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Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states

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ABSTRACT

Though Power-to-X pathways, primarily Power-to-Liquids, attract interest as solutions for decarbonising parts of the transport sector that are not suitable for electrification, the regulatory framework until recently slowed down their implementation. This paper examines the updates in the main aspects of the legal framework in the European Union from 2019 to the beginning of 2022 related to Power-to-X: support schemes, specific targets, and potential barriers. The results show increasing interest and market entrance of electrolysis and push from the different actors and regulatory parties to establish solutions that will enable faster upscaling. However, it is visible from the National Energy and Climate Plans and hydrogen strategies that the most emphasis is still on hydrogen as an end fuel for personal vehicles or power-to-gas. On the other hand, few countries have implemented legal frameworks facilitating diverse PtX pathways without focusing solely on hydrogen. Nevertheless, revisions of RED II have finally set up specific targets for electrofuels and Fit for 55 has introduced new actions supporting electrofuels in aviation and marine transport.

1. Introduction

Transport represents around a third of the final energy consumption in the European Union (EU). While other energy sectors have successfully reduced CO_2 emissions over the last decades, transport is lagging due to increased transport demand and the continued dominance of fossil fuels (European Commission, 2018). Shift to electrification is the most effective way to decarbonise the transport sector if renewable electricity is used (Connolly et al., 2014) and should be prioritised as a first measure for transitioning the transport sector towards future climate targets (Mathiesen et al., 2015). However, parts of the transport demand are not suitable for electrification due to the requirements for high energy density fuels, e.g., long-haul transport. Power-to-X (PtX) pathways are generally seen as solutions for these hard to abate applications, e.g., heavy-duty road transport, shipping, and aviation, since most of the targeted end-fuels can be used without significant changes in the engines or supply infrastructure. However, PtX pathways are also an interesting solution for other had to abate sectors such as industry and chemical production, as they offer a range of end-fuels that can be adjusted to needed purposes. Nevertheless, in 2018, there was only around 1 GW of electrolysis capacity in the EU, corresponding to around 1.6% of total hydrogen (H_2) production capacity (Kanellopoulos and Blanco Reano, 2019)and the current estimated capacity in EU is 2.6 GW if 70% efficiency of electrolysis is assumed (European Clean Hydrogen Alliance, 2022). This could suggest that the implementation of PtX technologies has been to some extent, hindered by the regulatory framework and low incentives, as well as the uncertainty of the future market demands, resulting in not attractive business cases.

Existing literature examined the strategic roles and the conditions under which H_2 energy systems become attractive for the energy transition, but the focus remained on power-to-power (PtP) and power-to-gas (PtG) (Parra et al., 2019). In their recent review published in 2020, Wulf et al. (2020) provided an overview of the development of PtX projects in Europe. The context for the market development of H_2 and PtH was studied in some specific countries: Italy (Saccani et al., 2020) Poland (Dragan, 2021), United Kingdom (UK) (Edwards et al., 2021), or France, Germany, Netherlands, Spain, Italy and the UK (Lambert and Schulte, 2021). Some analysed more globally the policy framework for a

Abbreviations: EC, European Commission; EU, European Union; GHG, Greenhouse gas; GOs, Guarantees of origin; H_2, Hydrogen; MS, Member State; NECP, National Energy and Climate Plan; PtF, Power-to-Fuel; PtG, Power-to-Gas; PtH, Power-to-Hydrogen; PtL, Power-to-Liquid; PtP, Power-to-Power; PtX, Power-to-X; RCF, Recycled Carbon Fuel; RED II, Renewable Energy Directive II; RNFBO, Renewable fuels of non-biological origin; UK, United Kingdom.

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hydrogen economy (Falcone et al., 2021; Dolci et al., 2019), while others conducted an assessment of green H_2 production in Europe (Kakoulaki et al., 2021), including possible regulatory regimes (Lavrijssen and Vitez, 2021). Some literature assessed the PtG technology (Gábor Pörzse et al., 2021), life cycle assessment of PtG business models (Tschiggerl et al., 2018), welfare distribution and price effects of sector coupling with PtG (Roach and Meeus, 2020), the role of strategic and innovation management in the commercialisation of the PtG technology (Zoltán Csedő and Máté Zavarkó, 2020), or market and portfolio effects of PtG (Lynch et al., 2019). Literature assessing the PtX technologies is scarcer. Reference (Daiyan et al., 2020) assessed the cost-competitiveness of renewable PtX, while (Decourt, 2019) took on a technological innovation system approach to examining the development of PtX in Europe. Several authors investigated production costs for different fuels (Schemme et al., 2020; Brynolf et al., 2018; Korberg, Brynolf et al., 2021b; Connolly et al., 2014).

However, to the best of our knowledge, previous peer-reviewed literature did not identify dedicated targets for PtX fuels, and this represents a neglected area. This paper, therefore, assesses the recent advances in the regulatory framework, including Amendments to Renewable Energy Directive II (RED II) (European Commission, 2021c) and new initiatives from Fit for 55 for PtX fuels and, more particularly, power-to-liquids (PtL) so-called electrofuels (e-fuels) in the EU and its Member States (MSs), as well as in the UK and Norway, as the North Sea is a major stake in the future production of green H_2 (Crivellari and Cozzani, 2020).

After defining the main PtX pathways considered in the present study, the first section of this paper examines the technologies addressed in relevant policies and other relevant roadmaps to focus on specific targets set for the different e-fuels. The second section analyses the support schemes already implemented or planned in the near future. The existing e-fuel demonstrator projects are then illustrated, leading to a discussion on the characterisation of the regulatory framework and the impact of PtX on the fuel supply.

2. Recent changes in the legal framework related to power-to-X in the European UNION and its member states

2.1. Definitions and terms

This article investigates further primarily the representation of power-to-X fuels for transport in the legal framework (electrofuels,e-fuels, power-to-liquids). This article uses the following phrases and terms and aims to shed light on the cross-terms used in different legislative frameworks:

Power-to-X (PtX): in this article, PtX are fuel pathways in which (renewable) electricity is converted via electrolytic hydrogen into various gaseous or liquid fuels such as methanol, DME, ammonia and e-kerosene. For hydrocarbon fuels, the origin of carbon can be both biogenic and non-biogenic (Ridjan et al., 2015). These are also referred to in this article as **electrofuels/e-fuels/PtL.** In this article, the authors do not include hydrogen (H_2) as e-fuels. The Commission has not yet legislatively used PtX, electrofuels or e-fuels as a term (even though they are mentioned in the Annexes of the RED II amendments (European Commission, 2021c); however, these are recognised terms in the industrial environments, research, and political environments in different countries (Energinet, 2019; Smolinka et al., 2018; Fossil Free Sweden, 2020).

Power-to-gas (PtG): in most cases, PtG represents electricity conversion into hydrogen, but it often also involves a power-to-methane pathway.

Renewable fuels of non-biological origin (RFNBO): according to RED II (Parliament, 2018), these refer to a liquid or gaseous fuels derived from renewable sources other than biomass. Electrofuels from biogenic CO_2 or direct air capture and ammonia are under this umbrella term as well as hydrogen.

Recycled carbon fuels (RCF): according to RED II (Parliament, 2018), these refer to liquid and gaseous fuels produced from liquid or solid waste streams of the non-renewable origin or waste processing gas and exhaust gas of non-renewable origin. Electrofuels from non-biogenic CO_2 are under this umbrella term, and coNECPts such as plastics-to-fuel, the origin of electricity, are not considered here.

Hydrogen-derived synthetic fuels: are used in some of the Commission's documents, such as The Energy System integration strategy (European Commission, 2020b) and Hydrogen strategy (European Commission, 2020a) and represent electrofuels.

Alternative fuels: stand for fuel or power sources that can partly or wholly substitute fossil oil in transport and have the potential to decarbonise the sector.

Synthetic and paraffinic fuels: another umbrella term for PtX fuels or e-fuels, including also fuels produced from xTL processes, like GTL, BTL and CTL.

Previous publications have indicated the issue of no clarity in the terminology for renewable fuels (Ridjan et al., 2015) and Power-to-X (Burre et al., 2020). However, Power-to-X is an emerging technology and variation in the definitions and policy interpretation will continue to be inevitable for some years until the interpretative flexibility slowly disappears (Mladenović and Haavisto, 2021).

2.2. European legislative level

Before the publication of the Renewable Energy Directive II (Parliament, 2018) in 2018, PtX fuels were not directly recognised as alternative options for the decarbonisation of the transport sector. More specifically, until then, most of the solutions for decarbonisation of the transport sector within the EU framework focused on biofuels, LNG, and direct hydrogen applications. RED II has introduced RFNBOs and RCFs under which PtX pathways are included with hydrogen (in the case of RFNBO). The main difference between these two fuel types is the origin of electricity and carbon source. The recent Directive amendments (European Commission, 2021c) bring some improvements that could lead towards a more stable and predictable legislative framework.

In 2020, as a part of the Green Deal, European Commission published a Hydrogen strategy for a climate-neutral Europe (European Commission, 2020a), emphasising that H_2 needs to become an intrinsic part of the EU integrated energy system, with at least 40 GW of renewable hydrogen electrolysers and the production of up to 10 million tonnes of renewable H_2 in the EU by 2030. The Hydrogen strategy does not use terms from the RED II directive. However, it introduces hydrogen-derived synthetic fuels or PtX fuels such as e-kerosene and other electrofuels such as methanol and ammonia for aviation and maritime sectors. The EU Commission hereby recognises methanol, ammonia, and other e-fuels necessary for primarily decarbonising the aviation and marine sector. The same year, the EU Commission adopted a Strategy for energy system integration (European Commission, 2020b) that outlines the role of clean fuels where electrification is difficult in achieving a smart energy system. This strategy is a significant step as it touches the base of the PtX idea of enabling cross-sector integration while offering needed options for the decarbonisation of the transport sector. Furthermore, it acknowledges the missing clarity in the terminology that can enable better distinguishing and promotion of electrofuels, among others.

Two new initiatives are introduced in the Fit for 55: ReFuelEU Aviation Initiative (European Commission, 2021d) to compel fuel suppliers to introduce sustainable aviation fuels, including electrofuels in jet fuel blends and FuelEU Maritime Initiative (European Commission, 2021b) to encourage uptake of sustainable marine fuels.

2.3. National Energy and Climate Plans

The NECPs were introduced by the Regulation on the governance of the energy union and climate action (European Parliament and

European Council, 2018), agreed as part of the Clean energy for all Europeans package (European Commission, 2018) which was adopted in 2019. These NECPs include opportunities for PtX technologies that contribute to achieving the 2030 climate and energy targets of the EU and its MSs. Almost all MSs apart from Cyprus and Finland have included plans for clean hydrogen in their NECP. In addition, 26 MSs have signed up to the “Hydrogen Initiative” (Federal Ministry Republic of Austria, 2018), the Pentalateral Energy Forum (consisting of Austria, Belgium, France, Germany, Luxembourg, the Netherlands, and Switzerland), published in June 2020 a joint declaration on the role of hydrogen to decarbonise the energy system in Europe (supported by Bulgaria, Portugal, Romania and Denmark), and 14 have included hydrogen in the context of their alternative fuels infrastructure national policy frameworks.

Table 1 presents the term search in NECPs to get an overview of the different focuses MSs have and provide a picture of the cross-use of different terms for the same fuel pathways. As visible in the table, the majority of MSs focus on green or renewable hydrogen in their NECPs (produced by electrolysers using renewable electricity). While PtG is mentioned in 16 NECPs, PtL is cited as a key technology only in 4 NECPs (Austria, Belgium, Italy, and the Netherlands –under the denomination “power-to-molecules” in the latter). Few countries detail the type of fuels they intend to promote/develop. In this case, only the gaseous fuels (hydrogen or methane) are addressed, e.g France, which promotes H_2 for mobility, or Italy, which plans the direct use of hydrogen to contribute to 1% of the renewable energy target for the transport sector. Except for France, which aims for 10–100 MW output from demonstrators for hydrogen by 2028, no specific targets are mentioned for setting up electrolysis capacity in any of the other countries’ NECPs.

In Denmark’s NECP, PtX is a priority that stakeholders pushed during the consultation process. Here the overall target of 70% reduction of the greenhouse gas (GHG) emissions by 2030 compared to the 1990 level was the signal that stakeholders needed to push the development of PtX further, backed up by the support provided by the Finance Act allocating €4 million in 2020, €3.6 million in 2021 and €1.1 million in 2022 in support of large-scale PtX technologies (Danish Ministry of Climate, Energy and Utilities, 2019).

Some countries set general principles in their NECPs regarding the role of PtX/e-fuels in the energy transition of the transport sector; e.g. the Germany’s NECP mentions that “*In the longer term, Power-to-X (PtX) fuels will also play an increasingly important role*” while Austria highlights that “*… the existing network infrastructure must take on additional tasks (e.g. power-to-gas, power-to-heat, wind-to-hydrogen, power-to-liquids)*”. On the other hand, Finland, Sweden, Latvia, Luxembourg, Malta, Lithuania, Slovakia, UK and Ireland do not mention any possible e-fuels for the greening of the transport sector, which is planned to be achieved through electromobility and the increase of biofuels and biogas only. Czechia focuses on bio-equivalent to LPG (by-product in the production of HVO) as they estimate that the age of their fleet and its slow renewal hinder the development of other alternative fuels.

2.4. National hydrogen or power-to-X strategies and roadmaps

Next to NECPs, National H_2 strategies, roadmaps, or plans are currently being developed by several MSs, foreshadowing or following the publication of the European strategy (European Commission, 2020a), as shown in Fig. 1 below. Sweden and Denmark have published a proposal and final strategy at the end of 2021 (Statens energimyndighet, 2021; Danish Ministry of Climate, Energy and Utilities, 2021). Croatia has published H_2 strategy at the beginning of 2022 (Croatian Government, 2022), while Austria, Bulgaria, Estonia and Romania are still preparing their strategies or roadmaps.

Most of these strategies mention targets for electrolysis capacity by 2030 (Fig. 2), which constitutes a clear signal for the market. However, it should be noted that the capacities announced by the strategies published to date do not allow achieving the European target of 40 GW of

Table 1
Mentions of hydrogen and PtX fuels planned to use/produce according to NECPs.

	AT	BE	BG	CY	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO	SE	SI	SK	UK
Green or renewable H_2	x	x	x[c]		x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PtX	x	x				x	x					x						x			x					x	x	
PtG	x	x			x	x	x		x	x		x		x		x	x				x	x		x		x		x
PtL	x															x					[a]	x						
Methane	x	x			x	x			x			x		x		x	x					x		x		x		
Methanol		x																				x						
Synthetic fuels	x[b]	x			x			x					x								x	x		x		x		
Ammonia					x																							

[a] The Netherlands mention “power-to-molecules” in their NECP.
[b] Only in industry context.
[c] As means of producing hydrogen.

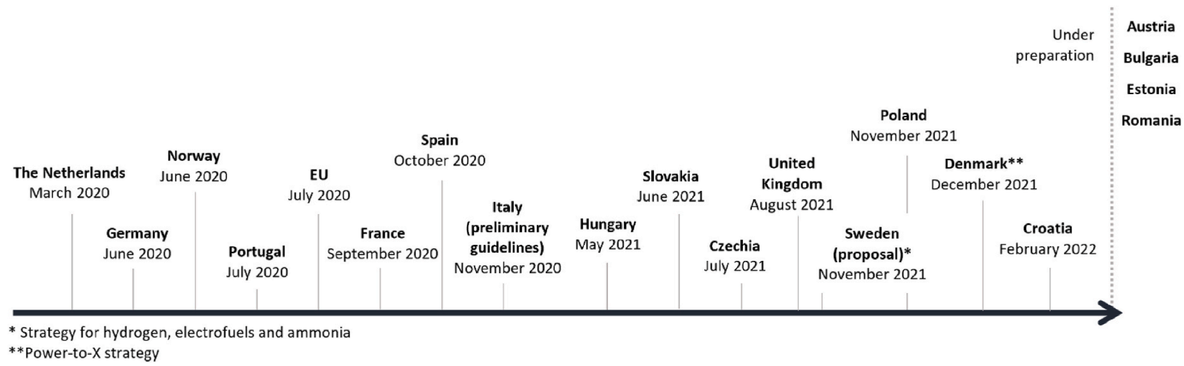

Fig. 1. Thirteen EU MSs have implemented National hydrogen/Power-to-X strategies (+ Norway and UK).

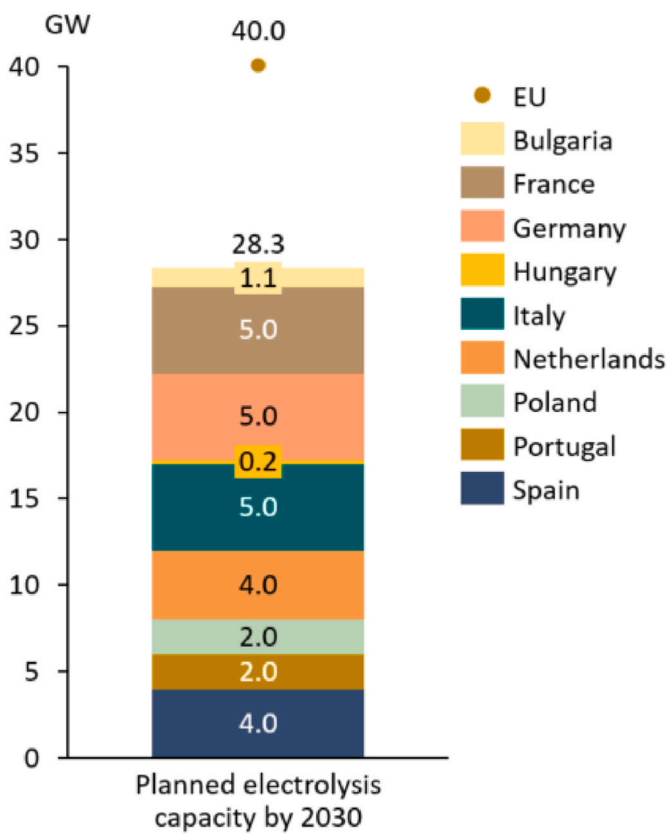

Fig. 2. Target for the electrolysis capacity by 2030, as announced in the EU and National hydrogen strategies published to date (and in an official announcement for Bulgaria). Unclear if some of the capacities will be for electrofuel production.

electrolysis capacity to be reached in 2030, and the rest of the countries will have to meet the gap. These objectives were, for the most part, reconfirmed with targeted investments in the National recovery and resilience plans (European Commission, 2021e) published in 2021 as part of the Recovery and Resilience Facility aiming at helping the EU emerge more robust and more resilient from the COVID-19 crisis. As a part of the RepowerEU communication European Commission proposed a Hydrogen Accelerator doubling the previous renewable hydrogen target (European Clean Hydrogen Alliance, 2022).

As indicated in the name, the H_2 strategies focus on hydrogen production and use rather than further fuels. However, in a few strategies, PtL is mentioned as an option for aviation and maritime shipping:

- Italy mentions synthetic fuels to provide zero-carbon alternatives to the aviation and maritime sectors;
- Portugal mentions an existing project for the production of synthetic fuel for aviation;
- The Netherlands mentions the production and consumption of synthetic kerosene for aviation (Sustainable Aviation Agreement: target of 14% blending by 2030 and 100% by 2050);
- Germany calls for a discussion of a PtL share of 2% in the aviation fuel mix until 2030;
- Spain supports PtL production and use in aviation.
- Croatia mentions ammonia as a possibility for industry and e-fuels as a supplement for the transport sector

Except for Norway, which focuses on ammonia for the shipping sector, Czechia considers that the H_2 Strategy "… *should not be limited to hydrogen alone. It should also cover its compounds, such as methane (biomethane and synthetic methane), methanol, ammonia, liquid synthetic fuels, hydrides and other hydrogen derivatives or mixtures of hydrogen with methane*". Italy mentions ammonia as a fuel expected to play a role in the decarbonisation of the maritime industry after 2023. Neither ammonia nor methanol are mentioned in other National H_2 strategies.Local stakeholders have taken up the issue in some countries. The Danish transmission system operator Energinet published in November 2019 a PtX strategic action plan (Energinet, 2019), Danish Energy has published a recommendation for Danish PtX strategy (Dansk Energi, 2020), Danish export potential for PtX (Rambøll, 2021) and Fossil Free Sweden developed a Hydrogen strategy for fossil-free competitiveness in Sweden (Fossil Free Sweden, 2020). There are possibly more national driven actions that have not been identified due to the language barriers. Presumably, these factors could be a reason both Sweden and Denmark did not publish H_2 strategies, but rather Proposal for hydrogen, electrofuel and ammonia in case of Sweden and Power-to-X strategy in the Danish case.

In April 2021, the German Federal Government's Ministry of Transport and Digital Infrastructure and the German Aviation Association published PtL-Roadmap (Pfeiffer and Spöttle, 2021), making Germany the first country to implement an official PtX/electrofuel strategy or roadmap. In the roadmap market ramp-up, PtL kerosene is presented, including the supportive political framework and specific production targets of 50,000 t in 2026, 100,000 t in 2028 and 200,000 t in 2030, which can be translated into half a per cent of e-kerosene by 2026 and two per cent by 2030.

2.5. Characterisation of policy framework in MSs

Considering the recent advances in the policy framework analysed in the previous sections, an attempt to characterise the policy framework for each pathway and MS is carried out in Table 2. The characterisation of the policy framework according to each PtX pathway considers three criteria: its mention in the NECP, its mention in the National hydrogen

Table 2
Characterisation of policy framework according to the PtX pathways based on NECP and National hydrogen strategies.

	AT	BE	BG	CY	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LU	LV	MT	NL	NO	PL	PT	RO	SE	SI	SK	UK
Power-to-H_2	SA	SA	SA	NA	A	A	A	SA	SA	A	NA	A	A	A	SA	A	SA	SA	SA	NA	A	SA	A	A	SA	SA	SA	SA	A
Power-to-CH_4	SA	NA	NA	NA	A	SA	NA	NA	NA	NA	NA	SA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	SA	NA	SA	NA	NA	NA	NA
Power-to-MeOH	NA	NA	NA	NA	SA	NA	A	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	SA	NA	NA	SA	NA	NA	SA
Power-to-Liquid	A	SA	NA	NA	A	A	A	SA	NA	NA	NA	NA	SA	NA	NA	SA	NA	NA	NA	NA	A	SA	SA	SA	NA	A	NA	NA	NA
Power-to-Ammonia	NA	NA	NA	NA	A	NA	A	NA	NA	NA	NA	NA	SA	NA	NA	SA	NA	NA	NA	NA	NA	SA	NA	NA	NA	A	NA	NA	SA

A Addressed
SA Somehow addressed
NA Not addressed

strategy, and the existence of a specific target. The PtX pathway is considered as:

- “addressed” if at least two of the criteria are met: it is sufficiently addressed in the NECP and/or in the National hydrogen strategy and/or a specific target has been set;
- “somehow addressed” if one of the previous criteria is met or two criteria are partially met;
- “not addressed” otherwise.

From this table, it appears that the most acknowledged pathway, from a policy standpoint, is the use of hydrogen as a fuel for fuel-cell vehicles (primarily in personal vehicles). This is deemed problematic as the electrification of personal transportation is the more efficient way of decarbonisation (Connolly et al., 2014). However, electrification of the sector is not solely going to decarbonise the sector if the electricity is not renewable and may even raise the fossil fuel demands for electricity production. The specific focus seems to be lacking for other pathways. Compared to other countries, Austria, Czechia, Denmark, Germany, Italy, Norway, Poland, Sweden and the UK seem to be implementing a more global policy framework, encompassing various PtX pathways.

3. Support schemes and potential barriers

As described in the previous section, the EU has recently and over time adopted several directives aimed at fostering the further development of H_2 and PtX pathways. In addition, several NECPs and/or H_2 strategies explicitly refer to general political intentions or commitments regarding promoting investments, exempting taxation, and addressing the legal framework. Therefore, this part aims to describe the primary regulatory tools planned or already deployed to support the development of green H_2 production, conversion technologies and distribution infrastructure, and final demand for advanced fuels.

Prior to the recently published amendments of the RED II directive (Parliament, 2018), few outstanding issues in the original Directive were still hindering the development of electrofuels.

- Missing clarity of counting towards the renewable targets, on the basis of final energy or the renewable electricity input;
- No specific targets for these types of fuels;
- The sustainability criteria and impact calculations of electrofuels in terms of GHG emissions were not clarified, but it was imposed that the GHG savings should be at least 70% from January 2021;
- To be defined as RFNBO or renewable electrofuels, the origin of electricity needs to be fully renewable, which is, according to the Directive only possible if the PtX units are connected to the electricity source directly and not to the grid;
- Recycled carbon fuels (RCFs) are not defined as renewable but may be included in fulfilling the targets for the share of renewable energy by individual MSs.

Some of these issues, specifically the connection of the PtX units to the renewable electricity, have been causing hesitance in investments due to connection price and inability to assure the fully counted renewable electricity via power purchase agreements or by Guarantees of Origin (GOs).

The recent Directive amendments (European Commission, 2021c) bring some improvements that could lead towards a more stable and predictable legislative framework. However, some issues are still outstanding:

- A specific target of 2.6% of RFNBOs/electrofuels in 2030 in the transport sector was introduced;
- Fuels are counted as final energy in the sector they are used;
- MSs should provide a simplified verification mechanism for sustainability criteria and GHG emissions savings for 5–10 MW installation;
- Fuel is counted with 1.2 times their energy content in aviation and marine (from original Directive);
- The Commission may decide that voluntary national or international schemes setting standards for the production of renewable fuels and recycled carbon fuels;
- Energy from electrofuels shall be counted towards MS share of renewable energy only if fuels provide at least 70% GHG emissions savings;
- The Commission will provide accurate data on greenhouse gas emission savings for the purposes of Requiring suppliers to provide compliance with sustainability and GHG emission savings;
- Union database for tracing these fuels;
- Suppliers of electricity or electrofuels do not need to comply with the minimum share of advanced biofuels and biogas.

Unfortunately, it still seems a bit unclear that GOs can be used for units that are grid-connected to prove that the electricity used for electrofuels is renewable. The renewable energy share counting of grid-connected units still seem to be limited to the average share of electricity from renewable sources in the country of production, as measured two years before the year in question.

The ReFuelEU Aviation proposal, which is currently under Commission's adoption, for the first time proposed blending obligation for sustainable aviation fuels (SAF) from 5% in 2030, 20% in 2035, 32% in 2040, 38% in 2045 and 63% in 2050 (volume share). The proposal also includes a specific sub-mandate for synthetic aviation fuels (also referred to as electrofuels/e-kerosene) to have minimum 0.7% share by 2030, 5% by 2035, 8% by 2040, 11% by 2045, and 28% by 2050 of the SAF share (European Commission, 2021d). The FuelEU Maritime Initiative (European Commission, 2021b) points that renewable and low carbon fuels, including e-fuels, should represent 6–9% of the international maritime transport fuel mix in 2030 and 86–88% by 2050.

3.1. Incentives for PtL production and end-demand

At the European level, with the RED II and its recent amendments (European Commission, 2021c), the EU Commission is committed to proposing a new classification and certification system for renewable and low-carbon fuels to promote clean fuels, including green H_2 and e-fuels. A certification mechanism is indeed needed to ensure that hydrogen is produced from renewables (Velazquez Abad and Dodds, 2020). One of the first steps in the ongoing standardisation process to support the new RED II provision is to develop a standard on GOs for hydrogen production. Adjusting the tariffs and different models for grid connection related to loads is needed to make the PtX units cost-competitive, as the electricity price currently represents the most intensive price element. However, electricity price potentially would not be the main price element in the future, and spillover effects will gain importance. These tariffs are directly connected to enabling renewable energy integrations and establishing flexible operation of PtX units.

MSs can implement three main incentives to generate demand for PtX fuels or e-fuels. In some cases, these incentives are binding regulations such as a carbon neutral footprint for the vehicles, technical standards, or fuel carbon footprint. The incentives can also consist of public subsidies for converting existing fleet or vehicle purchase. For example, Croatia plans to make public calls to co-finance the conversion of the existing fleet of ships and construction of new alternative fuel vessels. Some countries (e.g. Belgium, Spain, Norway, Netherlands) also grant registration tax exemptions for zero-emission vehicles (BEV or FCEV), primarily personal vehicles. These types of incentives, specifically subsidies for vehicle or tax exemptions, do not necessarily benefit some PtX fuels, as the users could continue using the same propulsion technology they already own while changing to green fuel. However, it is essential to minimise the undesired use of PtX fuels for the parts of the transport that should be electrified and postpone the needed energy efficiency improvements and modal shift. Other modes than road transport (and primarily personal transportation) are either excluded or underrepresented from current national policy frameworks, so incentives for choosing green solutions in different transport modes are needed.

Introduction of specific targets for e-fuels in aviation and marine by RED II amendments (European Commission, 2021c), ReFuelEU proposal (European Commission, 2021d) and FuelEU (European Commission, 2021b) are a necessary step for pushing the introduction of these fuels on the market as their current price is 3–6 times higher than the market price of fossil alternatives (Brynolf et al., 2018). Still, there is a concern that due to the FuelEU technology neutral formulation, the uptake of fossil-LNG will represent the majority of the targets as some of the LNG-powered vessels comply with the GHG target until 2039 (Delphine Gozillon, 2022). Different models could minimise the price gap, such as imposing taxes based on the carbon intensity of fuels, e.g., making fossil alternatives more expensive, or subsidising green alternatives by different means and hereby making them cheaper. Scheelhaase et al. (2019) suggest that the green certificate system seems to be a preferential option for raising the share of e-fuel in aviation while at the same time supporting the producers. Even though this is currently not clarified by EC, production of e-methane through methanation of CO_2 from biogas production with green H_2 could be eligible to feed-in tariffs like biomethane. Similarly, there is no support for producing other e-fuels from this CO_2 stream. With the newly introduced target for e-fuels of 2.6% in 2030, this will probably result in more incentives in different MSs. Some of the ideas to increase demand through regulation could be the introduction of international fossil-free services for ferries to establish international demand for PtX powered ships. European Commission's proposal for abolishing tax exemption on aviation fuels within Europe, introduced by Chicago Convention in 1944 (IATA, 2020), could help to minimise the price gap between e-kerosene and fossil one.

Regarding funding opportunities for new projects, apart from the EU funding for research and demo projects, some countries offer governmental funding for PtX projects like Denmark. Incentive structure through tendering could be one of the solutions to assure the security of the investments as they have shown a positive effect in promoting investment in renewable energy (Bento et al., 2020).

3.2. Incentives for the infrastructure deployment

In the revision of the Alternative Fuels Infrastructure Directive (European Commission, 2021a), e-fuels are mentioned, but the possible mandatory targets for the infrastructure changes for these fuels have been discarded as, according to the Directive, there is no demand for dedicated infrastructure throughout the EU. A full review of the Directive is scheduled for 2026, where future needs for legislative actions concerning emerging technologies will be identified. Furthermore, until 2024 Member States shall prepare and send a national policy framework draft (final framework by January 2025) that includes a deployment plan for alternative fuel infrastructures in marine ports such as ammonia.

At the end of 2020, the European Commission has adopted a proposal to revise the TEN-E regulation (European Commission, 2020c), where 13 strategic trans-European energy infrastructure priorities include electrolysers, hydrogen networks, smart gas grids, and carbon dioxide transportation which could be eligible for EU support as projects of common interest.

4. Electrofuel projects in EU

There have been many activities on announcing new electrofuels projects for decarbonisation of the transport sector, with Denmark being currently the leader in the big scale projects (Fig. 3). The overview of the project is based on the review of the announced projects through different channels and does not necessarily contain all projects due to the language barriers but represents data to the best of the authors' knowledge.

Seven new projects with commissioning after 2022, including the biggest power-to-ammonia project in Europe, are planned in Denmark (Ingeniøren, 2020; Godske, 2021; Frøhlke, 2021)While countries like Denmark and Germany have a broader approach to projects looking into methane, methanol, e-kerosene and ammonia, some countries are more focused on one specific fuel output. The Netherlands, for example, has a strong focus on e-kerosene in their airport hubs in Rotterdam and Amsterdam (Zenid, 2021). Norway has announced only e-kerosene projects for the aviation sector (Norsk e-Fuel, 2021). World's first commercial PtL e-kerosene plant was inaugurated in Germany this October and converts CO_2 captured from the air and from a biogas plant with electrolytic hydrogen (1.25 MW) to aviation fuel (Siemens Energy, 2021).

Nevertheless, there are other big projects that are not directly related to the production of liquid or gaseous fuels for transport, such as the world's largest electrolytic ammonia demo project (20 MW) for the chemical sector in Spain (Iberdrola, 2020) or project Air in Sweden launching industrial production of 200,000 t of methanol from a flexible mix of CCU and renewable hydrogen (Project Air, 2021).

It is interesting to note that the map of countries in which PtX/e-fuel projects underway do not fully correspond to the characterisation of the legislative framework presented in Section 1.5. Austria and Czechia, for example, present a favourable framework but do not yet have any planned projects. Denmark and Sweden are among the leaders in PtX projects, and these countries seem to have solid industrial consortiums driving the scene and pushing for the regulatory side's creation.

5. Discussion

Changing transport policies is a challenging task. Despite various transport initiatives for decarbonisation, emission reduction has not been successful primarily due to unclear objectives and a lack of strategic frameworks (Tsoi et al., 2021). Demand creation is a pivotal push to promote the deployment of PtX fuels. However, with the significant price gap between oil products and e-fuels, designing a robust policy framework paired with financial support schemes is necessary. Demand creation is also vital for establishing a competitive fuel market that is currently dominated by oil products. Today, oil products are highly

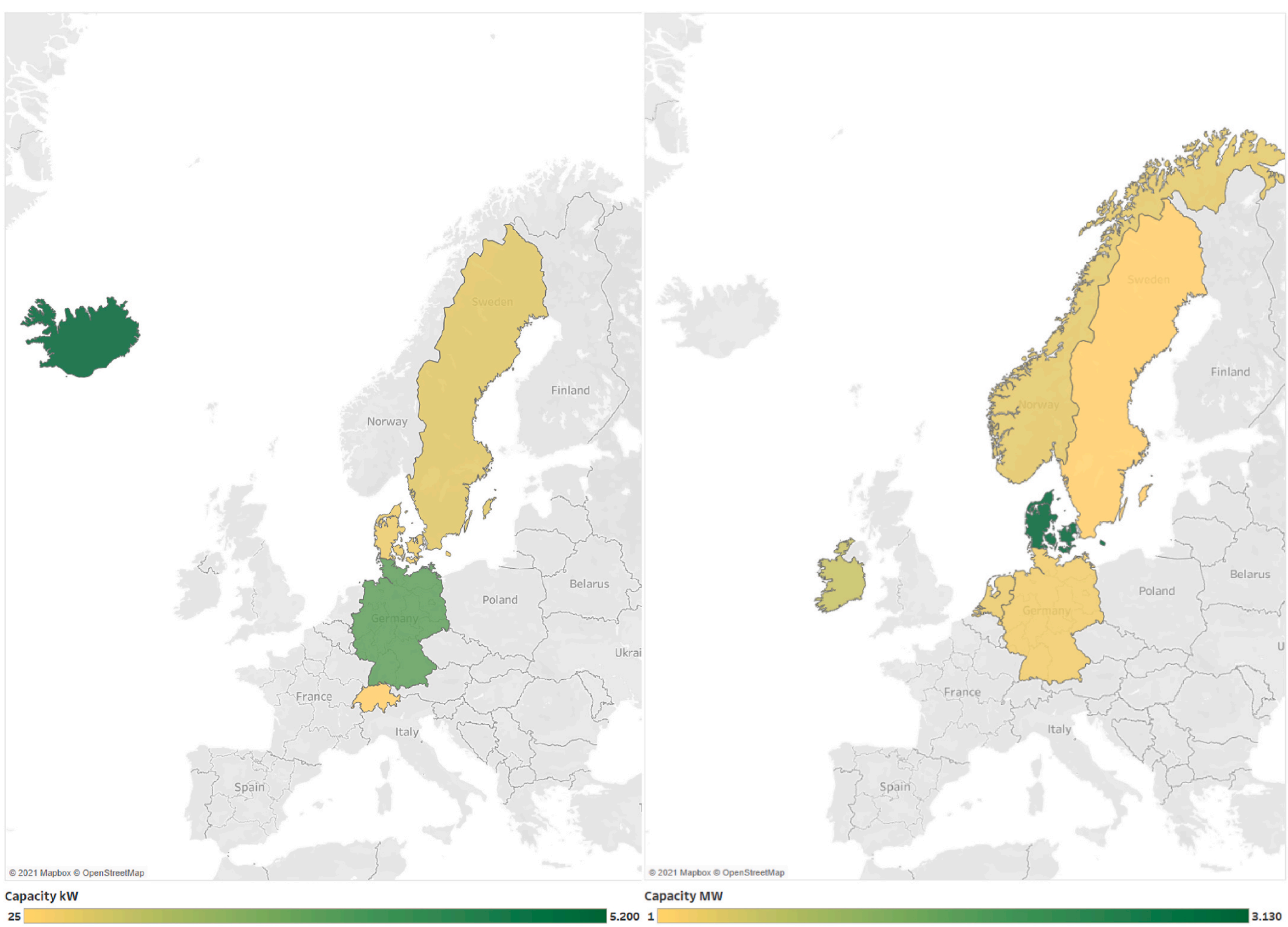

Fig. 3. Electrolysis capacity for e-fuel projects commissioned before 2022 (on the left in kW) and after 2022 (on the right in MW). All projects are related to the production of e-fuels for transport, excluding hydrogen only projects (data from December 2021).

subsidised worldwide (The International Institute for Sustainable Development and The Organisation for Economic Co-operation and The International Institute for Sustainable Development, 2021), and alternative fuels cannot be competitive nor have any market advantage. Therefore, market entry for these fuels is only possible with government intervention, in the contrary, competition will be slowly adopted and not necessarily facilitate upscaling of production, and as a result of this, the set targets for these fuels would not be reached.

It is visible from Fig. 3 that a pipeline of large-scale projects is growing. However, these projects could potentially encounter issues with unfinalized policy schemes or a lack of infrastructure that could impede the creation of new demand. Moreover, the capacities of PtX plants may be expanded faster than the upscaling of the needed renewable electricity capacities to ensure the green product. Therefore, it is essential to consider that this will likely occur, not be a long-term issue, but rather a part of the transitional phase of uptake. This also raised the point that to meet the fuel demands by e-fuels it is necessary to have coupled investments not only in the PtX units but also in the renewable capacities, as the demand is significantly higher than the excess electricity. This specificity of the PtX value chain will likely demand new business approaches.

Furthermore, the alternative fuel infrastructure policies must not lag behind the rest of the renewable policy frameworks set up, among other targets for renewable fuels, including PtX. Depending on the end-fuel, different infrastructure adoptions are needed. Some infrastructure is already in place but needs scaling and connection to supply chains. For example, the adoption of ammonia or methanol for shipping relies not only on the new ship development and fuel handling clarifications but also on infrastructure upscaling and making ports ready for these PtX products (McKinlay et al., 2021; Korberg, Brynolf et al., 2021a). This adoption will require significant long-term investments and will probably impact the competition between international shipping companies. In (ALFA LAVAL et al., 2020) authors give an overview of the existing ammonia infrastructure in Europe and globally and the vision of deployment of this fuel for marine transportation. The development of seaborne trade intensity is also doubtful with the economic development of countries. However, as the demand for fossil fuels will be reduced due to the climate policies, the fuel demand for shipping will follow (Müller-Casseres et al., 2021). The adoption of methanol has gained attention as it can be used both as an energy carrier to produce aviation fuels and as an end-fuel for marine transport and heavy-duty road transport (Gray et al., 2021). Depending on the adoption in different parts of the transport sector, adequate infrastructure will be needed for its direct use.

Spillover effects of using excess heat from PtX processes, both from electrolysis (Böhm et al., 2021), as well as other parts of the production chain, including auxiliary systems, not only have a positive impact on the economy of these plants (Li et al., 2021), but bring additional benefits to the system integration, especially in countries with district heating already in place (Nielsen and Skov, 2018; Yuan et al., 2021). Therefore, upgrading and adding new heat infrastructure to maximise the use of the excess heat produced coupled with reinforcements of the power grids to avoid slowing down the implementation of PtX plants. A strategic approach is also needed not to deploy the new infrastructure too quickly, which will not be utilised because of the lack of demand, which could potentially be the case for the hydrogen network infrastructure. Developing the hydrogen infrastructure in Europe by repurposing the natural gas pipelines for hydrogen transport will still call for the establishment of new dedicated hydrogen pipelines but will unlock the export potential and reconcile regional differences (Wang et al., 2021).

The main benefit of implementing PtX plants in the energy system is the enabling of cross-sectoral integration, higher renewable energy levels, and system flexibility (Parra et al., 2019; Crivellari and Cozzani, 2020; Mathiesen et al., 2015). Even though the energy autarky is unlikely to occur, it is also questionable if the massive production of e-fuels is established in the specific regions due to the earmarked potential (Fraunhofer, 2021; International Energy Agency, 2021), which could result in a similar fuel dependency path as oil dependency today. This centralisation could furthermore continue to impose the lack of security of supply. By pursuing this approach, the benefits of e-fuels for the future energy system on the national scale are eradicated, and as a result of this, other energy system designs will be needed to replace lost benefits. However, implementation of fuel hubs will probably be necessary, and if widely spread, the energy system benefits will not be lost. The overall design of the PtX supply chain is still unclear. It is doubtful should the e-fuels be produced directly in the countries and traded afterwards in the end-fuel form, or should the hydrogen be transported as the energy carrier to the destination country where e-fuels will be produced (Wang et al., 2021).

Conversely, the introduction of e-fuels could also be seen as a way to disrupt the oil production chain. E-fuels not only remove the need for new oil extraction in the upstream sector if the non-carbon-based fuels are produced, but also in the case of black carbon, biogenic carbon, or waste carbon streams used for fuel production. Moreover, there is a downstream disruption as the end-fuels are changed, and new fuel synthesis plants need to be established. However, most oil companies have already started their transition to energy companies. Moreover, Pickl (2019) points out a clear link between the renewable energy activity of oil major and their proven oil reserves. Nevertheless, offshore wind investments seem to be the only option that could provide the same scale as upstream oil investments (Pickl, 2019).

Our paper also suggests that there is not necessarily a correlation between the policies in place and the rate of investments in different countries and that solid industrial support and interest in investments are currently the primary momentum for the deployment of these technologies. Similar is the case for the infrastructure developments. However, it is of great importance to establish the proper policy framework to further support and establish the needed infrastructure across countries as the needed large-scale deployment of PtX technologies remains to be seen.

Taken together, it is also essential that a robust policy framework for e-fuels should not shadow the electrification potential for different transport modes and the precise role of these fuels, only for parts of the sector that is difficult to electrify, needs not to be overlooked.

6. Conclusion and policy implications

Green H_2 and PtX have the potential to play a role in the different energy sectors (electricity, gas, transport, industry) to achieve the EU CO_2 emissions decrease targets. This review analyses the current legal framework, incentives, and barriers concerning PtX pathways for the transport sector in the EU and MSs. Only a few countries have implemented legal frameworks facilitating diverse PtX pathways. Hence, the focus is still primarily on H_2 and PtG, to the detriment of other PtX pathways. However, the recent advances in the EU legal framework and some MSs show early signs of policies changing towards more substantial focuses on e-fuels and recognition of the role these fuels could have in the decarbonisation of the transport sector. Further monitoring of the implementation of these targets by MSs will give a better overview of the pace of implementation and which end-fuels different countries will consider. Furthermore, it is visible that there are tendencies to agree on where electrofuels should be applied and which fuels should meet the demands in aviation, marine and long-haul road transport. Finally, the holistic approach that would result in reliable roadmaps and strategies for PtX and electrofuels, such as the ones from Sweden and Denmark, could enable a more stable and predictable legislative framework for investments and consider the future benefits and need for these technologies.

CRediT authorship contribution statement

Iva Ridjan Skov: Conceptualization, Methodology, Visualization, Data curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Noémi Schneider:** Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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