production is based on water electrolysis, with which hydrogen is generated. Nevertheless, due to the obstacles in the management and usage of hydrogen as a fuel, molecular hydrogen is used to produce easily manageable liquid or gaseous fuels. These include methane and long-chain hydrocarbons from the reaction with carbon dioxide or ammonia from the reaction with nitrogen [4].

The environmental performances of these fuels were evaluated in many studies, such as in [5–7], where the authors performed an analysis using Life Cycle Assessment. The results show that the production of electrofuels when using renewable electricity has a lower impact in terms of GHG emissions compared to conventional technologies. Nonetheless, the origin of carbon dioxide also influences the result of the assessment, as well as the technologies used.

Electrofuels can be integrated into the existing energy framework and, besides being a product themselves, their production also offers ancillary services:

- *Balancing services to the power grid*. Indeed, the decarbonization of the energy system using renewable energy sources (RES) creates technical challenges related to their supply intermittency and the effect on the balance between supply and demand over time and space [1]. Through electrofuel production, it is possible to add flexibility to the power grid both on a spatial and temporal level and avoid renewable energy curtailment. In addition, if power-to-gas technology is considered, i.e., the production of methane from electricity, together with sector coupling with the gas grid, a higher level of renewable energy injection in the generation mix is reachable [8];
- *"Sequestering" CO_2 emissions*. If carbon dioxide is required for electrofuel production, the amount of CO_2 captured from the output of industrial processes or other sources can be considered as temporarily avoided emissions;
- *Store electrical energy into chemicals*. Large-scale storage solutions are required in countries with intermittent weather conditions, e.g., with a large production of renewable energy in the summer season and high power requests in the winter season (or vice versa). Electrofuels can provide long-term RES storage options and offer a solution to this issue [9]. Moreover, electrofuels can provide a storage solution when power production is too far away from the user, for instance, with offshore wind turbines or for electricity production in remote areas (e.g., the desert), and it is easier to transport than electricity. In Figure 1, the exclusive properties of electrofuel production as a storage technology are shown, namely large energy capacity and large discharging time, compared to the other existing technologies. This makes electrofuels a viable solution for seasonal storage.

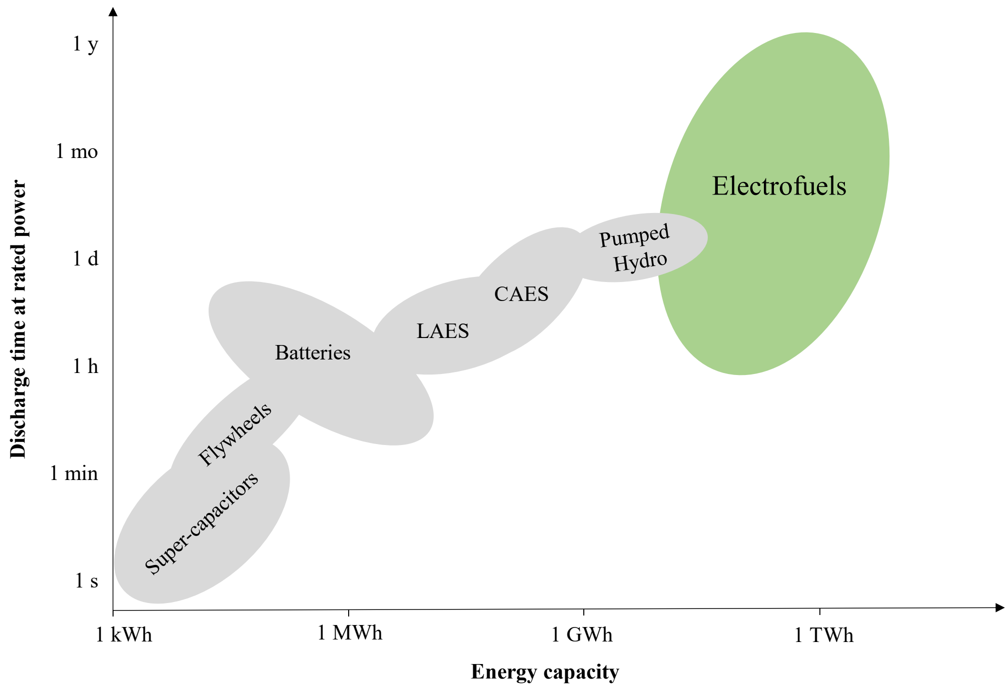


Figure 1. Mapping storage technologies according to performance characteristics (CAES = Compressed Air Energy Storage, LAES = Liquid Air Energy Storage). Data taken from [10].

A sector in which electrofuels can constitute a turning point in the energy transition is that of transport. Transport is Europe's largest climate problem, as it is the largest source of GHG emissions (27%): it is the only sector in which emissions keep increasing, and they are still higher than the levels recorded in 1990 [11]. Finding a pathway for the decarbonization of this sector is essential. Electrification can constitute a solution for passenger or light-duty vehicles, but not all transport modes can be electrified. For instance, long-distance transport, such as aviation and maritime, needs different solutions since batteries are too heavy for aviation and have too low energy density for usage in long-haul shipping routes [12].

In particular, as far as aviation is concerned, it is a growing GHG emitter, and its emissions in Europe have doubled since 1990. Without action, they could double or triple by 2050 [11]. The International Air Transport Association (IATA) has imposed a 50% reduction in CO_2 emissions by aircraft by 2050, compared to the emissions in 2005, with no increase in net emissions after 2020. However, during this time, IATA also expects the global aviation demand to increase drastically in terms of passengers. The limitations in increasing the efficiency of the aviation sector and the need to meet the requirements in the emission abatement have made it necessary to adopt Sustainable Aviation Fuels (SAF) [13]. In this context, power-to-liquid technology, i.e., the production of liquid electrofuels, is very promising, even though there are still challenges to be solved, such as the high costs of such fuels and the high amount of renewable energy and carbon dioxide needed to decarbonize the whole aviation sector [14].

In this work, research on the projects regarding the production of electrofuels funded by the Horizon 2020 Programme was performed. The projects were selected and then analyzed in terms of key features, and an overview was provided of the European state-of-the-art concerning electrofuel production to decarbonize different sectors, to balance the power grid, or to store surplus energy. Comparable reviews have been performed in recent years. For instance, in 2017, Bailera et al. [15] carried out a review of the worldwide existing projects dealing with power-to-gas processes. In 2018, Wulf et al. [16] collected data on European projects regarding electrofuel production, and in 2020 they performed another review considering only demonstration projects [17]. Moreover, Chehade et al. [18] carried out a similar review considering worldwide demonstration projects in 2019, while

Thema et al. [19] collected worldwide projects regarding only electrolysis and methanation technologies in 2019.

Concerning Horizon 2020 projects, similar research was conducted by Saletti et al. [20]: the authors proposed an overview of Horizon 2020 projects on smart distributed energy systems, focusing on district and cooling networks. Nevertheless, as far as the authors are aware, there is no research on Horizon 2020 projects regarding electrofuel production technologies and their management and integration into the energy system.

Therefore, the characteristics and novelties of this paper are as follows:

- This work is a review of Horizon 2020 projects dealing with electrofuel production and integration. It completes the previously mentioned reviews [15–19] since it deals with both research and demonstration projects, it considers several electrofuel production processes and their integration in the energy system, and it analyzes the whole Horizon 2020 period. Extensive research within the projects was carried out, the selected actions were examined and their main features were outlined;
- As Horizon 2020 was the most important program for research and innovation in Europe, this review aims to be a tool for researchers and stakeholders to find information on the actual state-of-the-art of these technologies and to investigate the main European pilot sites and projects for electrofuel production;
- As mentioned above, transport sector decarbonization is a challenging ambition. In particular, an analysis of the aviation sector was presented in this work, with the aim to find solutions for its decarbonization in the next few decades.

2. Context

This section provides some general information to better understand the reason for this research and the framework in which it is placed. First, a brief overview of the existing processes to produce electrofuel (also known as Power-to-X) is provided. Second, the framework in which Horizon 2020 operates is explained, and finally, an overview of the past, present and future Framework Programmes for Research and Innovation in Europe is assessed.

2.1. Definition of Electrofuels, Production and Current State-of-the-Art of Their Utilization

At the heart of Power-to-X is the conversion of electrical energy into chemical energy, and this occurs through water electrolysis. During this process, water is split into hydrogen and oxygen molecules by using an electrical current between two electrodes. In addition to the cathode and anode, an electrolyzer is composed of an electrolyte that conducts the ions and a diaphragm, or a separator, that avoids recombination of hydrogen and oxygen [21]. The existing technologies used to perform water electrolysis differ in terms of electrolyte, membrane and operating conditions, and their main characteristics are shown in Table 1.

Table 1. Main characteristics of different electrolyzer technologies [22–26].

	AEC (Alkaline Electrolysis Cell)	PEM (Proton Exchange Membrane)	AEM (Anion Exchange Membrane)	SOEC (Solid Oxide Electrolysis Cell)	PCEC (Proton Ceramic Electrolysis Cell)
State of development	Mature	Mature	Under developing	Under developing	Research status
Electrolyte	Alkaline solution	Proton exchange ionomer	Anion exchange ionomer	Solid electrolyte	Ceramic solid electrolyte
Cell separator	Diaphragm	Electrolyte membrane	Electrolyte membrane	Electrolyte membrane	Ceramic membrane
Temperature [°C]	65 to 100 [26]	70 to 90 [26]	50 to 70 [26]	700 to 1000 [22]	300 to 600 [24]

Table 1. *Cont.*

	AEC (Alkaline Electrolysis Cell)	PEM (Proton Exchange Membrane)	AEM (Anion Exchange Membrane)	SOEC (Solid Oxide Electrolysis Cell)	PCEC (Proton Ceramic Electrolysis Cell)
Advantages	Available for large plant sizes, low costs, long lifetime	High efficiency, high dynamics	Low costs, high dynamics	High efficiency, possible integration of waste heat	Dry hydrogen produced, low costs
Disadvantages	Low current density, low dynamics, corrosive environment	Expensive, low durability	Not mature technology, expensive, low durability	Expensive, low durability, corrosive environment, low dynamics	Not mature technology, low durability

As mentioned above, once hydrogen is produced from water electrolysis, due to its low volumetric energy density and high diffusion coefficient, which make it difficult to store, it can be converted into more complex fuels. For instance, methane can be produced by means of the methanation process: through the exothermic Sabatier reaction, hydrogen and carbon dioxide react, and CH_4 is formed [4]. Methane is easier to transport and utilize than hydrogen, and the existing infrastructure for ground transportation is a huge advantage for its integration into the existing energy system. Long-chain hydrocarbons can be obtained via power-to-liquid processes: part of the renewable hydrogen is used to reduce carbon dioxide to carbon monoxide, which is then mixed with another hydrogen to form syngas, and finally, the syngas is employed for the Fischer–Tropsch synthesis [4]. By using the power-to-ammonia pathway, a carbon-free liquid fuel can be produced. This process requires an abundant component of the atmosphere, namely nitrogen, which reacts with hydrogen to produce ammonia through the Haber–Bosch reaction. However, ammonia has some disadvantages: low energy density, reaching only one-third of that of regular gasoline/kerosene, a corrosive nature and toxicity [4]. Finally, direct electrochemical reduction of carbon dioxide or nitrogen to produce fuels such as methane, ethane, methanol, or ammonia [4,27] is also possible.

2.2. The European Strategy for a Net-Zero Economy

Climate change is a universally recognized problem, and it has been years since the first steps were taken to fight it. In 2009, the European Commission created the first SET-Plan (Strategic Energy Technology Plan), which imposed a 20% GHG emission reduction, 20% share of renewable energy source in the energy mix and 20% improvement in energy efficiency by 2020. In 2015, the 21st Conference of Parties (COP21) took place in Paris, between the Parties to the United Nations Framework Convention on Climate Change. During the conference, it was stated that it is necessary to keep the increase in world temperature below 2 °C above pre-industrial levels and make an effort to limit this increase to 1.5 °C above pre-industrial levels. In order to achieve these ambitious goals, the European Union (EU) has committed to go further and achieve a GHG emission reduction in at least 40%, have at least 32% of renewables in energy consumption, and increase energy efficiency by at least 32.5% by 2030. To meet these targets, the EU has adopted new rules into the new framework called "Clean energy package for all Europeans". However, the 2030 targets are not the end of the road, and Europe was the first major economy to present a long-term plan for a climate-neutral economy by 2050 [28].

2.3. The European Framework Programmes for Research and Innovation

The involvement of the European Union in research activities started in the 1970s, and at the beginning of the 1980s, the first Framework Programme (FP1) for research was proposed. It was a strategic tool to manage the adoption of research programs in a coherent way. With the following FPs, the aim of these research programs changed, from their original focus on technological development to the goal of helping to address the social challenges faced at the European level. They became financial tools supporting the implementation of this vision, and with FP8, the so-called Horizon 2020 Programme, a redefinition of the FP goals led to the extension of its scope to research and innovation activities [29]. Horizon 2020 was the biggest EU Research and Innovation program funded with nearly EUR 80 billion, and it lasted seven years (from 2014 to 2020). By combining research and innovation, it was a financial tool to ensure that Europe produced world-class science, removed barriers to innovation and facilitated collaboration between the public and private sectors in delivering innovation.

The Horizon 2020 Programme is divided into three main pillars [30]:

- Excellent Science. This pillar aims at supporting world-class science and ensuring the long-term competitiveness of Europe. Its goal is to develop and attract research talent and support the development of the best research infrastructures. It comprises funding (i) for individuals, through the European Research Council; (ii) for the development of new technologies, through the Future and Emerging Technologies; (iii) for innovative and interdisciplinary career opportunities, through the Marie Sklodowska-Curie Actions; and (iv) for research infrastructures;
- Industrial Leadership. This pillar supports key technologies in existing and emerging sectors, and it aims to make Europe an attractive place for private investment in research and innovation. It also aims to boost the growth potential of European companies and help innovative small and medium enterprises to become world-leading companies;
- Societal Challenges. This pillar reflects the strategic priorities of Europe and supports Research and Innovation Actions that target society and citizens. It is intended to cover activities ranging from research to commercialization, focusing on those related to innovation, such as pilot projects, demonstration projects, test beds and support for public procurement and commercial adoption. The social sciences and the humanities form an integral part of the activities aimed at addressing these challenges.

The third pillar focuses on many challenges such as health, food security, climate actions, smart and green transport, secure society and clean energy. The present work aims to focus on international projects included in the clean energy challenge.

In detail, this societal challenge is called "Secure, Clean and Efficient Energy" and aims at improving energy efficiency, enhancing low carbon technologies such as renewable energy sources or alternative fuels and developing smart city technologies and services [31].

The EU's next funding program for research and innovation is called Horizon Europe, and it will last for the next seven years (2021–2027). The budget of this program is even higher than that of Horizon 2020, EUR 95.5 billion. It tackles climate change and helps achieve the United Nations' Sustainable Development Goals, boosting the EU's competitiveness and growth. Among the novelties of this program, five mission areas were added, which include "Adaptation to climate change, including societal transformation" and "climate-neutral & smart cities" [32]. Hence, the research topic addressed in this paper will continue to be a central issue in European research over the next decade.

3. Research Method

An extensive internet search was performed, with the aim of finding actions dealing with electrofuel production as a solution to decarbonize different sectors or to store surplus energy. This section presents the research method and tools used for the investigation of the projects.

3.1. The CORDIS Portal

For the purpose of this work, the main tool used was the CORDIS (Community Research and Innovation Service) portal [33]. This portal is the primary source of results of all projects funded by the EU's programs for research and innovation and includes information such as project factsheets, participants, deliverables and links to open-access publications.

With reference to the three pillars explained in Section 2.3, the research was limited to the projects funded under the third pillar, namely societal challenges, in particular projects belonging to the "Secure, Clean and Efficient Energy" challenge [34].

In the third pillar, three funding schemes exist and were analyzed:

- Research and Innovation Actions (RIA). These are activities that aim to establish new knowledge or to explore the feasibility of new or improved technology, product, process or solution. This may include basic and applied research, technology development and integration, testing, demonstration and validation on a small-scale prototype;
- Innovation Actions (IA). These include actions consisting of activities with a strong focus on putting a product or a technology on the market, such as activities directly aimed at producing plans or designs for new or improved products, processes or services, possibly including prototyping, testing, demonstrating, large-scale product validation and market replication;
- Coordination and Support Actions (CSA). These actions consist mainly of complementary activities, such as standardization, dissemination, awareness and communication, networking and coordination between projects in different countries.

The difference between the first two types of action is basically the Technology Readiness Level (TRL) of the technology or solution studied. The TRL indicates the technical maturity of a certain technology: it is a number between 1 and 9, with lower values associated with less mature technologies, proofs-of-concept or technologies validated in the laboratory and higher values related to already mature and validated technology, as explained in Figure 2. Research and Innovation Actions comprises projects with a TRL lower than 5, while Innovation Actions focus on more mature products already validated and ready for commercialization or demonstration in an operational environment, with TRL higher than 5.

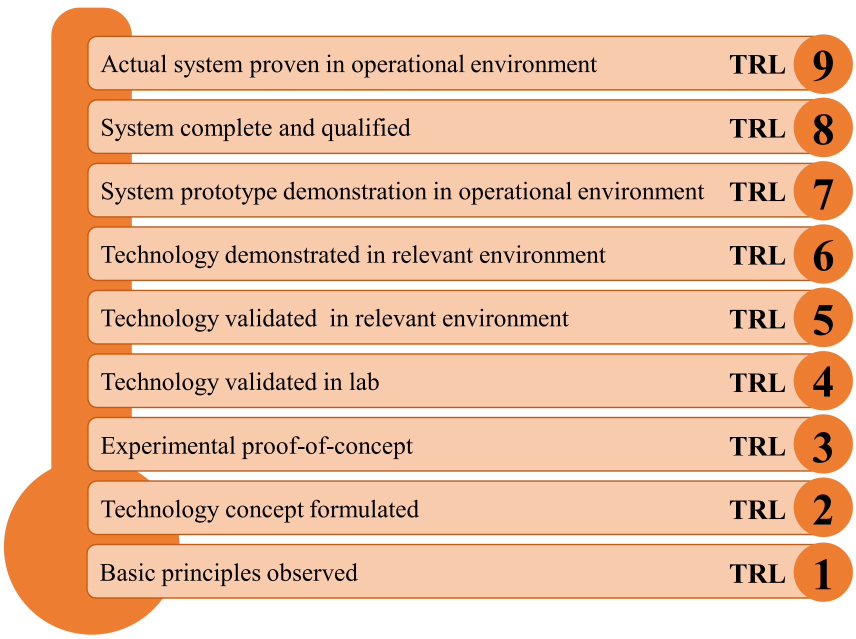


Figure 2. Technology Readiness Level (TRL) explanation.

3.2. The Fuel Cells and Hydrogen Joint Undertaking

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public–private partnership supporting research, technological development and demonstration activities involving fuel cells and hydrogen technologies in Europe. The three members of the FCH JU are the European Commission, fuel cell and hydrogen industries represented by Hydrogen Europe and the research community represented by Hydrogen Europe Research. The FCH JU aims at accelerating the introduction of hydrogen-based technologies into the market, helping Europe reduce dependence on hydrocarbons and fight carbon dioxide emissions. The FCH JU operated under the EU FP7 research program, underlying the key role that hydrogen and fuel cells play in Europe's shift toward decarbonization. In 2014, it was decided to continue this initiative and extend the funding under the Horizon 2020 Programme [35]. During the research phase, the FCH JU website was also used to integrate the collection of projects on electrofuel production under the Horizon 2020 Programme.

3.3. ERA-Net Smart Energy Systems

The ERA-Net Smart Energy Systems (SES) is a network of owners and managers of national and regional public funding programs in the field of research, which provides a joint programming platform to support transnational projects across Europe. ERA-Net SES's objective is to contribute to the implementation of SET-Plan Action 4 of the European Union: "increase the resilience and security of the energy system" [36]. The ERA-Net SES launches yearly joint calls for international projects proposals, which focus on specific topics and cross-cutting issues. ERA-Net SES receives funding from the EU through an instrument of Horizon 2020 called Cofund. This is a way of funding activities established or implemented by entities managing and financing research and innovation programs other than the EU.

Within different ERA-Net SES calls, one of major interest for this work is the SES Joint Call 2019 (MICall2019) on Energy Storage Solutions. This call supported projects that contribute to the development of sustainable storage solutions for both short- and long-term storage. Within this call, 14 projects were awarded funding, and five of them were selected for the purposes of this work, as they use Power-to-X technologies for electricity storage. The five projects selected are Ifaistos, CrossChargePoint, H2 CoopStorage, Power-2-Transport and USC-FlexStore. In addition, two projects funded in the previous call (SES Joint Call 2018) were considered, namely ZEHTC and SuperP2G.

4. Results and Discussion

The research described in the previous section led to the selection of 56 projects, with the mentioned characteristics, namely projects funded by the Horizon 2020 Programme, dealing with electrofuel production for storage or grid balancing purposes. In this section, the main results of the research are presented.

4.1. Identified Projects

In order to evaluate the selected projects, a profile sheet was created for each of them, in which the main characteristics were reported: name, website, logo, grant agreement ID, start and end date, EU contribution, coordinating country, participants, funding scheme, goals, features, demonstration sites and current status. The general characteristics of each project are reported in Table A1 in Appendix A.

In order to provide an overview of the analyzed projects, some general features are presented. For instance, the type of projects can be identified by looking at their funding scheme, presented in Section 3.1. According to Figure 3, more than half of the projects (51.8%) are funded as Research and Innovation Actions, showing a general low maturity of the studied technologies and solutions. Nonetheless, another relevant share (32.1%) is funded as Innovation Action: those projects are dedicated to consolidating technology with a TRL higher than 5. Finally, only two projects are funded as Coordination and Support Action, and seven projects are funded with the ERA-Net Cofund scheme.

Europe is working toward making electrofuels a viable solution for the decarbonization of many sectors, and funding Research and Innovation Actions are essential for these technologies to reach high TRLs in the future. An example of the effectiveness of these actions is the GrinHy project, a proof-of-concept project funded as RIA for the development of SOEC technology in 2016. This project was followed by the IA project GrinHy2.0, funded in 2019, which led to the upscaling and integration of the prototype into an operating environment [37].

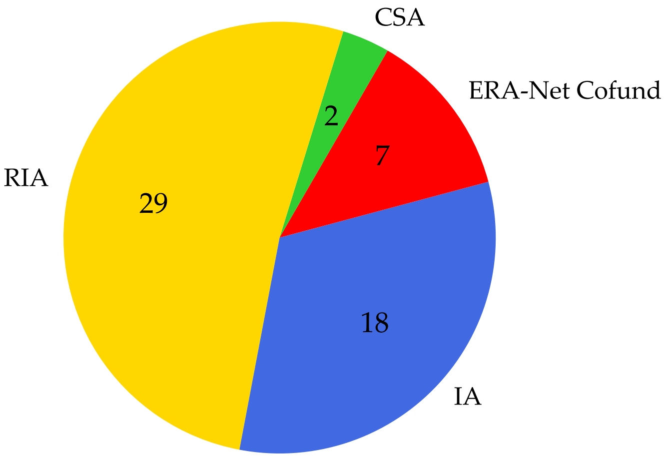


Figure 3. Number of projects per funding scheme.

The geographical and temporal aspects are also relevant. They can be helpful to understand where the major stakeholders in this sector are located and where and when the funding for research on these topics was allocated.

The coordinating countries of the 56 projects are shown in Figure 4. Italy is the country that coordinates the most projects, namely 10 (17.8%), followed by Germany with eight projects (14.3%) and Spain that represents six projects (10.7%). Participants from France, Denmark and the Netherlands are responsible for five projects each (8.9%), Norway and Austria coordinate four projects each (7.1%), Finland has three projects, the United Kingdom and Sweden have two projects each, and finally, Greece and Belgium are responsible for one project each. As clearly depicted in Figure 4, all the coordinating countries are located in western Europe, while stakeholders from eastern European countries did not participate as coordinators.

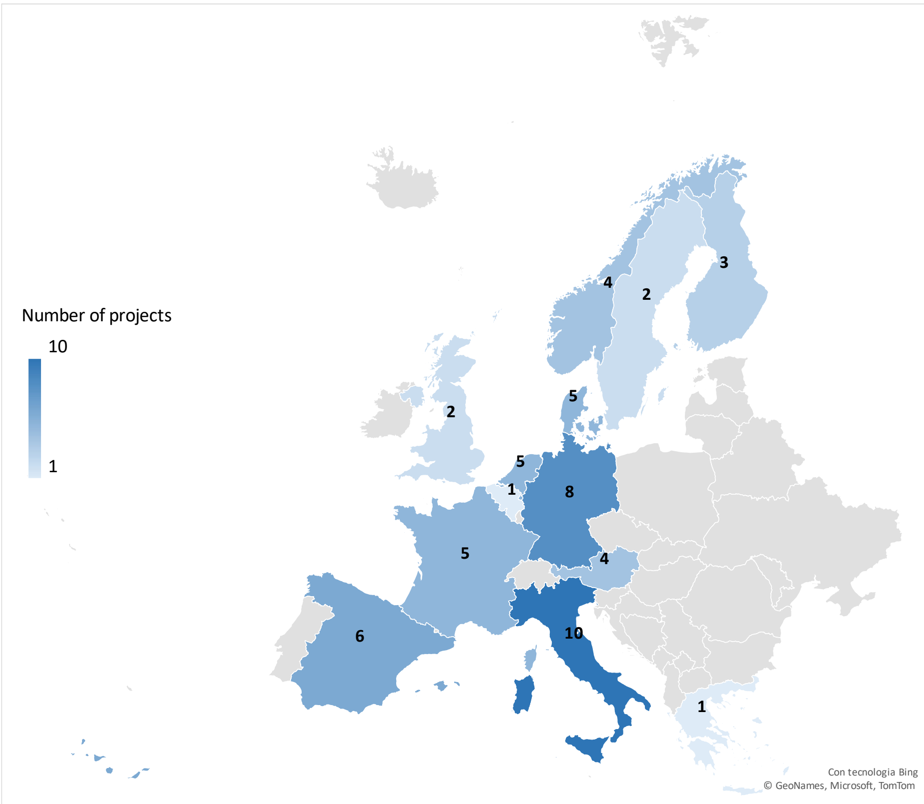


Figure 4. Number of projects per coordinating country.

However, looking at the participants of the selected projects, shown in Figure 5, their distribution encompasses a larger area, reaching countries in western Europe, albeit with only a few projects. It is worth noting that Germany and France have participants in more than half of the projects, in 34 (60.7%) and 29 (51.8%), respectively, followed by Italy with 26 (46.4%) projects and Belgium with 23 (41.1%). Most of the European countries are involved in at least one project, but the same trend displayed for the coordinators is repeated here, and many countries from eastern Europe are not involved in any projects at all. The Netherlands has partners in 21 projects, the United Kingdom in 20, Spain in 19, Switzerland in 15, Denmark in 14, Norway and Finland in 10, Sweden in 9, Austria in 8, Greece in 6, Poland in 5, the Czech Republic in 4, Iceland in 3, Estonia, Luxembourg and Slovenia in 2, and finally, Portugal, Ireland, Romania, Hungary, Malta and Lithuania have partners in just one project. Furthermore, there are some countries outside Europe that participated in some projects: Japan has partners in three projects, Israel in two projects and Brazil and South Korea in one project.

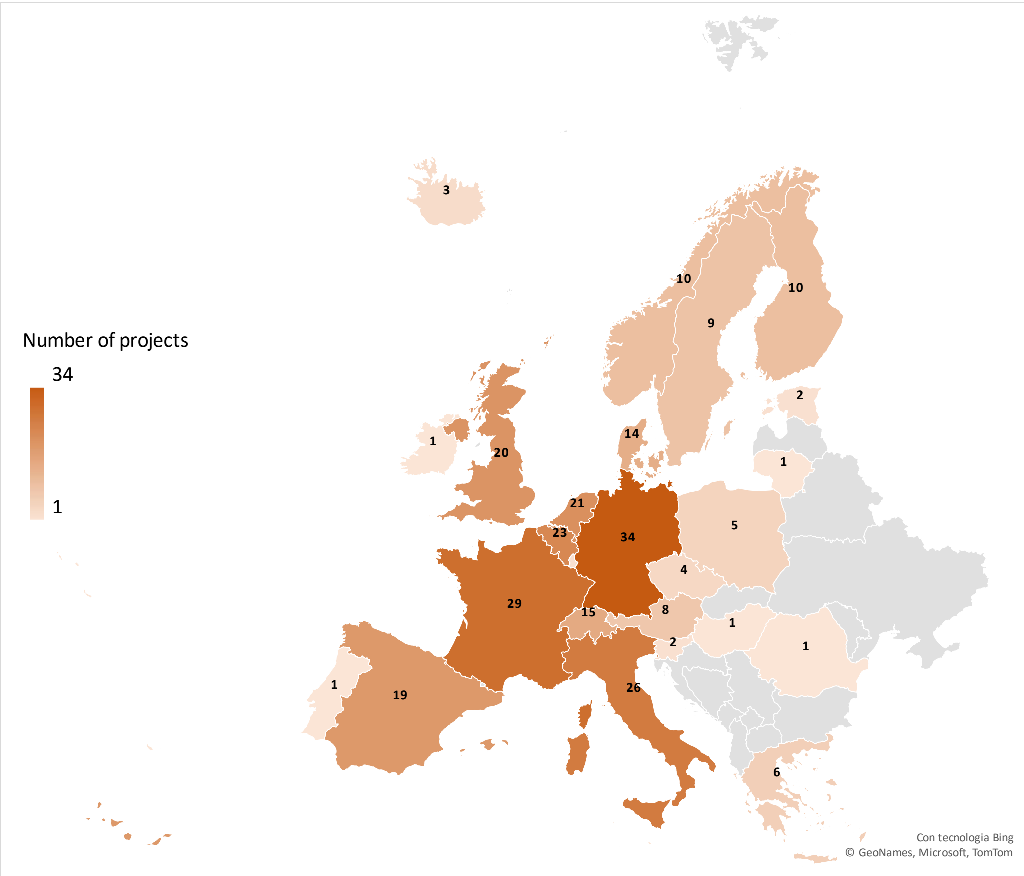
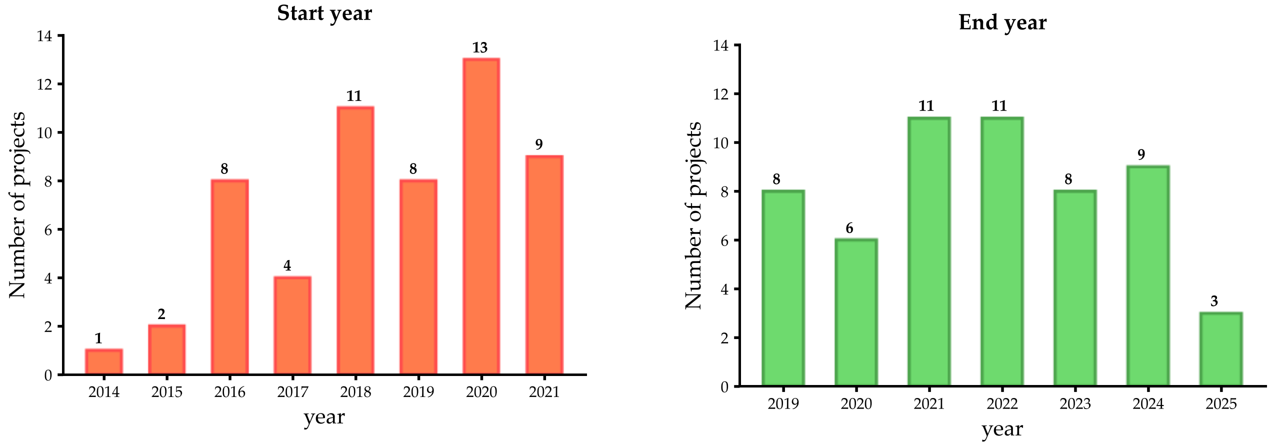


Figure 5. Number of projects per participating country.

Concerning the distribution of the projects over time, the start year of the projects is shown in Figure 6a and end year in Figure 6b: the majority started quite late, namely after 2018 (73.2%), and many of them (75%) are still ongoing. Nonetheless, since the program had already finished when the research was performed, it was possible to analyze all the calls and the projects funded. As the Horizon 2020 Programme recently ended, the latest projects are still at the preliminary phase, and, in some cases, the results are not yet available. This means that over the next few years, many results and reports are likely to be published.



(**a**) (**b**)

Figure 6. Number of projects per (**a**) start year and (**b**) end year.

4.2. Features

Some general characteristics of the projects were studied in the previous section. Here, to discuss the details of the selected projects, they were analyzed in terms of some specific features, which are helpful to characterize them and outline the key results obtained within this work. The identified features are listed below and are better explained in Table 2: aim of the production, final utilization of electrofuel, integration, type of electrofuel, electricity source, carbon dioxide source, the aim of the project and other outcomes. Specific features for each project are reported in Tables A2 and A3, both in Appendix A.

Table 2. Selected features for the characterization of the research and innovation projects on electrofuel production.

Feature		**Explanation**
Aim of the production	Storage	The scope of electrofuel production is to store energy
	Grid balancing	The scope of electrofuel production is to balance the electricity grid
Final utilization of the electrofuel		This identifies the final utilization of the electrofuel (industrial processes, aviation, trucks/vehicles, marine, electricity, heating system, gas grid)
Integration	Integrated	The project is implemented in an existing plant or structure
	Not integrated	The project is not implemented in an existing plant or structure; instead, it is a stand-alone project
Type of electrofuel		This identifies the type of fuel produced in the project (H_2, methane, methanol, kerosene/Jet fuel, ammonia, others)
Electricity source		This identifies the origin of the electricity used for the electrofuel production (wind, PV, hydroelectric, tidal, biomass-based, RES in general, conventional power plant, grid)
Carbon dioxide source		This identifies the origin of the CO_2 used for the electrofuel production if involved in the project (carbon capture, industrial processes, biogas plant, wastewater treatment plant, bio-ethanol plant, biomass)
Aim of the project	Development of a new technology	The aim of the project is to develop new technology for the production or utilization of the electrofuel
	Demonstration of project operation	The activity aims to demonstrate the operation of the project
	Roadmap	The aim of the activity is to draft a roadmap
	Business model	The activity aims to create a new business model for the industrialization or exploitation of the concept

Table 2. *Cont.*

Feature			Explanation
Other outcomes	Optimization tool		An optimization algorithm is implemented
	Model/Library		One of the outcomes of the project is a model or a library of models for the simulation of systems that involve the production of electrofuels
	LCA/LCC		Life Cycle Analysis or Life Cycle Cost are performed
	Database		One of the outcomes of the activity is the creation of a database
	Software/Platform		One of the activities is the creation of a software package or a platform for researchers and industries
	Control strategies	Other	The project includes the utilization of control strategies for monitoring the operation of the plant
		MPC	The Model Predictive Control strategy is used: the control is based on the future behavior of the system
	Retrofitting		The purpose of the project is to evaluate the addition of innovative technologies or functions to an existing system
	Planning		The purpose of the project is to perform long-term planning of the system

4.2.1. Aim of the Production

This feature characterizes the projects in terms of the primary reason to produce the fuel, which is identified as storage or grid balancing. Essentially, the aim of the production is grid balancing if the fuel is generated using electricity from the grid or RES in order to preserve the integrity of the power grid; otherwise, the fuel is considered as produced for storage purposes.

As shown in Figure 7, most projects (62.5%) do not consider grid balancing as the reason for electrofuel production. This result may be due to the fact that most projects have low TRLs, as they are Research and Innovation Actions, and they do not consider integration into real study cases, such as integration with the power grid. Nonetheless, 21 projects (37.5%) take grid balancing into consideration. Finally, in four projects, both aims are considered, namely HEAVENN, NEWsoc, PROMETEO and H2 CoopStorage.

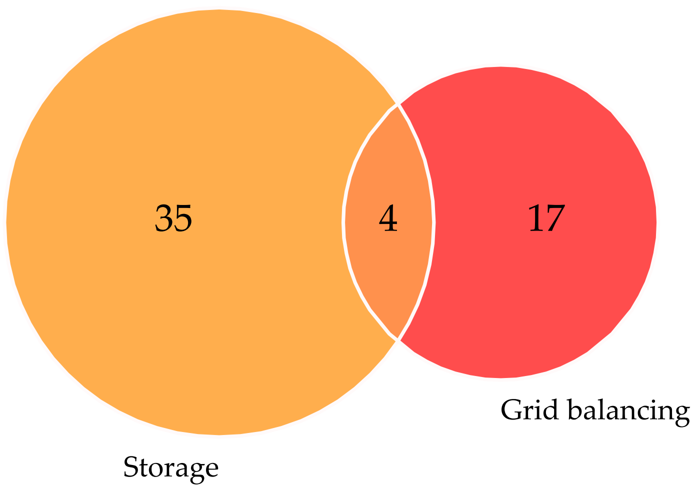


Figure 7. Number of projects per aim of the production.

4.2.2. Final Utilization

The final utilization of the electrofuels in the selected projects is shown in Figure 8. In many projects, multiple final utilization was considered; this demonstrates that these fuels can increase the flexibility and integration of different sectors. In 18 projects, final utilization was not specified: those were projects in which the technology was still not integrated and not mature enough to be put onto the market, such as RIA projects.

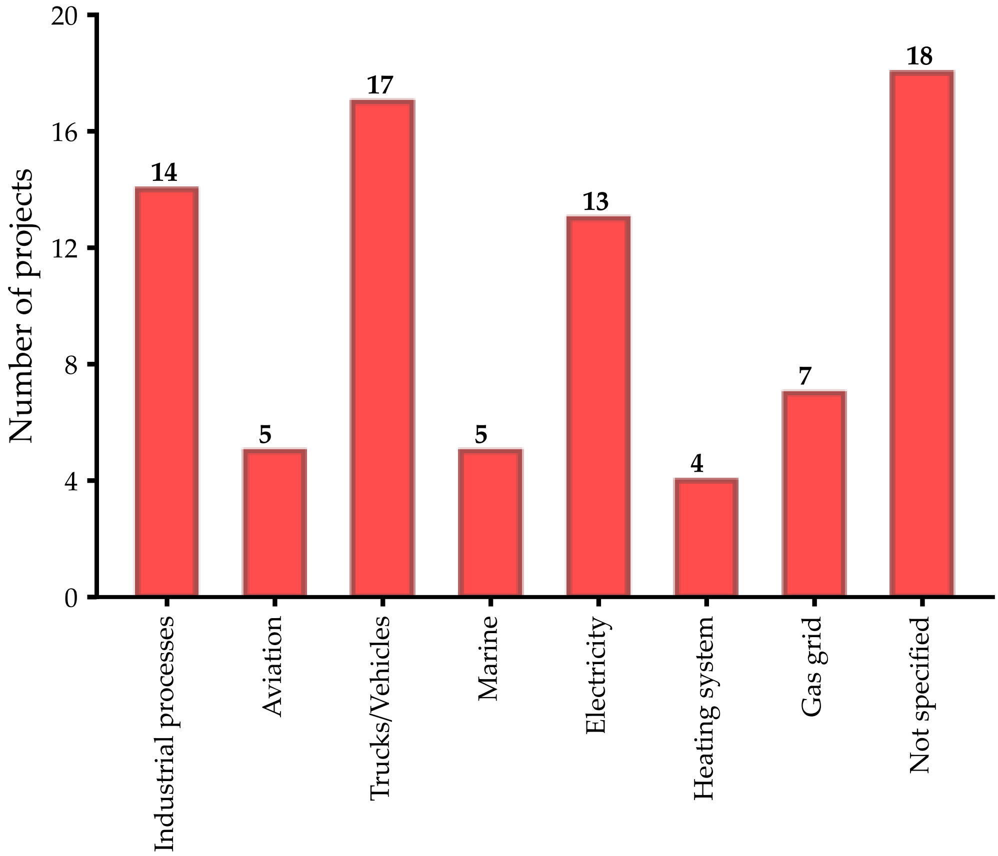


Figure 8. Number of projects per final utilization.

It is worth noting that a large number of projects consider transportation as the final utilization for the electrofuel: in 17 projects, road transport is contemplated; in five projects, marine is contemplated; and in five projects, aviation is contemplated. These numbers confirm the aforementioned extensive effort that is being made to decarbonize this sector. In 14 projects, the integration into industrial processes is considered: many industries such as the steel industries, refineries or fertilizer industries are part of the so-called hard-to-abate sectors, for which electrofuels are one of the most promising solutions for decarbonization. In 13 projects, re-electrification is considered, showing the effectiveness of electrofuels as a storage solution. Finally, sector coupling with the natural gas grid is contemplated in seven projects, while in four projects, the fuels are also used in heating systems.

4.2.3. Integration

The study of the integration of the projects into existing plants or structures is important to understand the reliability and technological advancement of such solutions.

As shown in Figure 9, among the analyzed projects, 23 (41.1%) are integrated, while most of them (58.9%) are stand-alone actions. As already mentioned, most actions have low TRLs, since RIA and these technological solutions are still at the preliminary phase. Despite this, there is no shortage of projects integrated into real systems, and this constitutes a promising result.

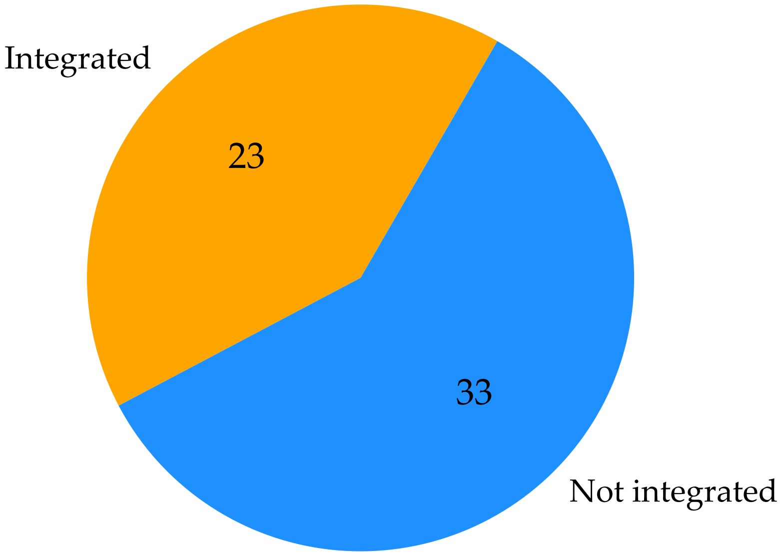


Figure 9. Number of projects per integration.

4.2.4. Type of Electrofuel

In Figure 10, the distribution of the projects based on the type of electrofuel considered is displayed. Despite hydrogen having some disadvantages regarding its transportation and utilization, in most of the projects, namely 39 (69.6%), hydrogen is produced from water electrolysis and used as the final product, although in eight projects, it is produced in combination with other electrofuels.

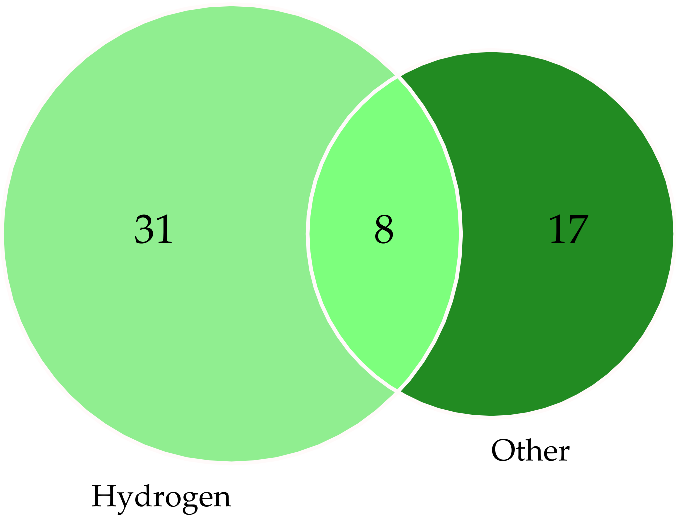


Figure 10. Number of projects per type of electrofuel produced.

In 25 projects (44.6%), other electrofuels are contemplated, in some cases more than one, and the detailed analysis of the different electrofuels considered in the projects are displayed in Figure 11. It can be noted that methane is the second most frequently used electrofuel in the projects, and it is present in 12 actions (21.4%): methane is easier to transport than hydrogen, since the infrastructure for its transportation already exists and in addition sector coupling between the power and gas grid can constitute a viable source of flexibility for the energy sector. Furthermore, methanol is considered in seven projects, while kerosene and ammonia are both considered in four projects. Finally, in five projects, other electrofuels are produced, such as formic acid, DME or long-chain liquid fuels.

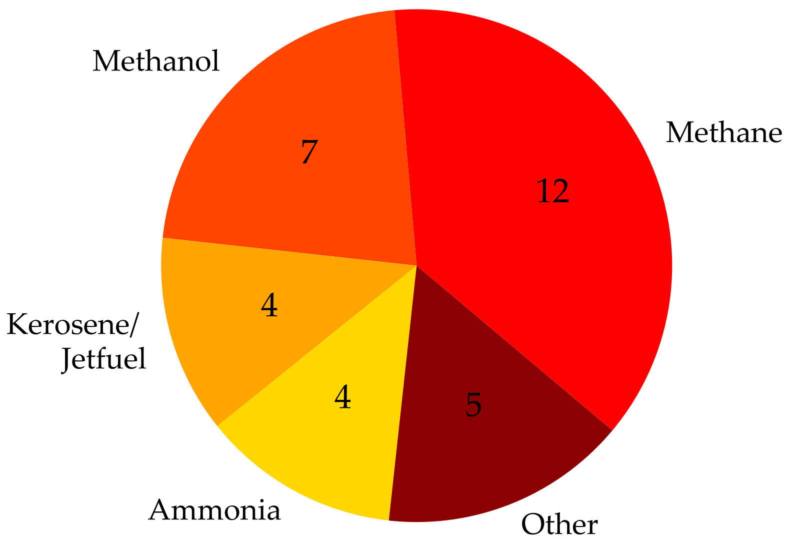


Figure 11. Number of projects per type of electrofuel produced other than hydrogen.

4.2.5. The Origin of the Electricity and Carbon Dioxide

In this section, the origin of the energy and the carbon dioxide used in the projects is analyzed. Concerning the origin of the electricity, Figure 12 shows that almost all projects (49 out of 56, i.e., 87.5%) consider RES as a primary source of electricity. This result was largely expected since the production of these fuels is reasonable only if finalized to reduce GHG emissions and to produce renewable fuels.

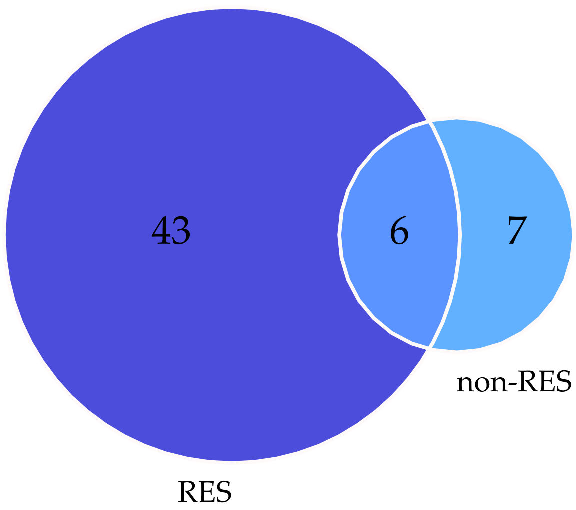


Figure 12. Number of projects per electricity source.

Nonetheless, some projects do not directly consider RES as a primary source, and those different sources are better explained in Figure 13. Most of them take electricity from the grid for grid balancing purposes: on paper, this is not actually a renewable source, but it is expected that the surplus electricity in the grid comes from fluctuating RES such as PV and wind. Only one project considers a conventional power plant as a primary source for electricity, which is ZEHTC, a Cofund action from ERA-Net. In this project, the electricity is taken both from PV and from a gas turbine manufacturing plant. Therefore, at the gas turbine testing center, there is excess electricity production, which could compromise grid stability: this electricity surplus is used to produce hydrogen, which is then utilized as fuel for the turbines.

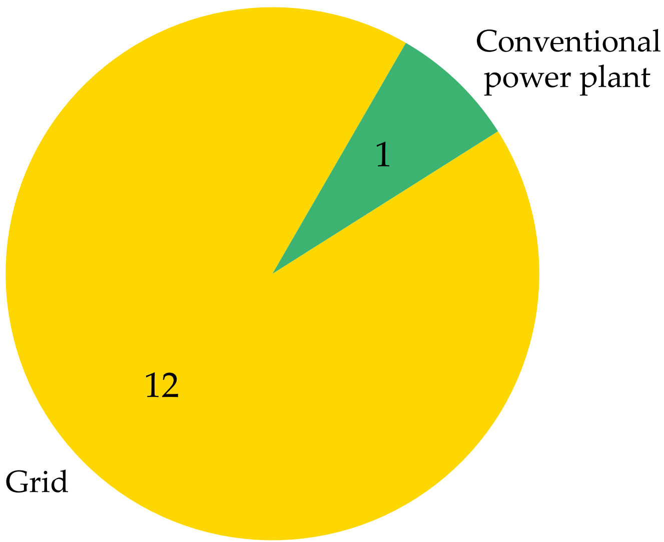


Figure 13. Number of projects per non-RES electricity source.

The distribution of the electricity sources in the 48 projects considering electricity from RES is depicted in Figure 14. In 33 projects, the source was not specified, while in many projects, more than one source is considered. PV and wind are the two renewable energy sources most utilized, while hydroelectric and tidal are only considered in two projects and one project, respectively. Concerning wind power, in five projects, onshore wind is used; in three projects, offshore wind power production is contemplated; and in the remaining four projects, this is not specified.

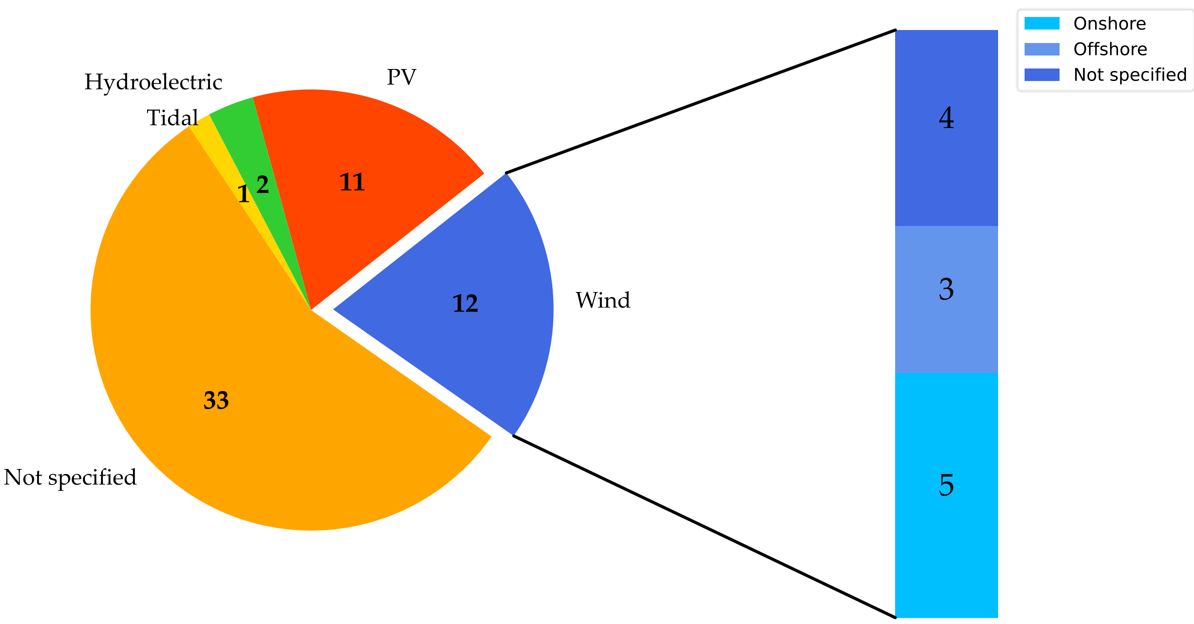


Figure 14. Number of projects per renewable electricity source.

Regarding carbon dioxide, there are 33 projects which do not include it, as they focus on the production of hydrogen or ammonia. The carbon dioxide sources considered in the other projects are displayed in Figure 15. In 12 of them, the source is not specified; six use carbon capture; in four projects, the carbon dioxide is taken from the output of industrial processes; two projects consider CO_2 either from a biogas plant, biomass or a wastewater treatment plant; and in one project, it is taken from a bio-ethanol plant.

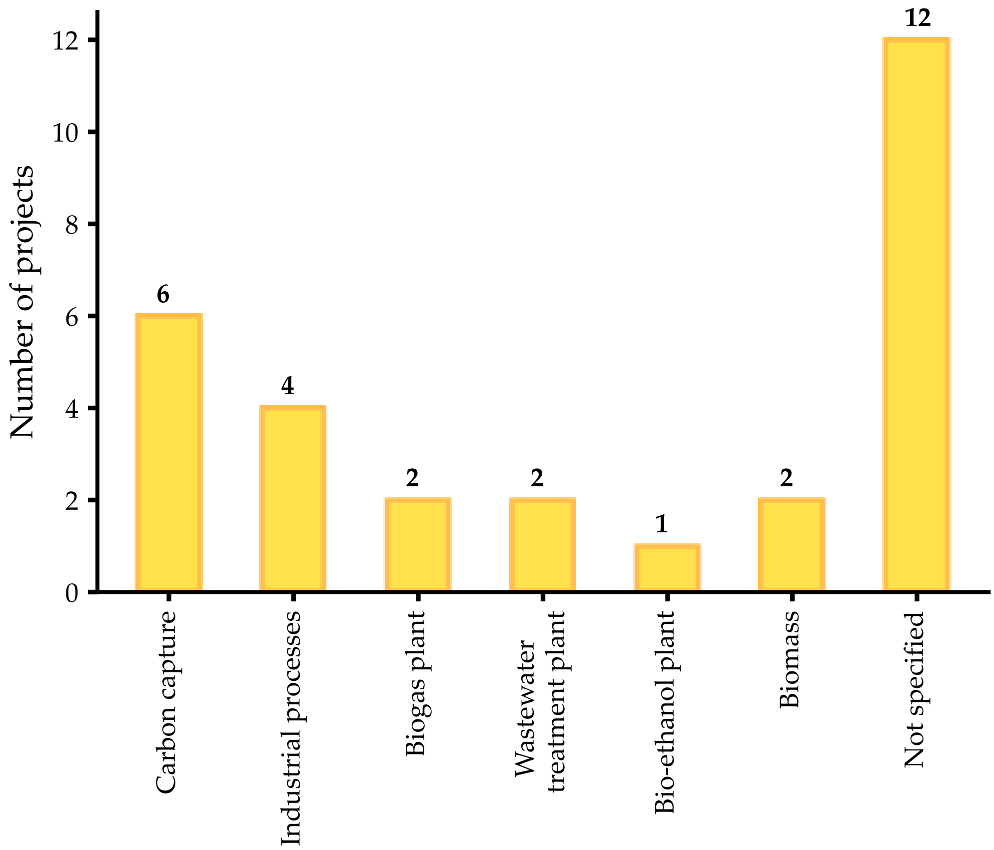


Figure 15. Number of projects per carbon dioxide source.

4.2.6. Aim of the Projects and Other Characteristics

The aim of the projects represents the main outcome obtained, and many projects present more than one aim. In Figure 16, the number of projects per the aim of the project is shown. Most of them (71.4%) consider the development of new technologies: 22 projects develop new electrolyzers, 11 projects study other production technologies (such as the methanation process) and finally, seven projects consider the development of new technology for their utilization. Furthermore, 28 projects (50%) aim to demonstrate innovative solutions and processes, and in 10 projects, business models are drawn up: the large number of projects focusing on business models shows the increasing interest of stakeholders from the economic point of view of these technologies. In fact, to make electrofuels a viable solution for decarbonization, it is essential to make them cheaper and more affordable. Lastly, nine projects focus on helping future developers and researchers, and one of their goals is to draft a roadmap.

In Figure 17, the distribution of the projects in relation to other identified outcomes is displayed. It is worth noting that in 22 projects (39.3%), a Life Cycle Assessment (LCA) or Life Cycle Cost (LCC) analysis is performed, showing the importance given to these analyses, which are useful tools to understand the advantages and drawbacks of the technologies studied better. Control strategies are developed in eight projects, and three of them use Model Predictive Control (MPC) as a control strategy. This latter was highlighted since it is a management technique that is arising in the paradigm of energy system digitalization.

In addition, in eight projects, a model is developed; in six projects, software or platform is given as output; and four projects provide the development of an optimization tool. Finally, planning is considered in four projects, retrofitting in three, while in two projects, one of the outcomes is a database.

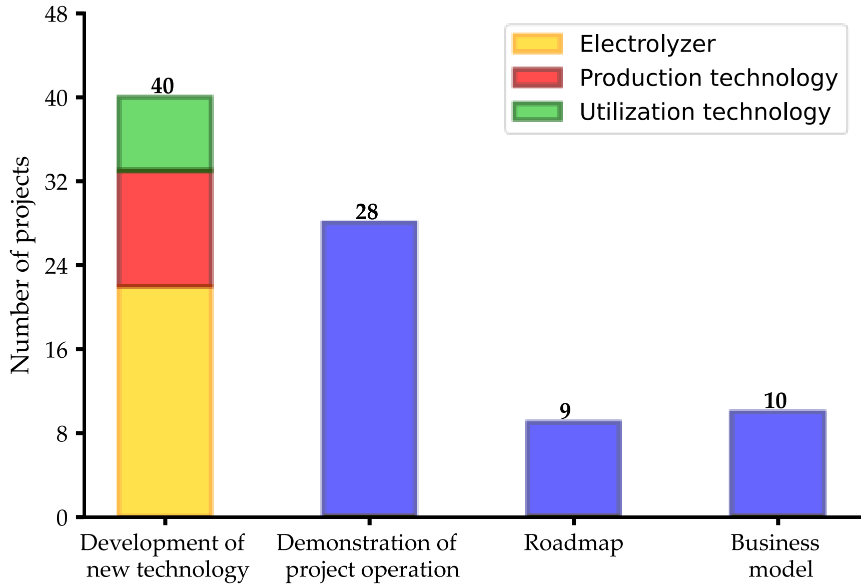


Figure 16. Number of projects per project aim.

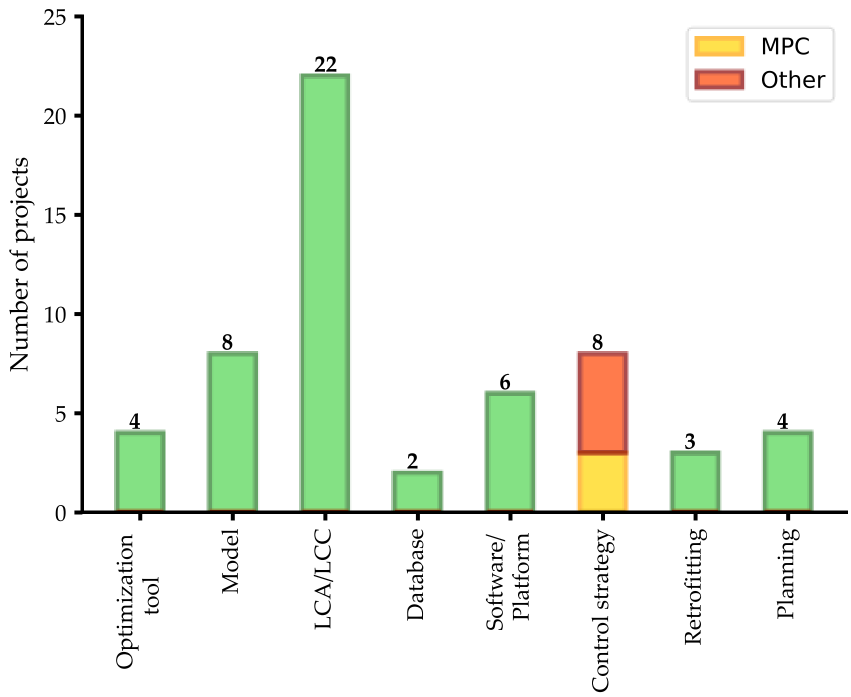


Figure 17. Number of projects per other outcomes.

The analysis performed outlined that research in this field is still at the early stages, and many projects focus on the development of new solutions and technologies. Nonetheless, optimization and control strategies are used in some actions, giving interesting results in terms of the integration of the electrofuels in smart energy systems. In particular, projects which develop innovative Model Predictive Control strategies are listed below.

- The FLEXnCONFU project [38] proposes control algorithms to enhance flexibility and make interoperability with the power grid possible. Innovative control strategies and an innovative MPC are implemented and tested in power-to-ammonia and power-to-hydrogen systems;

- One of the goals of the H2 CoopStorage project [39] is to dynamically manage the means of renewable energy production, storage and electric loads, with a control strategy based on IoT (Internet of Things) data and the MPC approach;
- The IFAISTOS project [40] aims to build mathematical models of electrofuel production and develop an MPC that allows the system to be optimally managed, considering renewable energy source variability and integration into a real environment.

4.3. Electrolyzer Technology Developed

As previously explained in Section 4.2.6, in 22 projects, one of the main outcomes is the development of an innovative electrolyzer. It is useful to look at the distribution of these technologies in terms of electrolyzer type to understand the state-of-the-art in the European context better. In Figure 18, projects divided per electrolyzer technology developed are shown. There is a net prevalence of projects studying SOEC technologies (10 out of 22), followed by PEM (six projects). Furthermore, AEM are developed in three projects, AEC in two projects and PCEC only in one project.

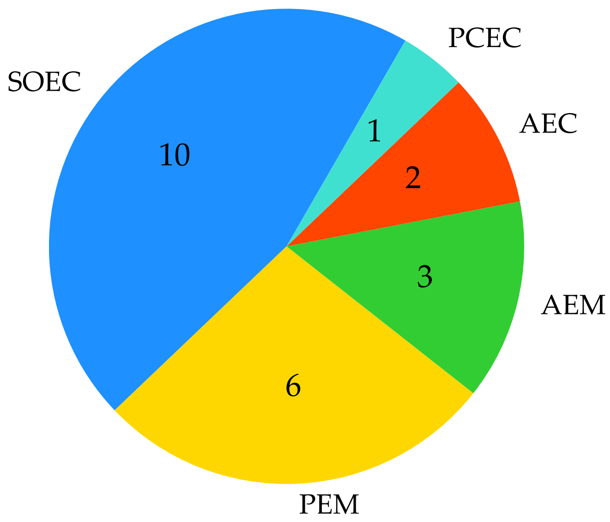


Figure 18. Number of projects per electrolyzer technology developed.

Investigating the type of projects that develop new electrolyzers, the results show that they are almost all Research and Innovation Actions, except some Innovation Actions developing SOEC and AEC technologies. Another relevant feature is the size of these technologies: the two projects developing AEC are focused on Pressurized Alkaline Electrolyzers (PAE) and consider electrolyzers with a nominal power of around 5 MW; the SOEC and PEM technology size are in the order of megawatts or hundreds of kilowatts. Finally, looking at the AEM technology, its TRL is still low, and the three projects test a 2-kW AEM prototype, trying to make them cost-efficient or improving the materials and design. Regarding PCEC, only one project considers it, namely the GAMER project, with a 10-kW electrolyzer system, which aims to ensure the progress of this technology from TRL 3 to TRL 5 [41]. These last two technologies, as seen in Section 2.1, are still at the development stage and have low TRLs.

4.4. Projects Focused on Airports and Sustainable Aviation

The decarbonization of the aviation sector is very challenging, and many studies are trying to find a pathway to achieve this. For instance, in [42], the authors present a review of alternative aviation fuels and propulsion systems, focusing on costs, and they include bio-jet fuels, electro-jet fuels, liquid natural gas, hydrogen, electricity and ammonia, and in [43], the potential of power-to-liquid kerosene is investigated. A roadmap to decarbonizing

European aviation was published in 2018 [44]: it outlines that policymakers must be actively engaged to ensure a decarbonized future.

In Section 4.2.2, it was shown that five projects included aviation as a final utilization. They are described better here to understand the main European actions addressing the decarbonization of the aviation sector:

- The KEROGREEN project [45] aims at the development and testing of an innovative process to produce green kerosene for aviation usage, synthesized from air and water and powered by renewable electricity, and recapturing the carbon emitted from the atmosphere, creating a closed carbon fuel cycle. The KEROGREEN conversion route is based on plasma-driven dissociation of CO_2, solid oxide membrane oxygen separation and Fischer–Tropsch kerosene synthesis;
- The ENABLEH2 project [46] aims to demonstrate the usage of liquid hydrogen in the aviation sector. It also provides a comprehensive roadmap for the introduction of liquid hydrogen for civil aviation;
- The concept of the EcoFuel project [47] centers on the integration of a set of chemical process steps toward a complete process chain for the generation of renewable, high-energy density liquid hydrocarbon fuels for mobility applications;
- The goal of the TAKE-OFF project [48] is to develop and validate the complete technology chain to produce SAF from CO_2 and H_2. The TAKE-OFF route consists of capturing CO_2 from industrial flue gas and making it react with green hydrogen to create light olefins, which are subsequentially upgraded to SAF;
- The 4airCRAFT project [49] aims to develop new catalysts for the conversion of CO_2 into liquid fuels for the aviation sector. The 4AirCRAFT technology will produce sustainable jet fuel at low temperatures (below 80 °C).

Other projects funded by Horizon 2020 are not considered in the review because they do not include electrofuel production. However, they focus on the decarbonization of this sector; for example, the HEAVEN project [50] aims at the spread of carbon-neutral fuels in the aviation sector. The goal of the project is to design the first aircraft powertrain based on a high power density fuel cell system and a cryogenic hydrogen storage system and integrate it into an existing 2–4 seater aircraft.

Other projects are centered on airport decarbonization, such as ALIGHT [51], OLGA [52], TULIPS [53] and STARGATE [54]. Several solutions are included in their strategies, and the most noticeable is the implementation of smart energy solutions to manage airport operations and the utilization of SAF, which include biofuels and electrofuels.

4.5. Other Projects

Other Horizon 2020 Programme-funded projects were identified. They consider electrofuel production as a solution for smart energy system development. These projects were not selected for the previous analysis since they deal with Power-to-X technologies in a small part of their program, but it is interesting to look at them to understand better how electrofuels can fit into a complex system.

- The inteGRIDy project [55] aims to integrate cutting-edge technologies and solutions into a scalable Cross-Functional Platform connecting different energy networks. This enables the optimal operation and coordination of distributed energy resources and the increasing share of renewables through collaborative storage schemes. In the project, hydrogen production is considered as a storage solution at the Xanthi pilot site: a PEM electrolyzer is integrated into a microgrid powered with photovoltaics and wind generators. The surplus energy produced is stored through batteries or hydrogen, which is then used in a fuel cell to produce electricity when required [56];
- The REFLEX project [57] aims to analyze and evaluate the development of the EU energy system up to the year 2050 toward a low-carbon energy system with a focus on flexibility options, including Power-to-X options to support a better system integration of RES. For the analysis of the European energy system, different single issue-specific models and tools are used, and then these detailed models are combined into an

integrated energy model system. A detailed explanation of the results and methods used can be found in [58].

Another project developed by the FCH JU, which can contribute to the development and distribution of the electrolyzer, is the HyLAW project [59]. It aims to remove legal barriers to the deployment of fuel cells and hydrogen applications and aims to promote the market uptake of hydrogen and fuel cell technologies by providing market developers with a clear view of the regulations, drawing policy makers' attention to the legal barriers to be removed. One of the main outcomes of this project is a public database compiling legal and administrative processes applicable to hydrogen and fuel cell technologies in 18 countries across Europe [60].

4.6. Drivers and Guidelines

The results presented in the previous sections give an overview of the current status of the European Research and Innovation Actions on electrofuels. In this section, the major guidelines to drive research and the stakeholders involved are presented.

First of all, the main driver, which is the reason why the effort to change the actual energy system is being made, is the requirement for net-zero emissions by 2050, imposed by the EU to fight climate change. However, to identify the pathway that future developers and researchers must follow in this field, the following drivers were identified:

- *Industrialization*. As previously shown, the TRL reached from many of these technologies is low, and there is still a long way to go to make them a viable solution for the decarbonization of different sectors. It is crucial to continue studying in order to make them marketable technologies;
- *Barrier abatement*. Hydrogen and the other renewable electrofuels are not yet ready for the market, as mentioned above, because the technologies are still not mature, but also because there is no clear legislation for their commercialization and identification. Policymakers should remove legal barriers for their diffusion and promote the use of these fuels through incentives [61];
- *Flexibility and sector coupling*. As it is a storage solution, a tool for grid balancing and a way to couple the power grid and the gas grid, electrofuels are a source of flexibility for the energy sector. This flexibility must be taken into consideration as an added value of these fuels in the planning of a more resilient and sustainable future energy system;
- *Smart management*. On the road to achieving carbon neutrality by 2050 and with the transition from fossil to renewable sources, many innovative solutions will be implemented in the energy grids, which will need to become smarter in order to be better managed. Smart energy systems, however, need innovative and intelligent control algorithms and further studies need to be conducted in this field.

These drivers must help the stakeholders to make better decisions and to find the best pathway to follow, and are mainly addressed to policymakers (who can remove legal barriers and implement incentives for the usage of electrofuels), researchers (to continue investigating these issues) and industries (which have to continue studying and innovating these technologies to reach higher TRLs and commercialization).

5. Conclusions

This work presented an overview of the projects funded by the Horizon 2020 Framework Programme, which deal with electrofuels as a solution to better manage the energy system, decarbonize different sectors, or store surplus energy. An extensive internet search was performed, and 56 projects were selected for in-depth study. The projects were analyzed using some general information and specific features such as the type of fuel produced, the aim of the action or the main outcomes, and the results were presented. A special focus was given to the actions dealing with electrofuels produced for aviation purposes.

Of the results showed, it was observed that more than half of the selected projects are Research and Innovation Actions, which are actions reaching low TRLs. This indicates that much progress is still required to make them a cost-effective and consolidated solution for decarbonization. In addition, the project partnerships are mainly coordinated by and composed of partners from western Europe, while many countries from eastern Europe were not involved at all. In addition, since most of the projects started only recently, and they are still ongoing, many publications and results are expected to be available over the next few years. The final utilization of the fuels in the projects suggests there is extensive interest in the transport sector, even though they are also frequently used in industrial applications or for re-electrification. In addition, many studies focus on the production of hydrogen, while a smaller number of them consider further transformation to more complex fuels. Concerning the aim of the actions, many projects focus on the development of new technology for the production or utilization of the fuels or on the demonstration of the feasibility of a new solution. Fewer projects focus on the control and optimization of the solutions in an integrated system. This shows that there is the need to keep studying innovative algorithms for their integration into real systems to make them a viable solution.

Finally, it was underlined that industrialization, barrier abatement, flexibility and smart management are the key drivers that should guide new researchers and developers in this field. Policymakers, researchers and industries are the major stakeholders who must act. This research represents a useful tool for everyone who wants to understand the status of the research in this field better.

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

Abbreviations

AEC	Alkaline Electrolysis Cell
AEM	Anion Exchange Membrane
CORDIS	Community Research and Development Information Service
CSA	Coordination and Support Action
EU	European Union
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Greenhouse Gases
IA	Innovation Action
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MPC	Model Predictive Control
PAE	Pressurized Alkaline Electrolyzer
PCEC	Proton Ceramic Electrolysis Cell
PEM	Proton Exchange Membrane
RES	Renewable Energy Sources
RIA	Research and Innovation Action
SAF	Sustainable Aviation Fuels
SES	Smart Energy Systems
SOEC	Solid Oxide Electrolysis Cell

Appendix A

In this appendix, general information and specific features of the 56 selected projects are reported.

Table A1. General information on the selected projects funded by the Horizon 2020 Programme. (n/a = not applicable).

Project	Title	Grant Agreement	Funding Scheme	TRL	Funding [€]	Coordinating Country	Start Date	End Date
4airCRAFT	Air Carbon Recycling for Aviation Fuel Technology	101022633	RIA	1–5	2,239,591	Spain	1 May 2021	30 April 2024
ANIONE	Anion Exchange Membrane Electrolysis for Renewable Hydrogen Production on a Wide-Scale	875024	RIA	1–5	1,999,995	Italy	1 January 2020	31 December 2022
BALANCE	Increasing penetration of renewable power, alternative fuels and grid flexibility by cross-vector electrochemical processes	731224	RIA	1–5	2,500,596	Finland	1 December 2016	30 November 2019
BIGHIT	Building Innovative Green Hydrogen systems in an Isolated Territory: a pilot for Europe	700092	IA	6–9	5,000,000	Spain	1 May 2016	30 April 2022
C2FUEL	Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem	838014	RIA	1–5	3,999,840	France	1 June 2019	31 May 2023
CHANNEL	Development of the most Cost-efficient Hydrogen production unit based on AnioN exchange membrane Electrolysis	875088	RIA	1–5	1,999,906	Norway	1 January 2020	31 December 2022
CrossChargePoint	Integrated MultiEnergy Storages Coupling the Power Network to the Transportation Sector	646039 and 775970	ERA-Net Cofound	5–8	2,074,703	Germany	1 February 2021	31 January 2024
Demo4Grid	Demonstration of 4MW Pressurized Alkaline Electrolyser for Grid Balancing Services	736351	IA	6–9	2,932,554	Greece	1 March 2017	31 August 2023
Djewels	Delfzijl Joint Development of green Water Electrolysis at Large Scale	826089	IA	6–9	10,999,999	Netherlands	1 January 2020	31 December 2025
Eco	Efficient Co-Electrolyser for Efficient Renewable Energy Storage	699892	RIA	1–5	2,500,513	Denmark	1 May 2016	30 April 2019

Table A1. *Cont.*

Project	Title	Grant Agreement	Funding Scheme	TRL	Funding [€]	Coordinating Country	Start Date	End Date
EcoFuel	Renewable Electricity-based, cyclic and economic production of Fuel	101006701	RIA	1–5	4,858,547	Austria	1 January 2021	31 December 2023
ELY4OFF	PEM ElectroLYsers FOR operation with OFFgrid renewable installations	700359	RIA	1–5	2,315,217	Spain	1 April 2016	30 September 2019
ELYntegration	Grid Integrated Multi Megawatt High Pressure Alkaline Electrolysers for Energy Applications	671458	RIA	1–5	1,861,309	Spain	1 September 2015	31 May 2019
ENABLEH2	ENABLing cryogEnic Hydrogen based CO2 free air transport	769241	RIA	1–5	3,987,680	United Kingdom	1 September 2018	31 August 2021
Energy-X	Transformative chemistry for a sustainable energy future	820444	CSA	n/a	976,115	Denmark	1 March 2019	29 February 2020
FLAG SHIPS	Clean waterborne transport in Europe	826215	IA	6–9	4,999,978	Finland	1 January 2019	30 September 2023
FLEXCHX	Flexible combined production of power, heat and transport fuels from renewable energy sources	763919	RIA	1–5	4,489,545	Finland	1 March 2018	28 February 2021
FLEXnCONFU	FLExibilize combined cycle power plant through power-to-X solutions using non-CONventional Fuels	884157	IA	6–9	9,887,141	Italy	1 April 2020	31 March 2024
GAMER	Game changer in high temperature steam electrolysers with novel tubular cells and stacks geometry for pressurized hydrogen production	779486	RIA	1–5	2,998,951	Norway	1 January 2018	31 December 2020
GrInHy	Green Industrial Hydrogen via Reversible High-Temperature Electrolysis	700300	RIA	1–5	4,498,150	Germany	1 March 2016	28 February 2019
GrInHy2.0	Green Industrial Hydrogen via steam electrolysis	826350	IA	6–9	3,999,993	Germany	1 January 2019	31 December 2022

Table A1. *Cont.*

Project	Title	Grant Agreement	Funding Scheme	TRL	Funding [€]	Coordinating Country	Start Date	End Date
H2 CoopStorage	Development of tools enabling the deployment and the management of a multi-energy (electric, heat, hydrogen) Energy Community integrating hybrid storage	646039 and 775970	ERA-Net Cofound	5–8	559,500	Belgium	14 September 2020	31 December 2022
H2FUTURE	Hydrogen meeting future needs of low carbon manufacturing value chain	735503	IA	6–9	11,997,820	Austria	1 January 2017	30 June 2021
Haeolus	Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation	779469	IA	6–9	4,997,738	Norway	1 January 2018	31 December 2021
HEAVENN	Hydrogen Energy Applications for Valley Environments in Northern Netherlands	875090	IA	6–9	20,000,000	Netherlands	1 January 2020	31 December 2025
HPEM2GAS	High Performance PEM Electrolyzer for Cost-effective Grid Balancing Applications	700008	RIA	1–5	2,499,999	Italy	1 April 2016	30 September 2019
HyBalance	HyBalance	671384	IA	6–9	7,999,370	France	1 October 2015	30 September 2020
HyCARE	Hydrogen CArrier for Renewable Energy storage	826352	RIA	1–5	1,999,230	Italy	1 January 2019	31 December 2021
HYFLEXPOWER	HYdrogen as a FLEXible energy storage for a fully renewable European POWER system	884229	IA	6–9	10,475,081	Germany	1 May 2020	30 April 2024
HyMethShip	Hydrogen-Methanol Ship propulsion system using on-board pre-combustion carbon capture	768945	IA	6–9	8,438,110	Austria	1 July 2018	30 June 2021
Ifaistos	Intelligent Electro-fuel Production for an Integrated Storage System	646039 and 775970	ERA-Net Cofound	5–8	668,740	Italy	1 November 2020	31 October 2023
Kerogreen	Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO2, syngas formation and Fischer–Tropsch synthesis	763909	RIA	1–5	4,951,958	Netherlands	1 April 2018	31 March 2022

Table A1. *Cont.*

Project	Title	Grant Agreement	Funding Scheme	TRL	Funding [€]	Coordinating Country	Start Date	End Date
LAURELIN	Selective CO2 conversion to renewable methanol through innovative heterogeneous catalyst systems optimized for advanced hydrogenation technologies (microwave, plasma and magnetic induction)	101022507	RIA	1–5	4,448,838	Spain	1 May 2021	30 April 2025
MefCO2	Synthesis of methanol from captured carbon dioxide using surplus electricity	637016	IA	6–9	8,622,292	Spain	1 December 2014	30 June 2019
MultiPLHY	Multimegawatt high-temperature electrolyser to generate green hydrogen for production of high-quality biofuels	875123	IA	6–9	6,993,725	France	1 January 2020	31 December 2024
NEPTUNE	Next Generation PEM Electrolyser under New Extremes	779540	RIA	1–5	1,926,221	United Kingdom	1 February 2018	31 January 2021
NEWELY	Next Generation Alkaline Membrane Water Electrolysers with Improved Components and Materials	875118	RIA	1–5	2,597,413	Germany	1 January 2020	31 December 2022
NewSOC	Generation solid oxide fuel cell and electrolysis technology	874577	RIA	1–5	4,999,726	Denmark	1 January 2020	31 December 2022
ORACLE	Novel Routes and Catalysts for Synthesis of Ammonia as Alternative Renewable Fuel	101022738	RIA	1–5	2,846,078	Denmark	1 May 2021	30 April 2024
OYSTER	Offshore hydrogen from shoreside wind turbine integrated electrolyser	101007168	RIA	1–5	4,999,843	France	1 January 2021	31 December 2024
PECSYS	Technology demonstration of large-scale photo-electrochemical system for solar hydrogen production	735218	RIA	1–5	2,499,992	Germany	1 January 2017	31 December 2020
PENTAGON	Unlocking European grid local flexibility through augmented energy conversion capabilities at district-level	731125	RIA	1–5	2,834,757	Italy	1 December 2016	30 November 2019

Table A1. *Cont.*

Project	Title	Grant Agreement	Funding Scheme	TRL	Funding [€]	Coordinating Country	Start Date	End Date
Planet	Planning and operational tools for optimising energy flows and synergies between energy networks	773839	RIA	1–5	3,999,695	Italy	1 November 2017	31 January 2021
Power-2-Transport	Energy storage for integration of renewables into public transport systems	646039 and 775970	ERA-Net Cofound	5–8	536,879	Sweden	1 January 2021	31 December 2023
PRETZEL	Novel modular stack design for high pressure PEM water electrolyzer technology with wide operation range and reduced cost	779478	RIA	1–5	1,999,088	Germany	1 January 2018	30 June 2021
PROMETEO	Hydrogen PROduction by MEans of solar heat and power in high TEmperature Solid Oxide Electrolysers	101007194	RIA	1–5	2,499,531	Italy	1 January 2021	30 June 2024
REFHYNE	Clean Refinery Hydrogen for Europe	779579	IA	6–9	9,998,043	Norway	1 January 2018	31 December 2022
REFLEX	Reversible solid oxide Electrolyzer and Fuel cell for optimized Local Energy miX	779577	RIA	1–5	2,999,575	France	1 January 2018	31 December 2021
REMOTE	Remote area Energy supply with Multiple Options for integrated hydrogen-based TEchnologies	779541	IA	6–9	4,995,950	Italy	1 January 2018	31 December 2021
STOREandGO	Innovative large-scale energy STOragE technologies AND Power-to-Gas concepts after Optimisation	691797	IA	6–9	17,937,358	Germany	1 March 2016	29 February 2020
SUNRISE	Solar Energy for a Circular Economy	816336	CSA	n/a	1,000,000	Netherlands	1 March 2019	30 April 2020
SuperP2G	Synergies Utilising renewable Power REgionally by means of Power To Gas	646039 and 775970	ERA-Net Cofound	5–7	1,417,301	Denmark	1 November 2019	31 October 2022
SWITCH	Smart Ways for In-situ Totally integrated and Continuous multisource generation of Hydrogen	875148	IA	6–9	2,992,521	Italy	1 January 2020	30 June 2023
TAKE-OFF	Production of synthetic renewable aviation fuel from CO2 and H2	101006799	RIA	1–5	4,998,788	Netherlands	1 January 2021	31 December 2024

Table A1. *Cont.*

Project	Title	Grant Agreement	Funding Scheme	TRL	Funding [€]	Coordinating Country	Start Date	End Date
USC-Flex Store	Underground Sun Conversion - Flexible Storage	646039 and 775970	ERA-Net Cofound	5–8	1,636,025	Austria	1 December 2020	31 May 2023
ZEHTC	Zero Emission Hydrogen Turbine Centre	646039 and 775970	ERA-Net Cofound	5–7	1,425,440	Sweden	1 October 2019	30 September 2022

Table A2. Relevant features of the selected projects: aim of the production, final utilization of the electrofuel, integration and type of electrofuel.

Project	Aim of the Production			Final Utilization of the Electrofuel							Integration		Type of Electrofuel					
	Storage	Grid Balancing	Industrial Processes	Aviation	Trucks/Vehicles	Marine	Electricity	Heating System	Gas Grid	Not Specified	Integrated	Not Integrated	Hydrogen	Methane	Methanol	Kerosene/Jetfuel	Ammonia	Other
4airCRAFT	✓			✓								✓				✓		
ANIONE	✓									✓		✓	✓					
BALANCE		✓	✓		✓		✓					✓	✓	✓				
BIGHIT	✓				✓		✓	✓			✓		✓					
C2FUEL	✓				✓	✓	✓				✓							✓
CHANNEL	✓									✓		✓	✓					
CrossChargePoint		✓			✓		✓					✓	✓	✓				
Demo4Grid		✓	✓		✓						✓		✓					
Djewels	✓		✓								✓			✓				
Eco	✓								✓			✓		✓				
EcoFuel	✓			✓	✓	✓						✓						✓
ELY4OFF	✓				✓		✓		✓			✓	✓					
ELYntegration		✓								✓		✓	✓					
ENABLEH2	✓			✓								✓	✓					
Energy-X	✓									✓		✓	✓	✓	✓		✓	✓

Table A2. *Cont.*

Project	Aim of the Production			Final Utilization of the Electrofuel							Integration		Type of Electrofuel					
	Storage	Grid Balancing	Industrial Processes	Aviation	Trucks/Vehicles	Marine	Electricity	Heating System	Gas Grid	Not Specified	Integrated	Not Integrated	Hydrogen	Methane	Methanol	Kerosene/Jetfuel	Ammonia	Other
FLAG SHIPS	✓					✓					✓		✓					
FLEXCHX		✓			✓							✓						✓
FLEXnCONFU		✓					✓				✓		✓				✓	
GAMER	✓									✓	✓			✓				
GrInHy	✓		✓								✓		✓					
GrInHy2.0	✓		✓								✓		✓					
H2 CoopStorage	✓	✓								✓	✓		✓					
H2FUTURE		✓	✓								✓		✓					
Haeolus	✓									✓	✓		✓					
HEAVENN	✓	✓	✓		✓		✓	✓			✓		✓					
HPEM2GAS		✓								✓		✓	✓					
HyBalance		✓	✓		✓						✓		✓					
HyCARE	✓						✓					✓	✓					
HYFLEXPOWER		✓					✓					✓	✓					
HyMethShip	✓					✓						✓	✓		✓			
Ifaistos	✓				✓				✓			✓		✓				
Kerogreen	✓			✓							✓					✓		
LAURELIN	✓									✓		✓			✓			
MefCO2		✓	✓								✓				✓			
MultiPLHY	✓		✓								✓		✓					
NEPTUNE		✓			✓							✓	✓					
NEWELY	✓									✓		✓	✓					
NewSOC	✓	✓								✓		✓	✓					
ORACLE	✓									✓		✓					✓	

Table A2. *Cont.*

Project	Aim of the Production			Final Utilization of the Electrofuel							Integration		Type of Electrofuel					
	Storage	Grid Balancing	Industrial Processes	Aviation	Trucks/Vehicles	Marine	Electricity	Heating System	Gas Grid	Not Specified	Integrated	Not Integrated	Hydrogen	Methane	Methanol	Kerosene/Jetfuel	Ammonia	Other
OYSTER	✓									✓	✓		✓					
PECSYS	✓									✓		✓	✓					
PENTAGON		✓								✓		✓		✓				
Planet		✓	✓		✓				✓			✓	✓	✓				
Power-2-Transport	✓				✓							✓		✓				
PRETZEL		✓								✓		✓	✓					
PROMETEO	✓	✓	✓								✓		✓					
REFHYNE		✓	✓		✓		✓	✓			✓		✓					
REFLEX		✓					✓	✓				✓	✓					
REMOTE	✓						✓				✓		✓					
STOREandGO	✓				✓	✓			✓		✓			✓				
SUNRISE	✓									✓		✓	✓	✓	✓	✓	✓	✓
SuperP2G	✓		✓						✓		✓		✓	✓				
SWITCH	✓				✓							✓	✓					
TAKE-OFF	✓			✓								✓				✓		
USC-Flex Store	✓									✓		✓		✓				
ZEHTC	✓						✓					✓	✓					

Table A3. Relevant features of the selected projects: electricity source, carbon dioxide source, aim of the project and other outcomes.

	Electricity Source							**Carbon Dioxide Source**								**Aim of the Project**					**Other Outcomes**						
Project	**RES (Not Specified)**	**Wind**	**PV**	**Hydroelectric**	**Tidal**	**Conventional Power Plant**	**Grid**	**Carbon Capture**	**Industrial Processes**	**Biogas Plant**	**Wastewater Treatment Plant**	**Bio-ethanol Plant**	**Biomass**	**Not Specified**	**Not Involved**	**Development of New Technology**	**Demonstration of Project Operation**	**Roadmap**	**Business Model**	**Optimization Tool**	**Model**	**LCA/LCC**	**Database**	**Software/Platform**	**Control Strategy**	**Retrofitting**	**Planning**
4airCRAFT	✓													✓		✓						✓					
ANIONE	✓														✓	✓						✓					
BALANCE		✓	✓											✓		✓						✓	✓				
BIGHIT		✓			✓										✓		✓										
C2FUEL	✓								✓							✓	✓										
CHANNEL	✓														✓	✓											
CrossChargePoint							✓							✓			✓		✓	✓					✓		✓
Demo4Grid							✓								✓	✓	✓		✓								
Djewels	✓													✓			✓										
Eco		✓	✓						✓	✓			✓			✓						✓					
EcoFuel	✓							✓								✓	✓					✓					
ELY4OFF	✓														✓	✓			✓		✓	✓			✓		
ELYntegration							✓								✓	✓			✓			✓					
ENABLEH2	✓														✓			✓				✓					
Energy-X	✓													✓				✓						✓			
FLAG SHIPS	✓														✓		✓									✓	
FLEXCHX	✓						✓						✓			✓		✓				✓					
FLEXnCONFU							✓								✓		✓			✓		✓			✓	✓	
GAMER	✓								✓							✓						✓					
GrInHy	✓														✓	✓	✓	✓	✓			✓					

Table A3. *Cont.*

	Electricity Source							Carbon Dioxide Source								Aim of the Project				Other Outcomes							
Project	**RES (Not Specified)**	**Wind**	**PV**	**Hydroelectric**	**Tidal**	**Conventional Power Plant**	**Grid**	**Carbon Capture**	**Industrial Processes**	**Biogas Plant**	**Wastewater Treatment Plant**	**Bio-ethanol Plant**	**Biomass**	**Not Specified**	**Not Involved**	**Development of New Technology**	**Demonstration of Project Operation**	**Roadmap**	**Business Model**	**Optimization Tool**	**Model**	**LCA/LCC**	**Database**	**Software/Platform**	**Control Strategy**	**Retrofitting**	**Planning**
GrInHy2.0	✓														✓	✓	✓										
H2 CoopStorage	✓						✓								✓		✓		✓					✓	✓		
H2FUTURE							✓								✓		✓										
Haeolus		✓													✓		✓		✓					✓	✓		
HEAVENN		✓	✓												✓		✓		✓								
HPEM2GAS							✓								✓	✓											
HyBalance		✓					✓								✓		✓										
HyCARE	✓														✓						✓	✓			✓		
HYFLEXPOWER	✓														✓		✓					✓					
HyMethShip	✓							✓								✓	✓									✓	
Ifaistos		✓												✓					✓		✓				✓		
Kerogreen	✓							✓								✓						✓					
LAURELIN	✓													✓		✓											
MefCO2							✓	✓									✓					✓					
MultiPLHY	✓														✓	✓											
NEPTUNE	✓														✓	✓						✓					
NEWELY	✓														✓	✓											
NewSOC	✓														✓	✓						✓					
ORACLE	✓														✓	✓											

Table A3. *Cont.*

Project	Electricity Source							Carbon Dioxide Source							Aim of the Project			Other Outcomes									
	RES (Not Specified)	**Wind**	**PV**	**Hydroelectric**	**Tidal**	**Conventional Power Plant**	**Grid**	**Carbon Capture**	**Industrial Processes**	**Biogas Plant**	**Wastewater Treatment Plant**	**Bio-ethanol Plant**	**Biomass**	**Not Specified**	**Not Involved**	**Development of New Technology**	**Demonstration of Project Operation**	**Roadmap**	**Business Model**	**Optimization Tool**	**Model**	**LCA/LCC**	**Database**	**Software/Platform**	**Control Strategy**	**Retrofitting**	**Planning**
OYSTER		✓													✓	✓	✓										
PECSYS			✓												✓	✓						✓					
PENTAGON	✓						✓							✓		✓		✓			✓				✓		
Planet	✓						✓	✓		✓	✓							✓		✓	✓			✓			✓
Power-2-Transport			✓											✓			✓				✓	✓		✓			
PRETZEL	✓														✓	✓											
PROMETEO	✓														✓	✓	✓	✓		✓	✓	✓					
REFHYNE	✓														✓		✓		✓								
REFLEX			✓	✓											✓	✓	✓										
REMOTE		✓	✓	✓											✓		✓										
STOREandGO		✓	✓					✓			✓	✓					✓	✓				✓					✓
SUNRISE			✓											✓				✓									
SuperP2G	✓													✓			✓				✓		✓	✓			✓
SWITCH	✓														✓	✓											
TAKE-OFF	✓								✓							✓											
USC-Flex Store		✓	✓											✓			✓										
ZEHTC			✓			✓									✓	✓	✓										

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