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From bioethanol containing fuels towards a fuel economy that includes methanol derived from renewable sources and the impact on European Union decision-making on transition pathways

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ABSTRACT

Decision-making on the optimum transition pathway to an energy economy that meets agreed carbon reduction goals in the European Union (EU) by 2050 is challenging, because of the size of the infrastructural legacy, technological uncertainties, affordability and assumptions on future energy demand. This task is even more complicated in transportation because of additional issues, such as minimum travel range at acceptable impact on payload and ensuring hazzle-free long-distance driving in case of regionally varying fuel economies. Biofuels were the first viable option for a large-scale partly renewable fuel economy. E10 and B7 fuels have been successfully and remarkably smoothly introduced, owing to the fact that these are liquid and can be used in conventional combustion engines with little impact on full-tank travel range. In contrast, the decision-making process on biofuels in the EU has been particularly turbulent, with an initially favourable assessment changing into controversial. Here the compatibility between the fuel economies of member states and avoidance of disruptive social effects are considered as essential pre-requisite of a viable transition pathway. Rebalancing three different aspects of the social dimension of sustainability is used to demonstrate that a succession of infrastructures based on liquid fuels, with biofuels as an interlock towards an economy that includes methanol-based eFuel, has the potential to bring continuity, reduce dependence on anticipated technological advances and improve cost management. Awareness of this underexposed prospect of biofuel may positively affect the assessment on its role in a low-carbon fuel economy, potentially influencing the current decision-making process on biofuels.

1. Introduction

The conceptual framework of the three dimensions of sustainable development, as put forward by the United Nation (UN) in the 2030 Agenda for Sustainable Development, presumes that sustainable development is composed of three dimensions that require to be balanced and integrated. The three dimensions, environmental, economic and social, will be used in the analysis presented in this paper [1]. Accordingly, we draw on different academic disciplines and their respective approaches and insights, including engineering, legal studies and political science, to demonstrate how linkages between these three dimensions can be provided, to improve transition pathways in practice.

The awareness of climate change and the extremely likely human involvement therein has resulted in different international agreements, such as the Kyoto treaty and the Paris agreement, which are intended to retard and stop the trend [2,3]. National governments and international actors have committed to design pathways to reduce their greenhouse gas emissions, notably carbon, and to agree on specific targets, although there still are some gaps in terms of adherence to the treaties, and to their implementation. For this reason the governments of European Union (EU) member states agreed to a 2030 climate and energy framework, including EU-wide targets and policy objectives on the reduction of greenhouse gas emission, use of renewable energy and energy efficiency gains in the period 2021–2030 [4]. The strategy for the subsequent period (until 2050) is communicated without binding targets yet in place, although a reduction by at least 80% in 2050 is aimed for, with 1990 is taken as the reference year [5]. For the EU the challenge is to design an optimum pathway towards a low-carbon energy

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economy that meets these targets with minimum negative socio-economic impact, while considering the huge infrastructural legacy of the electrical power generation or the fuel distribution systems. As a consequence any scenario should be rated for its effectiveness in actually achieving a low-carbon economy within the targeted time frame, in combination with complications to be dealt with, such as affordability and uncertainties in the extent that anticipated technical progress will actually materialize, while also the need for a non-disruptive transition, should be carefully considered [6]. These are challenges we aim to address in our article, focusing notably on transition pathways as regards vehicles and their large-scale use within the EU.

2. Material, methods and transition pathways

For this research, we draw on insights derived from engineering, combined with the study of legal provisions, economic aspects and of political decision-making processes. Generally, literature focused on the theme of our research distinguishes between three transition pathways [6]. The first is referred to as 'Market Rule' (MR), in which the main actors in the energy market are challenged by competition to make the necessary changes to meet the targets. In the second pathway, the Central Coordination (CC), a much higher degree of responsibility is claimed by governments. The third pathway follows a more bottom-up approach and emphasizes the benefits of decentralized, small-scale exploitation of many different sources of renewable energy and is referred to as 'Thousand Flowers' (TF) [7]. Many contributions on transition pathways focus on the United Kingdom (UK) (from a general comparative perspective [6,7], with an emphasis on power generation [8], and demand [9]). Additionally, reports on the impact of the different pathways towards a low-carbon economy on the electricity systems in Germany and the Netherlands are available [10,11].

Although the focus of this study in on transition pathways related to fuel and transportation, we acknowledge that a significant part of the research on transition pathways toward a low-carbon energy economy is directed to the electricity system [6]. Therefore, we seek to embed our research in this framework. The core element in the analysis of any such pathway is the need for matching of electricity supply and demand at any time. At the supply side of the grid, photovoltaic solar, wind (onshore and offshore) and tidal are increasingly made available, which are variable and uncontrolled renewable sources for electrical power generation and need to be supplemented by traditional power generation to meet the demand. At the demand side differentiation is usually made between domestic and industrial energy use, with transportation included as a sub-category. The emphasis is usually on efficiency gains in appliances. Significant carbon reduction can in some specific applications be achieved without imposing the full burden on the electricity grid. An example is the system for space and water heating using an electrically driven heat pump and geothermal power, which is an element in most pathways [6,9]. Ensuring matching of supply and demand is an uphill struggle in case of an increased supply from variable renewable energy sources. One consequence is the need for remaining traditional energy generators, running at low capacity at most of the time, but enabling a controlled rapid gearing up to full capacity in case this spare capacity is needed to match occasional high demand. Demand side participation is explored as a means to minimize the traditional power generation capacity needed. In this concept the 'smart grid' is used for effective exploitation of the renewable capacity and communication between the grid and the electricity consumers. Electrical energy storage for grid stability is generally limited and expensive [9].

A key issue in any proposed transition scenario is the impact of the legacy of the electric power generating system. The *status-quo* is basically the starting point and the remaining conventional electricity generation capacity is an important component in the balancing of supply and demand at high demand, which adds socio-technical uncertainty to some of the proposed incremental changes to be taken in the timeframe to 2050 [12]. A striking example is the dependence on electricity generation from nuclear power in the UK and the assumption of significant expansion of nuclear capacity in the different pathways to meet the 2050 targets [6]. Although this scenario is effective in reducing carbon emission, does facilitate balancing of supply and demand and is technologically valid, it could meet popular discontent and thus introduces uncertainty.

In this study the emphasis is on the aspects that call for an analysis on a larger regional level. Firstly, a simple solution at the national level may prove more complex at the international level. An example is the handling of a temporal electricity oversupply. The simple solution usually proposed is to export electricity via international connectors [13]. However, this solution assumes a trading partner at a very different phase of, for instance, the daily supply-demand cycle, which implies a customer a few time zones away. Secondly, constraining the assumptions at the demand side to a national economy may lead to a sub-optimum international solution. For instance, the TF pathway assumes that efficiency requirements results in '[…] Heavy emitting industry decline (being replaced by imports)' [6]. The relocation of such industries and the increase of transportation could hardly be considered a desirable global trend towards the greening of the planet as a whole. A third aspect is the need for regional compatibility of the different energy economies in transportation. An optimization of the transition pathway at the national level could easily result in an incomplete mix and non-compatible fuel infrastructures at neighboring states. However, cross-border transport requires hazzle-free operation of vehicles powered by these different fuel infrastructures. Consequently, the acceptable regional variation in fuel economy is highly constrained, which implies that the appropriate level of decision making would be at the regional level. In the case of Europe this would be the EU.

We will now focus on transition pathways in the EU, while notably discussing the role of biofuels as either impediments or solutions in this transition. The cross-border aspects of transition pathways became evident to the EU in 2015 when the European Commission, which is the main EU body in charge of daily governance, and its President Jean-Claude Juncker announced ten priorities for the period between 2014 and 2019 [14]. Nevertheless, a compromise between two of these priorities seemed inevitable in any viable transition scenario.

Firstly, the priority of 'a resilient energy union with a forward-looking climate change policy' reaffirms the belief that energy and climate policy are two sides of the same coin. The need for the EU to 'to move away from an economy driven by fossil fuels' is weighed against the aim of 'give households and businesses affordable energy' [15].

Secondly, as stated in the Juncker priority of 'a new boost for jobs, growth and investment', investment will be targeted towards infrastructure, including transport, and that priority will be given to: 'removing the significant regulatory and non-regulatory barriers which remain across key infrastructure sectors including (…) transport.' [16]. In other words, the current infrastructure differences between member states remain an impediment to intra-European mobility, which calls for innovation in the transportation sector.

The decision-making process on energy infrastructure and transportation in the EU is significantly complicated by the fact that these policy domains are a shared competence and therefore subject to the co-decision-making procedure (Article 126 of the Treaty on the Functioning of the European Union) and requires agreement of the Commission, EU member states as represented in the Council of the EU and the European Parliament [17]. The complications introduced by this co-decision procedure on energy transition have become especially apparent in the discussions on biofuels, which were the first viable option for a large-scale partly renewable fuel economy and are considered here as the case to study whether continuity of trans-European mobility can influence EU decision-making on transition pathways. Biofuels with a low non-fossil content (up to about 10%) have been successfully and remarkably smoothly introduced, owing to the fact that these can be used in conventional combustion engines and have a sufficiently high energy density for a limited impact on full-tank travel range in combination with greater energy security, a reduced impact on the environment and socio-economic advantages for the agricultural sector.

The term 'biofuels' is generally used to classify renewable fuels which originate from biomass or organic waste and are generally made available in the form of bioethanol or biodiesel blended with fossil fuels (petrol and diesel respectively). Biodiesel originates from vegetable oil (e.g. soybean or rapeseed). The main commercial sources of grown (i.e. first generation) bioethanol are sugar cane and maize, while second-generation bioethanol is derived from bio-waste [18]. Third-generation bioethanol is derived from algae, which uses barren or marginal land and water resources, such as salty water and wastewater and has become increasingly realistic [19]. Bioethanol can be easily blended with petrol (i.e. E10 and E85, which refers to petrol mixed with 10% and up to 85% of bioethanol by volume, respectively) with E10 for use in conventional petrol engines. Similarly, biodiesel can be blended with regular diesel fuel (B7 and B20) for use in diesel engines. The fact that E10 and B7 biofuels did not impose any significant impediment to the fuel infrastructures and thus could be implemented without any disruption of inter-European mobility was a major factor in its successful implementation. However, the controversies surrounding (first-generation) biofuels have complicated the introduction of measures aiming for a larger share of bioethanol in the fuel consumption by biofuel of higher ethanol content, such as E85, and have shifted focus towards alternative energy solutions, such as all-electric and hydrogen-fuelled vehicles.

For the case of biofuel, this implies that only one aspect of Juncker's priorities is addressed (i.e. 'making energy more sustainable'), while two equally important aspects (i.e. 'making energy more secure and more affordable') appear to be overlooked. While the European 'alternative fuels strategy' supports a comprehensive mix of fuels for ensuring 'technological neutrality' and diversification of the energy supply, it is questionable whether biofuels have been adequately considered [20]. Yet biofuels have the potential to function as the interlocking mechanism between state-of-the-art and a renewable energy-based infrastructure of the future for three reasons:

1. It would serve as intermediate source of controllable energy for electricity generation in a system with a reduced use of conventional fossil fuel to match supply and demand in situations of high peak demand, especially when combined in an infrastructure with eFuels.
2. It is compatible with the existing infrastructure built for fuels that are liquid at ambient conditions and a promising concept of methanol from electricity.
3. It would avoid the socio-economic unease associated with the ability of the more privileged to promptly participate in a newly released technological product, such as the latest edition of a smart phone. Research has already indicated that the intention of acquiring, for instance, an all-electric vehicle (EV) is positively correlated to income level (and the associated lifestyle and shopping habits) in European countries such as Germany and Sweden [21,22]. A similar correlation is found in an assessment of EV adoption in the U.S. [23], where EV demand also increases with (amongst other factors) higher income [24]. Moreover, another key social factor identified in research is education has an impact on the purchase of EVs [25,26].

These are all aspects related to disruption of some sort. Therefore, placing more emphasis on these disruption-restraining properties of biofuel would be advantageous for 1. Ensuring continuity of electric energy supply in the face of socio-technical uncertainties of the alternatives, 2. Maintaining inter-European mobility and 3. Avoiding public discontent caused by a perceived dependence of ability to participate on social class. Consequently, this argument, may act as a catalyst in the decision-making process. The co-decision procedure, although significantly complicating decision-making, provides a framework for assessing to what extent the continuity of trans-European mobility could potentially influence EU decision making. Hence, our description of materials available and methods to allow for transition, based on insights from different disciplines, can set the stage to derive potential new solutions to what seems to constitute a complex challenge, but is highly relevant in view of the requirements to implement transition pathways and arrive at more useful and sustainable patterns of energy use.

3. Theoretical framework

The framework of the three dimensions of sustainability was evaluated as a tool [27] and was actually applied to measure sustainable development (for example in the context of corporate sustainability management [28] and measuring nine key indicators of sustainable development [29]). And can also be applied to describe the EU's policy considerations regarding biofuels, which are: Firstly, the development of biofuels must cause as little harm to the environment as possible [30]. Secondly, sustainable biofuels need to provide a sufficient economic incentive for businesses, consumers and other stakeholders to comply with required targets. Thirdly, social factors, such as household energy security and employment, need to be considered when biofuel production or usage policies are developed. As shown here, a lack of emphasis on the social dimension of sustainable development creates disruptions in the transformation of the fuel market.

Different academic disciplines, however, have somewhat opposing perspectives on the three dimensions of sustainability; notably the social dimension. A politician or professional in a regional organization, for example, might take into consideration organisational and governance aspects, whereas a health studies expert may refer to general health and wellbeing, whereas an ecologist is likely to strictly maintain an environmental perspective [31]. The technical and socio-economic factors briefly mentioned above indicate that the three dimensions of sustainable development are somewhat out of balance and in the EU context, the socio-economic dimension of sustainable development seems not to be taken into account sufficiently.

Biofuels, it can be reasoned, can be conducive to a non-disruptive transition, helping to remedy some of the challenges mentioned above. However, there are trade-offs involved in discussions related to their introduction and potential wider use. We will now demonstrate this using the context and example of the EU, not least focusing on specificities related to decision-making in this area.

The most significant drawback of conventional (i.e. first-generation) bioethanol production is the need for (agricultural) land, which has inevitably led to the debate over food and energy security. This constraint does lead to a capacity limitation and results, for instance, in a statement of biofuel in a transition pathway '[…] being constrained within the UK' [6]. Ever since 2008, when the EU became more reluctant to promote biofuels.

EU-wide for environmental reasons, farmers and civil society groups have met this development with unease and protest. The general agricultural position as expressed by an influential interest group for European farmers, COPA-COGECA, that bioethanol gives ' […] prospects of new economic opportunities' [32] is opposed by environmental civil society groups, which have emphasised the dangers of continuing crop-based (first-generation) bioethanol production in the EU and have urged the EU to cease bioethanol production activities altogether [33]. However, the discussion and decision-making in the EU is complicated by at least four institutional and political factors.

- Firstly, in almost all policy areas related to biofuels (primarily transport, energy, environment, and agriculture) the EU and member states *share competences*, with trade still as a notable example of a largely exclusive EU competence, while tax policies, land-use policies and the energy mix remain competences that are primarily in the hands of member states. The mixed competences force the EU and member state actors to coordinate their actions, both within the

EU as well as in external forums. As a result many interests need to be balanced.
- Secondly, the policy debate has led to some U-turns in EU policies, which have led the member states to fragmented initiatives, with some countries focusing on hydrogen (e.g. Germany) and others on electrification, instead of controversial food-based biofuels.
- Thirdly, transport and agriculture are so-called 'non-ETS' sectors in the European Union (these sectors are not part of the EU Emissions Trading System (ETS)) and therefore are not regulated at the EU level. It is therefore the responsibility of member states to define and implement national policies and measures to limit emissions. The Effort Sharing Decision from the 2030 EU Energy and Climate Package nevertheless sets national annual binding targets for emissions not covered under the EU emission trading scheme. However and specifically relevant for biofuels, emissions from land use, land use change and international shipping are not included. The 2014 directive on 'alternative fuel infrastructure' focuses more on the deployment of infrastructure [34]. Because of this 'Non-ETS' characteristic Member States could develop their own 'national policy frameworks' setting up the market development of alternative fuels and deployment of relevant infrastructure only within the remit of their own national borders [35].
- Fourthly, related to the above-mentioned factors, the Council versus Commission discussions on transport policies in general are traditional 'institutional turf battles' in which member states are reluctant to transfer powers to the European Commission [36].

The change in the 'green credentials' of bioethanol after the negative side effects became widely known, forced the EU to gradually decrease first-generation bioethanol production to 2030, while at the same time second-generation bioethanol is to be promoted [37]. However, the discussion mainly centres on the environmental and economic dimensions of sustainable development, while the arguments that are derived from the social dimension are scarce and typically limited to country-specific circumstances. For instance, while Norway predominantly relies on electrical and hydropower, Sweden has historically been much more leaning towards use of bio-waste for biofuel purposes [38].

Transition pathways presented can be characterized as evolving energy infrastructures composed of a mix of sources with time-dependent weighing factors. In the case of fuel for transportation, some (fossil) components are phased out and others (renewables) are phased in. Including biofuels as intermediate fuels would enable a reduction of the carbon emission at an early stage of the transition while technological progress on, for instance well-to-wheel efficiency of eFuels is uncertain. Moreover, centralised use of biofuels rather than, for instance, nuclear power is more suitable in any EV-dominated transition pathway as a controllable backup source of energy for ensuring the continued matching of supply and demand in the electricity system with reduced carbon emission as compared to fossil fuel. The merit of a reduced risk of disruption offered by a pathway that includes a significant biofuel part is not yet generally realised and is a key argument in this study.

Based on these reflections on trade-offs and challenges derived from processes of decision-making which involve actors with different preferences and priorities, we will now present ways in which transition could be envisaged that aims to address all three dimensions of the transition process.

4. Results: the fuel transition pathway and transportation

When analysing a fuel infrastructure system, it is useful to divide it into three parts: (a) generation and central processing, (b) fuel distribution and dispensing infrastructure and (c) in-vehicle sub-systems. Central processing can be a large-scale industrial operation which can be designed for high efficiency, for instance for electrolysis in a hydrogen scenario or chemical conversion in methane and methanol scenarios. However, it can also be the aggregate of many small-scale producers, such as privately owned solar panels on the roof of their homes connected to a smart grid in an all-electric scenario. The public discussion is focused on the generation of renewable energy and central processing. However, these are not the critical parts of the system. The impact of fuel storage, distribution and dispensing on infrastructure is often underestimated, for instance the compatibility requirements imposed to serve all vehicle types in circulation. The difficulty with the in-vehicle part of the system is that the vehicle is the actual mass-fabricated component of the system. Consequently, it is more difficult to achieve high efficiency in such a small system and to justify changes due to the costs associated with the large number of units involved.

The positioning of bioethanol fuel within the spectrum of recognised viable renewable fuel infrastructures requires an overview of the available options. It should be noted that this paper is not intended as an overview of the issues and merits of any of the acknowledged fuel infrastructures nor is it a comparative study of any of these. Overviews on, for instance, the hydrogen economy are already available [39,40]. Moreover, no claims will be made on the technical or economic superiority of biofuel. The sole purpose here is to position the bioethanol and methanol fuel economies as more than suitable candidates within a chain of transition infrastructures composed of several liquid fuel types ('the energy mix') to enable a non-disruptive energy transition. Options based on different sources, processing and distribution infrastructures in-vehicle subsystems, are shown in Fig. 1.

In the following, we will not provide a comparative analysis of these options, but rather some insights into relative advantages of selected options.

Related to in-vehicle sub-systems, the state-of-the-art infrastructure is based mainly on liquid fuels in combination with traditional fossil fuels and biofuels (combination of Scenarios 1a and 1b). In Europe the standard biofuel obtainable at petrol stations is E10 fuel. With few exceptions conventional petrol combustion engines can burn E10 without problems, so the petrol station can simply be modified to dispense the low-ethanol blend without the customer even noticing the slight decrease in energy content per unit of volume. High-ethanol content E85 biofuel is widely available in some countries, notably the USA [41]. So-called flex-fuel vehicles are specially designed to run on fuel mixtures consisting of any ratio between petrol and ethanol, using a sensor system to notify the engine management system, which allows in principle any ratio to be used [42]. This flexibility enables matching of bioethanol use to availability (for instance high ethanol content in agricultural areas in an attempt to maximise the local socio-economic benefits).

The negative turn in the discussion on bioethanol, however, has brought the all-Electric Vehicle (EV) scenario (option 1c) to the foreground, which has a pervasive public appeal due to the evident unconverted use of renewable energy. Disadvantages such as the use of rechargeable batteries and the associated environmental problems of mining and recycling are included in the margin of the debate and generally considered manageable [43]. The current electricity grid is not dimensioned to deliver an enormous amount of energy to enable e-mobility on a large-scale [44]. Moreover, the increased demand for electric power caused by charging EVs comes at the same time with an increased variability of supply due to more power being generated by wind and solar energy. One proposed solution is the smart grid, which would alleviate the demands on the grid by, for instance, attempting to match supply and demand at the local level by employing communication systems, and large-scale storage of off-peak generated power. The embedding of the enormous, diverse electric power network in the energy infrastructural legacy is one of the major causes delaying the availability of sufficient capacity to ensure e-mobility until 2050, as indicated in the Technology Roadmap of the International Energy Agency [45].

Another operational challenge is the limited travel range between recharging nodes, which has resulted in the use of the term 'range anxiety' to express the reluctance of would-be users to drive electric vehicles.

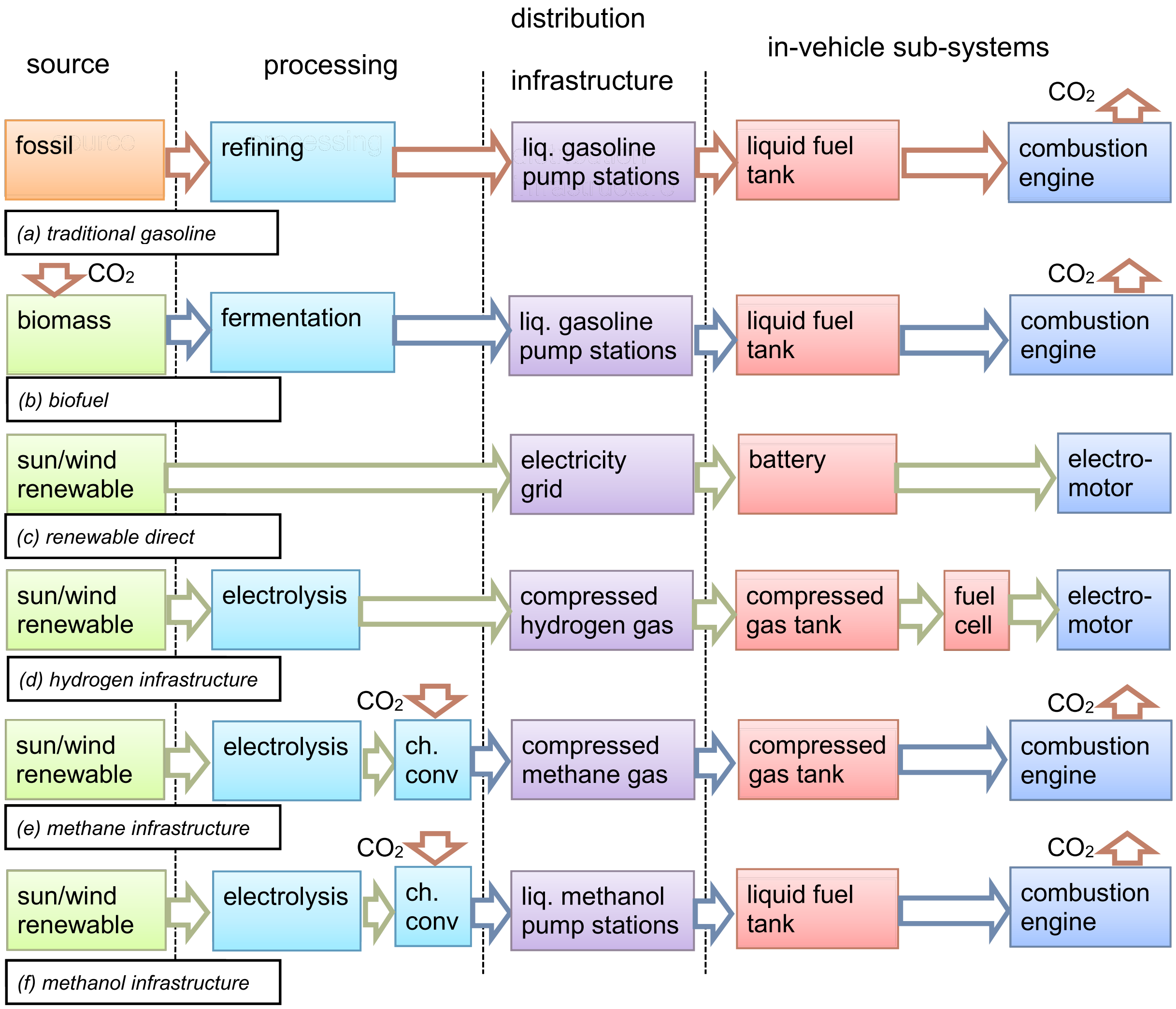

Fig. 1. Scenarios for different energy infrastructures (designed by authors based on their interpretation of general perceptions on fuel infrastructures).

Unsurprisingly, the expected increased use of battery-powered electric vehicles was found to depend mainly on the availability of charging nodes beyond home and the workplace [46]. Especially when fast charging is factored, the load on the electricity grid can grow rapidly. When charging a 100 kWh battery up to 80% within a time span of 40 minutes, as in the typical case of current state-of-the-art fast charging capabilities, 107 kW of power is required during charging, which in practice will introduce peak loads on the grid that become challenging to manage in terms of supply-demand balancing in the large-scale EV scenario [7]. These issues are typically down-played by the public's confidence in future technological developments [47]. In preparation to large-scale EV adoption, networks of charging points are in development in several European countries ("Charging Infrastructure" and "Charging on the Go") [48,49].

Complications of the EV scenario, due to the energy density of the fuel or the energy storage medium, have prompted research into alternative options for renewable energy infrastructures as listed in Fig. 1d–f. Electricity remains as the renewable source of energy and for this reason these fuels are often referred to as 'eFuels'. In each option, the primary input is electricity from renewable sources which is converted in hydrogen by electrolysis in the hydrogen-based fuel economy (Fig. 1d) and subsequently into methane (in Fig. 1e) or methanol (in Fig. 1f) by means of a catalytic reaction and binding of atmospheric CO_2. Although experimental implementations exist which demonstrate the concept of an internal combustion engine (ICE) running on hydrogen, these typically require major changes in engine technology. Components requiring a dedicated design are for example material selection, lubrication methods, cooling systems and the complete fuel system. A mature version of a hydrogen-based ICE would require more research on fundamental problems. The pressurised fuel tanks of a hydrogen-based car can be considered more complex than traditionally fuelled cars. However, experimental implementations show tank pressures of 350 bar and beyond using materials such as carbon and aluminium [50]. It should be noted that compression when cooling fuels that have a gaseous composition at ambient conditions, for the purpose of achieving a practical energy density, takes energy and thus leads to a loss in overall well-to-wheel efficiency.

The traditional combustion engine remains to be used in options (e) and (f), albeit modified to run on methane or methanol. The electromotor in Fig. 1d calls for a more structural vehicle re-design, but avoids in-vehicle CO_2 generation and pollutants altogether. Ignoring the carbon recycling makes the hydrogen-based fuel economy appear more effective in reducing CO_2 emission. The methane-based fuel economy relies on the Sabatier reaction, in which environmental CO_2 and hydrogen is converted into methane and water at a high temperature and pressure using a nickel catalyst. Low-temperature systems are being explored using iron and sunlight [51]. Although methane is itself also a greenhouse gas [52] and requires pressurised tanks, in several European countries, natural-gas powered buses are used for public transportation [53]. The liquid fuel infrastructure in Fig. 1, option (f) would not suffer from such operational constraints. Both methanol and ethanol are liquid alcohols that can in principle be produced from hydrogen in a catalytic reaction. Although ethanol derived from electricity via hydrogen would be seamlessly compatible with a bioethanol infrastructure, production of methanol from hydrogen (here referred to as the methanol-based fuel economy) can be less difficult and more efficient. This methanol-based fuel economy concept has indeed already been promoted, leading George Olah receiving the Nobel Prize in Chemistry for his research in 1994 [54]. The practical use and the efficiency has been significantly improved by the design of the catalytic reaction, but still falls short as compared to the EV [55].

5. Discussion: advantages of step-wise adaptation of the fuel mix during the transition pathway

Based on the results and insights provided above, it seems important that a transition pathway considers the option of strategically adapting the fuel mix over time. We will now highlight some technical and socio-economic aspects related to such change, using the EU again as an example. As was mentioned the policies on biofuels in the EU have shifted from a predominantly economic focus to an environmental one. The argument presented here is that shifting more explicitly the focus to the third ‘social’ dimension may lead to a different decision-making process at the EU-level, which would take into account both technical and social aspects by bolstering a sequence of non-disruptive transitions. It is important to note that, although a disruptive technology is often considered beneficial and can spur economic growth, this condition is unlikely to apply to the abrupt renewal of energy infrastructure for several reasons.

- Firstly, any viable change needs to include a transition phase in which the conventional and new infrastructure would co-exist. EU general agreement on the choice of energy infrastructure would be needed to ensure trans-European mobility, which would be subject to the co-decision-making procedure and shared competences in practice. However, the degree of participation in renewable fuels and type thereof in transport systems in EU Member States differ substantially. For example, in 2015 in the Netherlands there were 145 EV charging points per 100,000 city inhabitants, while in Romania this number was merely 2 [56], thus impeding the EV driving through Europe.
- Secondly, the transportation infrastructure based on energy from renewable sources other than bioethanol may increase the cost of mobility. The mere fact that petrol and bioethanol are both liquid fuels implies that the available infrastructure of fuel storage and dispensing can be maintained. Although re-balancing the costs of fossil fuel versus other renewable fuels in the transportation sector can be achieved through (fiscal) stimulus measures [57], any significant increase in hardware requirements for vehicles (implementing battery packs or fuel cells) would be an impediment that is difficult to avoid. Fuel storage, distribution and dispensing infrastructures have barely been considered in the assessment of the different fuel economies. A liquid-fuel based infrastructure network has significant advantages in terms of storage, handling, energy density and compatibility with the state-of-the-art and, consequently, offers the best promise for a non-disruptive transition towards renewable energy on a large scale.
- Thirdly, studies have demonstrated that the ability to promptly participate in an abrupt change in the transportation infrastructure is income-dependent, because an EV at the early phase of its market introduction is relatively expensive. This effect should be a particular concern to the EU in terms of social justice norms related to energy transition, as it is suggested in literature to partly explain the difference in degree penetration of EV in different member states [21,22]. Any fiscal stimulus should be designed not to be disproportionally beneficial for people who can afford to, which would disqualify a deductible of income tax in a progressive tax system. In previous assessments it was also found that education level is a significant determinant in purchasing EV [25]. People that are higher educated generally show more interest in purchasing EV and at an earlier stage as compared to lower educated groups [26]. Campaigns designed to target lower-educated groups may help levelling these social barriers. Within the framework of this study it is suggested that, despite the urgency of the energy transition, attention should be paid to exploring these societal aspects, while realistic transition solutions should be offered that continue to include the groups of society that persist in using conventional vehicles.

The hydrogen-, methane- or methanol-based eFuel economy have in common the use of electricity originating from any renewable source, followed by conversion into a high-energy density fuel. The specific advantage of methanol is its liquid composition, which makes it compatible with current state-of-the-art automotive technology, and the biofuel-based distribution and dispensing networks.

An important operational characteristics of a fuel is the energy density, which (along with conversion efficiency) determines the travel distance between re-fuelling when considering a storage capacity that is sufficiently proportional to the dimensions of the vehicle [58]. The relatively low energy density of Lithium-ion (Li-ion) batteries results in a penalty in terms of additional mass of the portable energy and, consequently, in a limited travel range. Hydrogen-based infrastructure is seriously being considered in EU Member States to overcome these limitations (notably Germany through the H2 Mobility initiative [59]). Liquid fuels at room temperature have a competitive fuel density compared to Li-ion batteries or hydrogen without required pressurizing or cooling steps of the liquid fuel.

The applicability of a particular scenario for a fuel economy based on renewable energy strongly depends on the overall utilisation of the energy, as expressed in the well-to-wheel efficiency. Obviously, any conversion of energy, such as a catalytic reaction, takes place at a certain efficiency. The well-to-wheel efficiency is estimated to reduce from 73% in the case of battery operated EV, to 22% for hydrogen obtained by electrolysis and 13% for methanol via catalytic reaction from hydrogen [60]. Although the values assumed for losses in charging and engine efficiency seem somewhat biased as compared to loss in a catalytic converter and also the energy needed for transporting the battery pack is ignored, this comparison convincingly highlights the strength of the direct use of electrical energy in e-mobility. However, this advantage needs to be balanced against the limitation of battery energy density. Socio-economic criteria, such as the compatibility of eFuels with the state-of-the-art in fuel storage and dispensing infrastructure, are often considered less relevant, but are the core consideration here.

The energy content of fossil fuels and several renewable fuels that are generally considered viable alternatives differ hugely. Conventional petrol has a convenient energy density of 34 MJ/L (or specific energy of 46 MJ/kg), which for a typical fuel-economic car with a 50 L fuel tank results in an average range between re-fuelings of about 750 km [61,62]. A state-of-the-art electrical car design requires 545 kg of Li-ion battery capacity for 85 kWh, because of the low specific energy of about 0.4 MJ/kg [63]. As a result a fully charged battery contains about 305 MJ of energy, which results a typical travel range of about 420 km between re-chargings. The lower specific energy results in a high impact of the battery on the mass of the vehicle and a more limited range (‘the payload’). Although sufficient for local travel, the use of the all-electric car for long-haul transport is debatable, mainly caused by the re-fueling time and current availability of so-called fast charging throughout the entire EU.

Recent research on transition pathways in transportation indicates that an optimized mix of mass-EV and use of low-carbon fuels is the most promising approach for achieving the carbon reduction goals at manageable costs and socio-technical risks [44]. The term mass-EV denotes the situation where EV’s are adopted at a massive scale, while low-carbon fuels indicate here biofuels and eFuels (such as hydrogen produced from electricity by electrolysis, or methane or methanol from hydrogen via a catalytic conversion). These options for low-carbon fuels in transportation add heavily to the demand on the electricity grid, as the primary input source, with the exception of biofuel, is electricity. However, the electricity-intensive production of eFuel would have to be industrially implemented at large scale and can potentially be scheduled in times of off-peak oversupply, and thus would contribute to grid stability. Low-carbon fuels are highly suitable as buffer fuel for powering conventional electricity generators used for providing spare capacity. However, considering the state-of-the-art in catalytic conversion efficiency, biofuels are the most suitable short-term candidate for this role in the energy infrastructure.

Bioethanol has a specific energy of 26 MJ/kg, which implies that the energy density of E85 is 35% lower than that of conventional petrol. Similar to the seamless integration of E10 biofuel in the existing infrastructure, large-scale implementation of E85 in the fuel distribution system is without significant technical or logistical problems. The energy density of methanol is 23.8% lower compared to bioethanol, which is a smaller step compared to the transition from fossil fuel to bioethanol. Research has indicated the viability of the methanol-ethanol-petrol blend is flex-fuel vehicles to enable a gradual partial replacement of ethanol in E85 with methanol [64]. Integration in the infrastructure can be expected to be equally smooth. Therefore, a biofuel-based energy infrastructure (scenario b in Fig. 1) can be considered an intermediate step towards a methanol-based infrastructure (scenario f in Fig. 1), with the essential advantage of avoiding disruptions.

A disadvantage of the methanol-based fuel scenario, as illustrated in Fig. 1, scenario f, is the reliance on the combustion engine, which is liable to emit other pollutants, such as: hydrocarbons due to unburned fuel, CO due to partially oxidized/burnt fuel and oxides of nitrogen (NOx). Three-way catalytic converters (TWC) are used to effectively reduce the emission of these components in the exhaust gas before exiting through the tailpipe to meet increasingly stringent emissions standards. Nevertheless, one may be tempted to consider the electromotor as a solution for all problems at once, despite the benefits of compatibility mentioned in this paper. However, it should be emphasised that the merits of the methanol-based fuel economy are primarily found in the fuel storage, distribution and dispensing infrastructure and high energy density, and not in the engine. The internal combustion engine in the vehicle in the case of the methanol scenario is of secondary relevance, as the combustion engine can (gradually) be replaced by an electromotor plus a fuel cell, as shown in Fig. 2. This has the advantage that the combustion reaction is interchanged with a catalytic reaction in the fuel cell directly delivering electricity to an electromotor.

Clearly, this transition might lower socio-economic costs, while allowing for a pathway that is feasible and desirable from a more technical point of view and with this, could be a viable option not least for implementation within the EU.

A non-technical complication of the methanol-based fuel economy is public acceptance. The concept of fuel produced by sustainable electricity in the methanol fuel economy does in principle not lead to a net carbon generation, as the CO_2 uptake and release are inherently balanced. CO_2-recycling (uptake at the large-scale centralised chemical plant where the catalytic reaction is to take place and release in each combustion engine) is not at the same location and not as obvious as the direct use of renewable electricity, which may adversely affect perception and public support. Another issue is the overt focus on 'well-to-wheel' efficiency, which is indeed an essential aspect of the viability of any eFuel scenario, as the effective use of the generated renewable energy is reduced. A third concern is safety. Toxicity is an issue (as with most fuels) and methanol has a low boiling temperature of 65 °C. However, the self-ignition temperature of methanol is higher than that of petrol, while it is biodegradable in water.

A mixed biofuel/methanol-eFuel economy can have clear advantages. The specific advantage of biofuel and methanol are their liquid compositions, which makes these compatible with current state-of-the-art automotive technology, and the available distribution and dispensing networks. Moreover, the huge power strain on the electricity grid as imposed by mass EV adoption can be circumvented, since methanol production from electricity via hydrogen could easily be organised off-peak in a centralised facility with the significant storage capacity that is customary in the petrochemical industry. For these reasons, methanol as eFuel can be considered a perfect successor of biofuel. A transition pathway comprised of biofuel towards methanol eFuel would provide the opportunity for phasing out biofuel, if required, depending on the persistence of environmental concerns and the uncertain success of algae-based biofuel, while providing storage capacity for excess supply, thus easing the supply-demand balancing during the build-up of the capacity of the electricity grid loading. Depending on how the (technical) uncertainties are resolved over time, a biofuel-eFuel mix would result. Such a mix of these two with significant contributions of the EV and low carbon (biofuel plus eFuel) scenarios was found optimum in achieving the intended carbon reduction at better management of technological uncertainty and lower cost as compared to the all-EV scenario [44].

6. Conclusion

As our article has demonstrated, different visions between actors and in the case of the EU, between different member states, hinder a transition to outcomes allowing for more sustainable patterns of energy use. Fuel policies seem to be one of the traditional battles in which there is Member State reluctance to transfer powers to the supranational level and notably, to the European Commission. Simultaneously, shared competences in this policy area imply that there can be a formulation of domestic standards, but mutual recognition in the internal market framework and compatibility, which may facilitate the decision-making process by avoiding the need to get intergovernmental agreement on a specific solution.

Based on a mix of insights derived from technical, legal and political approaches, we have aimed to demonstrate the hurdles to a transition that respects the targets the EU has formulated in terms of future energy use and shown ways in which vehicle production could benefit from technological innovations that allow for a transition pathway with little damage in socio-economic terms. In other words, our proposals seem to contain steps that a) lead to desired results and b) might be acceptable to a larger public, also within the EU, as they avoid abrupt transitions or highly unequal burdens in the transition pathway.

The key issue discussed in our article is the aspect of non-disruptive transition, both from the technological and societal perspective. Referring to this specific aspect, it can be concluded, based on our analysis

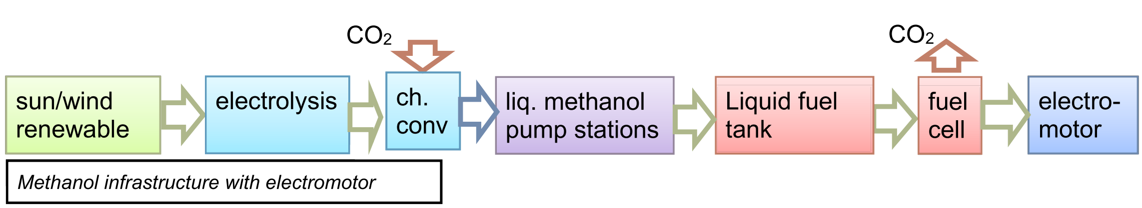

Fig. 2. Evolution towards the methanol-operated vehicle with electromotor.

provided above, that the transition to methanol via bioethanol has significant merit, but this does not imply a disqualification of alternatives. In light of the above, it is highly likely for the different fuel infrastructures in Fig. 1 of our article to co-exist for a significant period of time, as shown in Fig. 3, which is in line with the state-of-the-art in which (B7 and sometimes B10) diesel, (E10 and sometimes E85) petrol, CNG and LPG are presently the selectable options at petrol stations. From a technical perspective it can be concluded that the proposed gradual introduction of biofuel blends, be that methanol or ethanol, with existing petrols, due to the continuity of the liquid phase-based infrastructure are unlikely to result in major technical challenges. The energy density of biofuels does not significantly compromise travel range. Although the well-to-wheel efficiency in catalytic methanol production from green electricity is at the present state of technology low compared to the more direct usage of green electricity in an EV, development in efficiency of large scale catalytic processes for methanol production do strengthen the business case of methanol as a viable renewable fuel. Furthermore, socio-economic factors (income and education) affect positively EV adoption, which can be interpreted as a social disruption. In the current transition it is important to include the less privileged share of the population in carbon reduction goals in a fuel economy that takes at least into account those non-interested, or unable to participate, in EV.

Therefore, the methanol-based fuel economy, as a direct extension of bioethanol, should be more seriously considered in order to balance better the sustainable development of the fuel market, to ensure compatibility with existing infrastructures, allow automotive manufacturing technology to evolve, maintain long-haul transportation security and avoid any income-dependent ability of participating in a transition pathway.

The technical impediments for the E85 intra-European bioethanol infrastructure mentioned did not apply to the low-concentration E10 blend, simply because of the fact that the vast majority of conventional combustion engines can be operated without any modification. This resulted in a state-of-the-art solution in which the use of E10 was fluently introduced, making widespread distribution throughout the EU possible. This penetration by stealth is an advantage, but by this very nature has also resulted in little awareness.

Free movement of goods, people, services and capital across borders is key to the EU internal market and is not served by the kind of disruptive innovation on which business R&D thrives. Therefore, we have explicitly applied this aspect as a key issue when considering the societal dimension, as reflected in the points on intra-European mobility. In general, the seamless transition between compatible fuels avoids disruption, which is highly desirable in socio-economic terms and consequently adds value to the chain departing from all-fossil fuel (Scenario a in Fig. 1), via the biofuel scenario (Scenario b) to a methanol-based infrastructure (Scenario f).

In terms of future research, the results from this combined technical and non-technical study could pave the way to study scenarios for alternative fuels in which decision-making procedures and challenges in socio-economic terms are discussed in conjunction with the technical enablers of new fuel economies. Therefore, there could be significant merit in taking a closer look at the technical potential of these advanced biofuels in combination with the decision-making procedures in a context such as the EU, preferably by taking into account (and comparing) the situation in other regional blocs globally, as well as the multilateral context, to allow for comparison and an analysis of external factors. We would also like to suggest that future research could build on the present study and scrutinise the influence of mixed competences in the EU, the case-law of the European Court of Justice and other legally defined powers on the political decision-making process when addressing alternative options for fuel policies. More political and legal research on this topic could point to the 'institutional' constraints that currently hinder the introduction of a genuine 'single market' on alternative fuels in the EU. One of the contributing factors might also be the current absence of multilateral cooperation on this topic, which as a result keeps the EU and its Member State decision-makers within their own ambition cycle and strongly influenced by domestic stakeholders. Agreement on both regional and global levels will be key to effectively address the challenges discussed above, while trade-offs and considerations as presented in this article can help to derive effective and efficient solutions, supported by acceptability in societal terms. Clearly, the new European Commission under the Presidency of Ursula von der Leyen will have an ambitious agenda in terms of climate and energy strategies, which may make research as presented here (and beyond) even more relevant, and urgent, for practice.

Fig. 3. Artist impression of an user panel at a fuel station in the 2030-ies based on different fuel scenarios (designed and drawn by Thierry Wolffenbuttel).

Author contribution statement

Thijs Bonenkamp: Conceptualization, Methodology, Validation, Investigation, Writing Original Draft, Writing – Review & Editing **Luke Middelburg:** Investigation, Methodology, Validation, Writing Original Draft, Writing – Review & Editing **Madeleine Hosli:** Methodology, Investigation, Writing Original Draft, Writing – Review & Editing **Reinoud Wolffenbuttel:** Supervision, Conceptualization, Methodology, Investigation, Visualization, Writing Original Draft, Writing – Review & Editing.

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List of Abbreviations (in order of appearance)

UN	United Nations
EU	European Union
MR	Market Rule (pathway)
CC	Central Coordination (pathway)
TF	Thousand Flowers (pathway)
E10	Petrol with 10% bioethanol by volume
E85	Petrol with 85% bioethanol by volume
B7	Diesel fuel with 7% vegetable oil by volume
B20	Diesel fuel with 20% vegetable oil by volume
eFuel	Synthetic fuel fabricated from renewable electricity
EV	(all)-Electric Vehicle
COPA-COGECA	Combination of two European agricultural interest groups: Committee Of Professional Agricultural organizations, and COmité Général de la Coopération Agricole (General Confederation of Agricultural

	Cooperatives)
ETS	Emissions Trading System
CO2	Carbon-diOxide (popularly referred to as 'carbon')
CO	Carbon-monOxide
ICE	Internal Combustion Engine
Li-ion	Lithium-ion (battery)
NOx	Group of Nitric-Oxides
TWC	Three-Way catalytic Converter
CNG	Compressed Natural Gas
LPG	Liquefied Petroleum Gas (pressurised propane or butane)

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