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Original Research

Feedstock analysis, technical and achievable potential of advanced biofuels, renewable gases and recycled carbon fuels for the Greek transport sector until 2050

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Abstract

We find that there is sufficient technical feedstock availability for Greece to reach its medium-term targets on the production and use of advanced biofuels, renewable gases, electrofuels and recycled carbon fuels for the Greek transport sector. Our analysis suggests that the biomass fraction of municipal solid waste, the biomass fraction of industrial waste, animal manure and sewage sludge, tree prunings, carbon dioxide feedstocks from industrial sources and refuse derived fuels/plastics are feedstocks with sufficient availability until 2050 for the production of renewable fuels and gases for the transport sector in Greece. As a rough indicator, if all the technically achievable feedstocks covered in this study are converted into associated advanced fuels (excluding recycled carbon fuels), this could equate to 7% in 2020, 8.2% in 2030, 9.3% in 2040 and 10.3% in 2050 of the total energy consumed in the transport sector. With policy support, the production of biomethane from the biomass fraction of municipal solid waste, hydrotreated vegetable oil and recycled carbon fuels have possibilities in Greece by 2030, while electrofuels and biomethane from other sources have possibilities by 2040 and lignocellulosic ethanol does not have possibilities in the long run due to limited feedstocks and high costs.

Keywords: advanced biofuels; electrofuels; feedstock analysis; technical potential; achievable potential; feedstocks

1. Introduction

The Greek context

In 2020, Greece had the lowest share of RES in transport in the EU at 5.3% [1]. Various technologies, including electro-mobility, biofuels and electrofuels, focused on decarbonising and de-fossilising the transport sector are being promoted across the EU. Advanced biofuels are integral to the EU's green transition, as they support reductions in carbon emissions and imported fossil fuel dependency while supporting local employment [2].

In the recast Renewable Energy Directive, EU Member States are required to pursue advanced biofuels in the transport sector [3], in addition, European and Greek median- and long-term strategies require that the Greek transport sector decarbonises. More specifically, the recast Renewable Energy Directive (RED II) targets that by 2030, 3.5% of all energy used in transport in EU Member States comes from advanced biofuels [3]. More ambitiously, the recent Greek National Energy and Climate Plan (NECP) targets that the use of advanced biofuels in transport is 8.2% by 2030 [4]. Currently, almost no advanced biofuels are produced in Greece [5], while many advanced biofuel technologies are in the process of becoming commercially available in the European context [6]. In this context, the achievement of these national and regional goals will require the development and use of new technology-feedstock combinations for transport in Greece.

Over the past decades there have been significant developments in the technologies associated with advanced biofuels. Paris *et al.* (2021) [7], conducts an economic analysis of advanced biofuels, renewable gases and recycled carbon fuels for Greece, and provides a detailed breakdown of the different advanced fuels and conversion technologies relevant for this study and Greece. This paper is complementary as it investigates the same feedstocks and conversion routes as the present paper. The conversion routes, and their associated feedstocks, that are considered relevant for Greece are electro-chemical conversion with a TRL of 8-9, thermo-chemical conversion with a TRL 8-9, oleochemical conversion with a TRL of 7 and biochemical conversion with a TRL of 5-7 [7]. The results from this study also indicate that on a purely market level no advanced biofuels are likely to be cost competitive with fossil fuels at current or similar market prices. However, this study does illustrate that, with some level of policy support or large increases in the price of fossil fuels, certain advanced biofuels could be economically competitive in Greece in the long-run. Similarly, a number of other studies have investigated the potential of bioenergy and biofuels in Greece. Moustakas *et al.* (2020) evaluate the biogas potential from agricultural biomass in Western Greece, finding that up to 715,080 tonnes are available for biogas production [8]. Boukis *et al.* (2009) develop a policy plan for Greece to reach its biomass and biofuel goals.

Skoulou *et al.* (2011) assess the potential of energy crops for biofuels in Greece [9]. Mitkidis *et al.* (2018) conduct a market analysis for second generation biofuels in Greece finding that in particular there is a gap in RES implementation for transport but that Greece has sufficient resources to achieve medium-term climate goals [10]. Tsita *et al.* (2020) propose nine next-generation biofuels from thermal and chemical conversion for the Greek transport sector [11].

A variety of review articles on advanced biofuels have been published [12–15]. Oh *et al*. (2018) highlight that a major challenge for advanced biofuels is the feedstock supply [16]. Hoefnagels and Germer (2017) investigate the supply potential of lignocellulosic feedstocks for advanced biofuels. They highlight that although significant supply for advanced biofuels exists in the EU, substantial efforts, in terms of educating farmers, infrastructure and regulations, need to be made for the EU to reach its targets [17]. It is important to note that no studies focus on the long-term supply of feedstocks for advanced biofuels in Greece. However, numerous studies have been conducted that investigate the availability of various feedstocks that are relevant for advanced biofuels in Greece. Although their estimations vary considerably, all of the studies emphasize that municipal, agricultural and industrial waste in Greece contains a high proportion of biomass for bioenergy. Indicatively, Alatzas *et al.* (2019) estimate 7.5 million dry tonnes of agricultural residues in Greece that could potentially be used for bioenergy [18], CRES (2016) puts this figure at 8.7 million with 5.5 of it as theoretically available [19], while Panoutsou *et al*. (2016) estimate that there are 6.24 million dry tonnes [20]. Malins' (2017) study on electrofuels finds strong long-term potential for the production of renewable electricity in Mediterranean countries, including Greece, which can be partly used for electrofuel production [21].

However, there is a gap existing in the literature providing an accurate overview of the technical availability of individual feedstocks in Greece and to what extent these feedstocks and their associated advanced fuels can contribute to the Greek transport sector. This study aims to fill this gap by conducting a technical feedstock analysis on the theoretical and technical availability of a variety of feedstocks for advanced fuels in Greece until 2050. This is important as it overcomes the drawbacks of other studies focused on feedstocks in Greece by combining data from respected sources and utilising a clear and detailed methodology. This study also considers the technical potential of these feedstocks until 2050 if these feedstocks are converted into their associated advanced fuels; the fuels covered in this paper include lignocellulosic ethanol, biomethane, HVO, electrofuels and recycled carbon fuels. This is important as a widely accepted methodology for estimating the potential of advanced fuels does not currently exist, although clearly it would aid in supporting a green transition. By providing such a simple methodology, this study supports further research into the development of accurately estimating feedstock availabilities.

This paper is structured as follows: section 2 describes the methods and methodology used; section 3 reports the results; section 4 discusses the major findings and the achievable contribution these advanced fuels can make to Greece's transport sector as well as limitations of this study; section 5 provides concluding remarks.

2. Methods

The feedstocks covered in this paper refer to the feedstocks for advanced fuels listed in Part A and Part B of Annex IX of RED II that are applicable to Greece [3], while the production of renewable electricity and the availability of industrial sources of carbon dioxide (CO_2) for the production of recycled carbon fuels are also considered. The availabilities of these feedstocks are estimated until 2050. Specific feedstocks covered include: the biomass fraction of mixed municipal solid waste (MSW), the biomass fraction of industrial waste, straw, animal manure and sewage sludge, fruit tree prunings, grape narcs and wine lees, used cooking oil (UCO), crude glycerine, perennial crops, CO_2 feedstocks from industrial sources and plastics.

2.1 Data sources and estimating feedstock availability

Feedstock availabilities for 2020 were directly drawn from studies and databases in cases where the data were considered reliable. To be included, studies were required to have gone through a peer review process and published in academic journals, while databases and reports needed to be published by reputed organisations, for instance, relevant government or research institutions. The most significant sources of data include ELSTAT, EUROSTAT and CRES. In cases where no reliable data exists, we estimated availabilities according to deductions based on information from relevant indicators. In these cases, specific methodologies are discussed on a case-by-case basis in section 3. For instance, certain agricultural feedstocks were estimated via the expected feedstock production with the actual level of agricultural production of specific crops. Municipal feedstock levels were estimated based on average per capita waste production levels. Feedstock projections until 2050 were estimated through incorporating changing demographics, crop production levels and the impacts of climatic change where relevant. In cases where no changes were expected or in cases where we were not able to develop reliable predictions, we assumed that feedstock levels would stay constant until 2050. It is important to note that the existing data on the availability and projections of certain feedstocks from a variety of sources show large variations. To incorporate this limitation, conflicting data estimations are discussed for each feedstock. In cases where estimates conflict the sources that have been peer-reviewed are considered most reliable and are used.

Our feedstock results distinguish between the theoretical and technical feedstock availability. The theoretical availability refers to the total amount of availability of the feedstock in Greece, while the technical feedstock availability refers to the feedstocks that could be recovered, once competing uses, spoilage and geographical location are considered, for the production of the advanced fuels considered in this study. In order to provide realistic estimates, the technical availability proportions that are realistically recoverable are informed by previous studies. It is important to note that the technical availability estimated assumes ideal real-world conditions in terms of collection and spoilage. In this sense, the technical availability estimates are likely higher than could be achieved in real-world conditions. In order to account for this limitation, in our discussion section, we discuss the 'achievable potential', which discusses the potential of different fuel-feedstock combinations for Greece in the medium and long term. It is important to note that previous studies indicate considerable variation in the amount of biomass recoverable for energy purposes due to wide variations in what is considered recoverable and different methodologies for estimation. For instance, Berndes *et al*. (2003), which reviews results from 17 studies, finds the possible contribution of biomass to future energy supply ranging from around 100 EJ per year to 400 EJ per year [22].

In deducting final estimates, we generally use the arithmetic mean from a range of previous studies depending on the feedstock. For the organic fraction of MSW we estimate that all waste currently being landfilled, apart from being composted, can be technically recovered. For biomass from industrial wastes, we generally estimate a high potential recovery rate of 60%. This is in line with Mirabella *et al.* (2014) [23]. For agricultural biomass, our estimates are crop specific due to their different characteristics and these are discussed on a per case basis in the results section. Generally, we assume a recovery rate of around 20% of agricultural biomass that would technically be recoverable for advanced biofuels. This is in line with results from Milhau & Fallot (2013) [24], due to their geographic spread and high number of competing uses. UCO is an exception for which we consider that the entire feedstock is recoverable as our estimates are solely based on UCO produced by the hospitality sector. Similarly, we estimate that all CO_2 feedstocks from steel mills, cement production and petroleum refining are technically recoverable.

2.2 Estimating energy potentials

Estimates for the technical energy potential of various feedstock-fuel combinations to contribute to the Greek transport sector until 2050 are also presented. The potential of the following fuels is explored: lignocellulosic ethanol, biomethane, HVO, electrofuels and recycled carbon fuels. These fuels were chosen as they cover all feedstocks presented in this study and also reflect relevant and promising fuel feedstock pathways identified by the EU. Again, it is important to note that these estimates are likely to be higher than what would be achievable in real-life conditions as it considers ideal real-world feedstock collection systems.

These estimates are calculated by converting the technical feedstock availability of each feedstock into relevant fuels and calculating the energy content of the fuel as depicted in Equation (1):

$$Y = (F \cdot X) \cdot E \quad (1)$$

where Y refers to the total energy content, F refers to the annual technical feedstock availability, X refers to the feedstock to biofuel/biogas conversion ratio, E refers to the energy content of the converted feedstock.

This is then used to estimate to potential contribution these fuels can make to energy use in transport in Greece until 2050. This is calculated according to Equation (2):

$$T = \frac{(F \cdot X) \cdot E}{C} \quad (2)$$

where T refers to the potential contribution of these fuels to Greece total energy use in transport, F refers to the annual technical feedstock availability, X refers to the feedstock to biofuel/biogas conversion ratio, E refers to the energy content of the converted feedstock, C refers the total estimated energy use for transport per time period. For electrofuels we estimate that 10% of the total energy produced from RES can be used for electrofuel production, the total RES estimates until 2050 are taken from the NCEP and LTS. We include data on the energy potential of recycled carbon fuels from steel mills, but not from petroleum refineries or cement production as the technology has not yet been commercially proven and current trials by Lanzatech are focused solely on producing recycled carbon fuels from carbon emissions from a steel mill. For recycled carbon fuels from refuse derived fuels (RDF) feedstock, we estimate that 10% of the technical availability of plastics could be converted into liquid transport fuels (e.g., ethanol). Multipliers (as defined in the RED 2018/2001) have not been used in this study for the calculation of the share of advanced biofuels as well as for the rail, maritime and aviation sector [3].

2.3 Limitations and bias risk

There are a number of considerable limitations associated with this study. Different data sources, at times, provide feedstock estimates that vary considerably. As indicated, we compensate for this limitation by estimating feedstocks on a case-by-case bases using a clear methodology for each case that is supported by existing literature. In addition, we rely only on sources that are peer-reviewed and published in high quality journals or in high quality reports or databases that provide clear methodologies.

The valorisation routes explored are relatively simple and the estimates presented are simple estimates that do not include the diversity, seasonality, purity and disperse nature that characterise many of these fuels. This is a significant limitation as in practice the valorisation routes are likely to be considerably more complex and rely on combining multiple feedstocks in specific areas. To do this effectively, it requires in-depth research on local conditions per fuel-feedstock combination, which is beyond the scope of this study but an important area for future research. Despite this, we consider our results useful and relevant as they can be considered as rough estimates as to which fuel-feedstocks combinations are promising for Greece in the medium and long term. Similarly, it is clear that considerable uncertainty should be associated with the estimates presented in this study, however, data are presented without uncertainty. This is done as existing data are fragmented and not enough data points are available for the calculation of confidence intervals, therefore all estimations from this study should be seen as rough estimations, which mainly illustrate the potential of various feedstock-fuel combinations.

3. Feedstocks and Energy Estimation

3.1 Feedstocks

3.1.1 Biomass fraction of mixed municipal waste

Updated and reliable data on the biomass fraction of MSW do not exist [25]. According to Eurostat, the total amount of MSW created in Greece in 2017 was 4.5 million tonnes, up slightly from 4.2 million tonnes in 2004 and down from 5.1 million tonnes in 2010 [26]. Various studies have pointed out that the proportion of biodegradable mass in mixed municipal waste in Greece is very high — on average this percentage is estimated to be around 45% [27]. According to this estimate, in 2017, there was a theoretical annual feedstock of 2.03 million tonnes.

In practice, accurately measuring changes in MSW is difficult due to impacts of multiple trends including socio-economic factors, changes in production and consumption, and policy impacts [28]. Certain trends such as socio-economic factors are generally shown to have a positive correlation with MSW levels [28]. However, it is also clear that, with the goal to reach carbon neutrality and associated policy support, through the green deal for instance, considerable efforts will be made to reduce MSW generation in the short and medium term. Regarding future projections, based on these trends, we assume that the amount of MSW produced per capita will stay relatively constant, based on the 2017 figures, while the total amount of MSW is adjusted according to future population projections. According to the latest available population predictions from Eurostat, Greece’s population is expected to decline from 10.69 million in 2020, to 10.37 million in 2030, 10.03 million in 2040 and 9.62 million in 2050 [29]. Based on these estimations, the proportion of the theoretically available biomass fraction of MSW will decrease to

2.02 million tonnes in 2020, to 1.96 million tonnes in 2030, 1.9 million tonnes in 2040, to 1.82 million tonnes in 2050.

As laid out in the EU's Waste Framework Directive, the recycling of raw material (in this case composting) should be prioritized over recovery (energy recovery), thus biomass fractions of MSW that are already composted are not technically recoverable for energy purposes and thus cannot be considered for feedstock [30]. In Greece, currently only 2% of MSW (approximately 100,000 tonnes) is recovered through composting [25], thus Greece has a technical potential feedstock availability of 1.99 million tonnes on an annual basis. Given that the recovery of organic material through composting has been growing annually, from 1995 to 2017, by 5.2% on average across the EU [26], it is projected that composting rates in Greece will increase from 2.3% in 2020, to 3.9% by 2030, to 6.4% by 2040 and to 10.6% by 2050. It follows then that, the technical availability of potential feedstock in 2020 will be 1.97 million tonnes in 2020, 1.88 million tonnes in 2030, 1.77 million tonnes in 2040 and 1.63 million tonnes in 2050. Regarding the geographic distribution of this waste, it is clear that the availability is, and will continue to be, centred around the main population areas, namely Attica (with around one third of the Greek population), Thessaloniki and Patras. As a caveat, it is important to note that, due to tourist seasons, this waste in many regions of Greece experience large seasonal variations, which is not accounted for here.

3.1.2 Biomass fraction of industrial waste

Similarly, there is no clear or accurate indication on the biomass fraction of industrial waste for Greece. Based on the information available in the literature, there are a number of significant and important industrial waste streams that contain large amounts of biomass. These are especially prevalent in the agro-processing and food industries. However, the estimates vary significantly: a study by Vlyssides *et al.* (2015) [31] on the energy generation potential in Greece from agricultural residues and livestock manure estimates the total biomass contained in agro-processing plants at 2.3 million tonnes, while Panoutsou *et al.* (2004) [32] estimate that 0.5 million tonnes are produced per year. From existing literature, we identify the residues from the processing of tobacco, cotton ginning, olive oil and sugarbeet industries as the main recoverable industrial waste streams. However, sugarbeet feedstocks are not included in this study as in recent years multiple sugarbeet industries have closed and thus reliable data on sugarbeet waste are not available; for instance, Vlyssides *et al*. (2015) [31] estimate high amounts of waste from sugarbeet based on production levels that are significantly higher than current production levels. It is also important to note that a proportion of the biomass fraction of industrial waste from agro-processing plants is already used for local bioenergy purposes.

Regarding waste generated from olive oil processing, the waste residues estimations are based on olive oil production. In 2017, olive oil production in Greece stood at 0.312 million tonnes. It is estimated that, on average, the production of 1 kg of olive oil generates around 1.375 kg of dry biomass. Based on this, we estimate that 0.429 million tonnes of dry biomass are theoretically available as a feedstock. This is in line with findings from other studies, such as Panoutsou *et al.* (2004) [32], which finds that there are 0.423 million tonnes of dry biomass available. With regards to future projections, we estimate that feedstock availability will remain stable, as, on the one hand, olive oil production has experienced a steady historical increase while, on the other hand, multiple studies discuss the negative impact of climatic change on olive yields. Geographically, there are numerous centres of olive oil production across the country. The regional units with the highest olive waste production are Ilia, Messinia and Heraklion with an estimated theoretical availability of 78,000 tonnes, 62,000 tonnes, and 52,000 tonnes of dry olive wastes respectively [33].

Regarding wastes associated with the processing of cotton, we draw data from the paper of Panoutsou *et al.* on 'Agricultural Biomass in Greece: Current and Future Trends.' In their study, they find that the annual dry organic residues from cotton ginning factories in Greece is 132 thousand tonnes [32]. This is also in line with the estimations of the paper by Alatzas *et al.* (2019) [18], which calculates cotton wastes to be over 100,000 tonnes. The main cotton producing regions in Greece are Thessaly, Macedonia and Thrace [34]. Similar to the problems associated with olive production, we are unable to make accurate predictions on future feedstock capacity, as such, for the purpose of this study, we assume that annual cotton waste production remains stable until 2050.

Regarding waste from tobacco production and rice mills (rice husks), the existing literature on industrial wastes estimations refers to around 24 thousand tonnes and 30 thousand tonnes respectively [31,32]. These estimates are relatively low and, hence, not included in this study.

3.1.3 Straw

There are some evident variations in the existing estimates on the availability of straw in Greece per year — the two most reliable figures we have found are from CRES [19] and S2Biom [20], which estimate a theoretical potential of around 1.15 million tonnes and 1.06 million tonnes of dry matter per year. We predict future straw availability using the trends of two historical 10-year averages of cereal production in Greece, and find that, between 2000–2009 and 2010–2019, cereal production declined by 12.6%. Applying this to future straw predictions, we use 2020 as a base year and the latest available data of 1.06 million tonnes of dry straw annually; we estimate that the theoretical straw availability will decrease to 0.93 million tonnes in 2030, 0.81 million tonnes in 2040, and 0.71 million tonnes in 2050.

There is a clear distinction between the theoretical and technical potential for straw as a feedstock for Greece as it has a large number of competing uses. The Institute for European Environmental Policy estimates that around 20% of straw is recoverable [35], which reduces the estimation of the technical potential availability for straw to 0.21 million tonnes in 2020, 0.19 in 2030, 0.16 in 2040 and 0.14 million tonnes in 2050. Most straw production is centred around Thessaloniki and Larissa [19].

3.1.4 Animal manure and sewage sludge

According to Eurostat data, Greece produced 119,768 dry solid tonnes per year of sewage sludge in 2017, down from a high of 151,000 tonnes in 2009 [26]. This trajectory corresponds closely with the effects of the Greek economic crisis. Therefore, as the Greek economy recovers, we expect a sustained moderate increase in sludge production of 1% per year. Based on this, we estimate sewage sludge production at 123,000 tonnes in 2020, 135,000 tonnes in 2030, 148,000 in 2040 and 160,000 in 2050. Geographically, sewage sludge can be found near the largest urban centres, namely Athens, Thessaloniki and Patras.

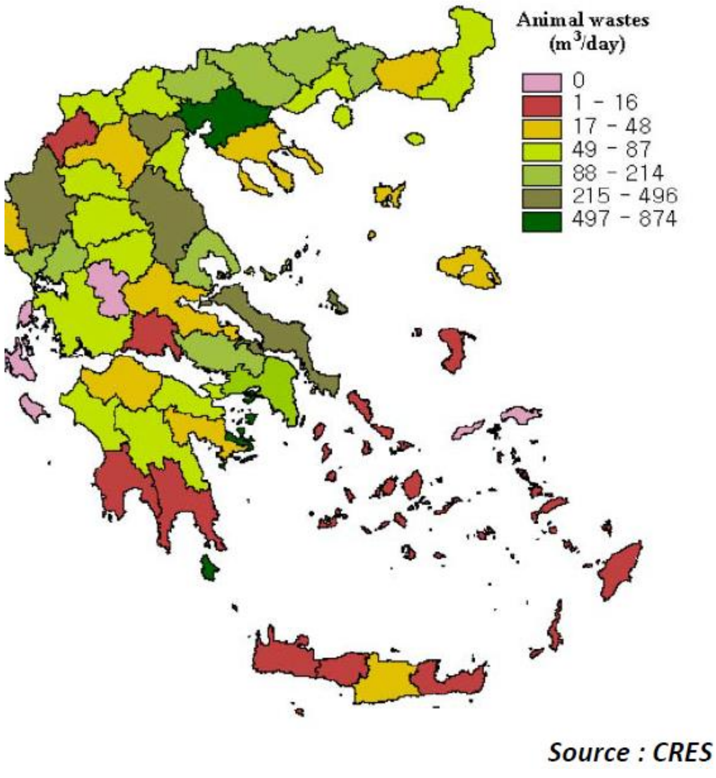

Figure 1 Amount of animal wastes produced per day and region [19] (permission of using the image has been obtained).

Estimated animal (livestock) manure production in Greece in 2011 was 11.76 million tonnes [36], which corresponds roughly with the 10.3 million tonnes estimated by Vlyssides *et al.* (2015) [31]. Attempting to make future projections, we extrapolate changes in livestock numbers as measured in the last two agricultural censuses (2000 and 2010), where livestock numbers decreased by 5.2% [37]. Based on this, we estimate animal manure production to be at 11.2 million tonnes in 2020, 10.6 million tonnes in 2030, 10 million tonnes in 2040 and 9.5 million tonnes in 2050. Figure 1, from CRES [19], shows the amount of animal wastes produced per day and region, and illustrates that the highest production of animal wastes is in the region of Thessaloniki, followed by Larissa, Evia, Ioannina and Imathia. Drawing from ratios observed in other studies, we estimate that for animal manure around 65% is technically recoverable for advanced biofuels [38].

3.1.5 Grape narcs and wine lees

There are no reliable estimates on the amount of grape pomace in Greece. In order to estimate the amount of theoretically available grape pomace, we extract data from the amount of grapes used annually for wine production and estimate the grape pomace to be 20% of this. The figure is generally assumed to be the percentage of the weight of the grapes that remains as pomace after processing [39]. According to Elstat, 465,000 tonnes of grapes were used for wine production in 2017 [40]. Based on this, we estimate that a potential feedstock of 93,000 tonnes is available in Greece annually. Geographically, the production of wine is fairly dispersed around the country, with the major producers being Crete, the Peloponnese and the Region of Western Greece.

Future estimates on wine production show variations, for instance, study by Lionello *et al.* (2013) [41] finds that wine production will decrease by 20–26% in a typical Mediterranean climate due to changes in temperature and rainfall, while study by Georgopolou *et al.* (2017) [42] on climate change impacts and adaptation options for agriculture in Greece until 2050 state that monetary income for grape producers for the production of wine will increase in Greece as a whole. These variations can be attributed to several issues including decreases in yields in some areas, increases in others, and the implementation of adaptation strategies. Based on this, we suggest that wine production will remain relatively stable over the long run. Previous studies have shown that, despite some uses, most grape pomace is currently largely disposed of. Based on this, and due to its similarities with the biomass fraction of industrial waste in terms of geographical concentration, we estimate that 60% could technically be recovered for the production of advanced biofuels.

3.1.6 Fruit tree prunings

Regarding biomass from tree plantations, olive tree prunings are by far the most abundant woody material that is relatively accessible, with a total number of 148 million olive trees in Greece [33]. A recent study from Sagani *et al.* (2019) [43] on the biomass potential from fruit tree prunings in Greece finds that there is an average annual yield of 0.015 wet tonnes (and around 0.0075 dry tonnes) of pruning per olive tree.

According to the European Bioenergy System Planners handbook, the potential of olive tree prunings is calculated as the number of olive trees multiplied by the average pruning yield [44]. This amounts to an annual theoretical feedstock capacity of 2.2 million wet tonnes with an associated 1.1 million tonnes of dry matter. This is somewhat in line with other studies that estimate olive prunings at 0.9 million dry tonnes [32] and an earlier study estimates that there is an annual yield of 1.5 million tonnes of olive tree prunings [45].

Regarding the geographical distribution of olive trees, the Peloponnese and Crete have the largest availability with 0.3 million dry tonnes and 0.26 million tonnes respectively. More specifically, the regional units of Messina (in the Peloponnese) and Heraklion (in Crete) have the largest biomass available, with 0.12 million tonnes each. Regarding future projections, as mentioned earlier in this study, we estimate that feedstock availability will remain stable as, on the one hand, olive oil production has experienced a steady historical increase, while on the other hand, multiple studies discuss the negative impact of climatic change on olive yields. With regards to estimation of the technical availability, we assume that 25% of all feedstock would be lost due to the high loss expected with agricultural harvesting of biomass.

Regarding other fruit trees (lemon trees, orange trees, mandarin trees, apple trees, pear trees, kiwi trees, pomegranate trees, peach-nectarine trees, apricot trees, cherry trees and fig trees, almond trees, walnut trees, chestnut trees, hazelnut trees), the total number of trees in Greece comes to 78,000. The study by Panoutsou *et al.* (2004) [32] estimates that the total combined dry matter value of these prunings comes to 0.62 million dry tonnes per year. As fruit tree prunings are difficult to collect and geographical spread out, we estimate that only around 50% are technically recoverable.

3.1.7 Forestry material

Greece has a significant amount of forests, with around 2 million hectares of the country covered by forest. S2Biom (2016) [20] estimates that primary forestry production accounts for 1.93 million dry tonnes per year, while Alatzas *et al.* (2019) [18] refers to around 2.7 million tonnes. However, it is clear that this theoretical availability is vastly spread out and generally inaccessible, and hence, is unable to be considered in this study. This is an important area for future research.

3.1.8 Used cooking oil

According to Greenea (2016) [46], around 21,600 tonnes of UCO are collected in Greece annually from the professional (restaurants, hotels, *etc*.) sector out of a total availability of 26,000 tonnes. This is in line with information gathered at meetings we had with Elin verd and Hellenic Petroleum (two companies that produce biofuels in Greece), who highlighted that almost all the available UCO from professional enterprises is already being collected. By contrast, during a meeting with Elin Verd we were informed that almost no UCO is currently being collected from households in Greece. Though they mentioned that a pilot program will launch in the near that will target household UCO collection. If these trials are successful, it could significantly increase the theoretical and technical availability of UCO as a feedstock, which could be used for the production of hydrotreated vegetable oil (HVO).

3.1.9 Crude glycerine

Crude glycerine is a by-product of the biodiesel production process. During the production process around 10% of the weight of biodiesel is produced as crude glycerine [47]. According to the latest available data, 157,000 tonnes of biodiesel were produced in Greece [48]. Based on this, we estimate a theoretical and technical availability of 15,700 tonnes of annual crude glycerine feedstock availability in Greece. Over the past decade, biodiesel consumption in Greece has been increasing by 4.9% annually. Thus, in the medium term, we estimate that biodiesel production will continue to increase by this rate for the next 10 years and remain stable after 2030 due to EU regulations on conventional biofuel use as well as concerns over feedstock availability and the development of other technologies.

3.1.10 Perennial crops

According to data provided by S2Biom, Greece has an annual sustainable theoretical potential for dedicated perennial crops of around 1.17 million tons, the majority of which is found in western Greece and the Peloponnese [20]. It remains unclear how this availability will change in the coming decades and what proportion of these crops are technically available for biofuel production, especially considering that a large proportion of these crops would be located in hard-to-reach areas. Further research is thus needed to determine future theoretical and technical availabilities.

3.1.11 RES production

According to the National Energy and Climate Plan (NECP) [4] and the Long-Term Strategy for 2050 [49], the RES share in gross final electricity consumption will reach between 61% and 64% by 2030 and increase further after with different rates according to different scenarios. Such a situation means that there are likely to be significant periods during the year where more RES is produced than consumed.

Malins' study (2017) [21] estimates the amount of additional RES required for electrofuels account for 10% of total transport energy demand by calculating how much electricity is required to reach this level compared to total EU electricity production. Malins finds that around 15% of current gross EU electricity production is required to reach the 10% level. Following this approach, we estimate the amount of electricity required to reach the same 10% of electrofuel use in 2020, 2030 and 2050 for Greece by taking the predicted amount of energy consumed in transport in 2030 and 2050 according to the NCEP and LTS and dividing it by the total estimated electricity production in these years. Our estimates show that 14.7% of Greek electricity production is required to reach this level in 2020, which decreases to 9.9% by 2050 (see Table 1). It is important to note however, that Malins' methodology does not take into account the low efficiencies and large amount of electricity lost during electrofuel production. Transport and Environment estimates a 44% energy loss during the production process of power to liquid fuels [50]. If this is taken into account, then the proportion of electricity needed to reach the 10% will more than double.

Table 1 Share of Greek electricity production required for electrofuels to account for 10% of the energy consumed in transport.

	10% Transport Energy 2020	**10% Transport Energy 2030**	**10% Transport Energy 2050**
Required Electricity (TWh)	8.13	8.21	7.94
Fraction of gross electricity production in Greece in 2020, 2030 and 2050	14.70%	10.90%	9.90%

3.1.12 CO_2 feedstocks

Various existing technologies, such as electrofuels and recycled carbon fuels, require CO_2 as a feedstock for the production of fuels through carbon capture and utilization (CCU), and industrial emissions can be a significant source for this. Greece has various significant industrial CO_2 sources, including annual emissions of 5.6 million tonnes of CO_2 from the petroleum refining sector, 0.12 million tonnes from the steel and iron sector [51] and 3.36 million tonnes of CO_2 from cement production [52].

Regarding future projections, the production of steel and cement has almost halved since 2008, but has seen minor increases in recent years and is currently close to long term averages [53]. Based on this, we estimate that emissions from the steel and iron sectors will remain relatively stable in the long run. By contrast, over the past decade, Greek refineries have added around 20% in capacity [54]. However, due to stringent environmental regulations and the transition to use of alternative fuels, we predict that petroleum refining and associated emissions will decrease by 1% per year until 2050.

3.1.13 Non-recyclable wastes

Refuse derived fuels (RDF) are feedstocks derived from a variety of wastes such as MSW, industrial and commercial waste, in particular from non-recyclable plastics. According to a recent WWF report, Greece produces around 700,000 tonnes of plastic per year, of which around 10% is recycled [55]. To estimate the amount of technical feedstock, we expect that recycling rates will increase by 1% and, due to the expected imposition of stricter environmental legislation and enforcement, we estimate that plastic feedstock will decrease by 1% per year. In addition, around 30% of plastics are used for long-term purposes, for instance, PVC piping, and therefore are not considered technically recoverable [56].

For an overview of the theoretical and technical availability of feedstocks covered in this study in 2020, 2030, 2040 and 2050 see Table 2.

Table 2 Feedstock potential in Greece in million tonnes of dry matter.

			2020	2030	2040	2050
Biomass fraction of mixed municipal waste		**Theoretical**	2.02	1.96	1.90	1.82
		Technical	1.98	1.88	1.77	1.63
Biomass fraction of industrial waste	**Olive Mills**	**Theoretical**	0.43	0.43	0.43	0.43
		Technical	0.26	0.26	0.26	0.26
	Cotton Mills	**Theoretical**	0.13	0.13	0.13	0.13
		Technical	0.08	0.08	0.08	0.08
	Rice Mills	**Theoretical**	0.03	0.03	0.03	0.03
		Technical	0.02	0.02	0.02	0.02
	Tobacco	**Theoretical**	0.02	0.02	0.02	0.02
		Technical	0.01	0.01	0.01	0.01
	Sewage Sludge	**Theoretical**	0.12	0.14	0.15	0.16
		Technical	0.12	0.14	0.15	0.16
Agricultural Residues	**Straw**	**Theoretical**	1.06	0.93	0.81	0.71
		Technical	0.21	0.19	0.16	0.14
	Animal Manure (wet tons)	**Theoretical**	11.20	10.60	10.00	9.50
		Technical	7.28	6.89	6.50	6.18
	Grape Pomace	**Theoretical**	0.93	0.93	0.93	0.93
		Technical	0.56	0.56	0.56	0.56
	Olive Tree Prunings	**Theoretical**	1.10	1.10	1.10	1.10
		Technical	0.55	0.55	0.55	0.55
	Fruit Tree Prunings	**Theoretical**	0.62	0.62	0.62	0.62
		Technical	0.31	0.31	0.31	0.31
	Used Cooking Oil	**Theoretical**	0.03	0.03	0.03	0.03
		Technical	0.03	0.03	0.03	0.03
	Crude Glycerine	**Theoretical**	0.02	0.02	0.02	0.02
		Technical	0.02	0.02	0.02	0.02
	Perennial Crops	**Theoretical**	1.17			
CO_2 Feedstocks	**Production of Steel and Iron**	**Theoretical**	0.12	0.12	0.12	0.12
		Technical	0.12	0.12	0.12	0.12
	Production of cement	**Theoretical**	3.36	3.36	3.36	3.36
		Technical	3.36	3.36	3.36	3.36
	Petroleum Refining	**Theoretical**	5.60	5.04	4.48	3.92
		Technical	5.60	5.04	4.48	3.92
Non-Recyclable Wastes	**Plastics**	**Theoretical**	0.70	0.63	0.56	0.49
		Technical	0.63	0.50	0.39	0.29

3.2 Technical energy potential

Table 3 provides an overview of the technical energy potential per feedstock if the feedstocks are converted in their associated fuels. This is achieved by converting the technical amount of feedstock available into energy (ktoe) according to standard energy conversion ratios per technology. This table illustrates that if the technical availability of feedstocks is converted into associated fuels, these could produce significant amount of fuel for the Greek transport sector. The results from this table are used to further calculate the results presented in Tables 3, 4, 5 and Figure 2.

Table 3 Technical energy potential per fuel according to feedstocks (ktoe).

	2020	**2030**	**2040**	**2050**
Bioethanol (Straw)	37.59	34.01	28.64	25.06
Biomethane (Tree Prunings)	73.96	73.96	73.96	73.96
Biomethane (MSW)	170.28	161.68	152.22	140.18
Biomethane (Animal Manure)	70.85	67.05	63.26	60.10
Biomethane (Sewage Sludge)	32.00	37.00	40.00	43.00
Biomethane (Biomass from Olive Mills)	22.19	22.19	22.19	22.19
Biomethane (Biomass from Cotton Mills)	6.71	6.71	6.71	6.71
Biomethane (Grape Pomace)	0.48	0.48	0.48	0.48
Crude Glycerine	10.00	10.00	10.00	10.00
HVO (UCO)	22.00	22.00	22.00	22.00
Electrofuels (10% of predicted RES production)	46.00	144.00		299.00
Ethanol (Recycled Carbon Fuels) (Steel Mills)	46.00	46.00	46.00	46.00
Ethanol (Recycled Carbon Fuels) (RDF feedstock, 10% of feedstock availability)	40.00	32.00	25.00	19.00

Tables 4 and 5 illustrate how the fuels covered in this study could be allocated to each transport sector in 2030 and 2050. This is achieved by comparing the technical available energy potential per fuel per feedstock to the total fuel consumption by sector in 2030, and 2050. Fuel consumption per sector in 2030 and 2050 is estimated according to changes in the total energy consumption in transport as estimated in the LTS (an increase of 11 % by 2030 over 2015 levels and a decrease of 0.3 % by 2050 over 2015 levels) [4,57]. To the road transport sector, we allocate bioethanol (from straw and glycerine), half of the proportion of electrofuels, and ethanol from recycled carbon fuels. These fuels added together are equivalent to 3.4% and 4.8% of the energy consumed in total road transport in 2030 and 2050 respectively. For the maritime sector, we allocate liquified natural gas (LNG) from biomethane (from the biomass fraction of MSW and industrial sources, animal manure and tree prunings). This would require the maritime sector to shift to and retrofit ships to be powered by LNG. This requires an extra cost, which would also need to be considered. Biomethane from LNG represents

64% and 67% of the energy consumed in maritime transport in 2030 and 2050 respectively. For the aviation sector, we allocate HVO (from UCO), and half of the proportion of electrofuels. These fuels added together are equivalent to 9% and 17.4 % of energy used in aviation in 2030 and 2050 respectively.

Table 4 Energy consumed by transport sector in 2030 and potential proposed contribution of advanced fuels to each sector (ktoe).

	Total Fuel Consumption by Sector in 2030	**Bioethanol**	**Biomethane (LNG)**	**HVO**	**Electrofuels**	**Ethanol (Recycled Carbon Fuels, CO_2 from steel mills)**	**Ethanol (Recycled Carbon Fuels, RDF feedstock)**	**Potential % Advanced Fuels from RES in Total Fuel Consumption per Sector**
Road Transport	5551	34	0	0	77	46	32	3.40%
Maritime	577	0	369	0	0	0	0	63.96%
Aviation	1096	0	0	22	77	0	0	9.03%
Rail	65	0	0	0	0	0	0	0.00%
Total	**7289**	**34**	**369**	**22**	**154**	**46**	**32**	**9.01%**

Table 5 Energy consumed by transport sector in 2050 and potential proposed contribution of advanced fuels to each sector (ktoe).

	Total Fuel Consumption by Sector in 2050	**Bioethanol**	**Biomethane (LNG)**	**HVO**	**Electrofuels**	**Ethanol (Recycled Carbon Fuels, CO_2 from steel mills)**	**Ethanol (Recycled Carbon Fuels, RDF feedstock)**	**Potential % Advanced Fuels from RES in Total Fuel Consumption per Sector**
Road Transport	4986	25	0	0	150	46	19	4.80%
Maritime	518	0	347	0	0	0	0	66.91%
Aviation	984	0	0	22	150	0	0	17.43%
Rail	59	0	0	0	0	0	0	0.00%
Totals	**6547**	**25**	**347**	**22**	**299**	**46**	**19**	**11.57%**

Figure 2 illustrates the technical contribution of these fuels per feedstock to the final energy consumption in the Greek transport sector in 2020, 2030, 2040 and 2050. This is estimated using the technical feedstock availability per fuel per feedstock and comparing it to the total energy consumption in the Greek transport sector in 2020, 2030 and 2050 as estimated in the NCEP and LTS [4,49]. Based on this, we estimate the total technical energy contribution of the fuels covered in this study (excluding recycled carbon fuels from petroleum refineries) to the total energy consumed in the transport sector would rise from 7% in 2020 to 8.2% in 2030, to 9.3% in 2040 and 10.3% in 2050.

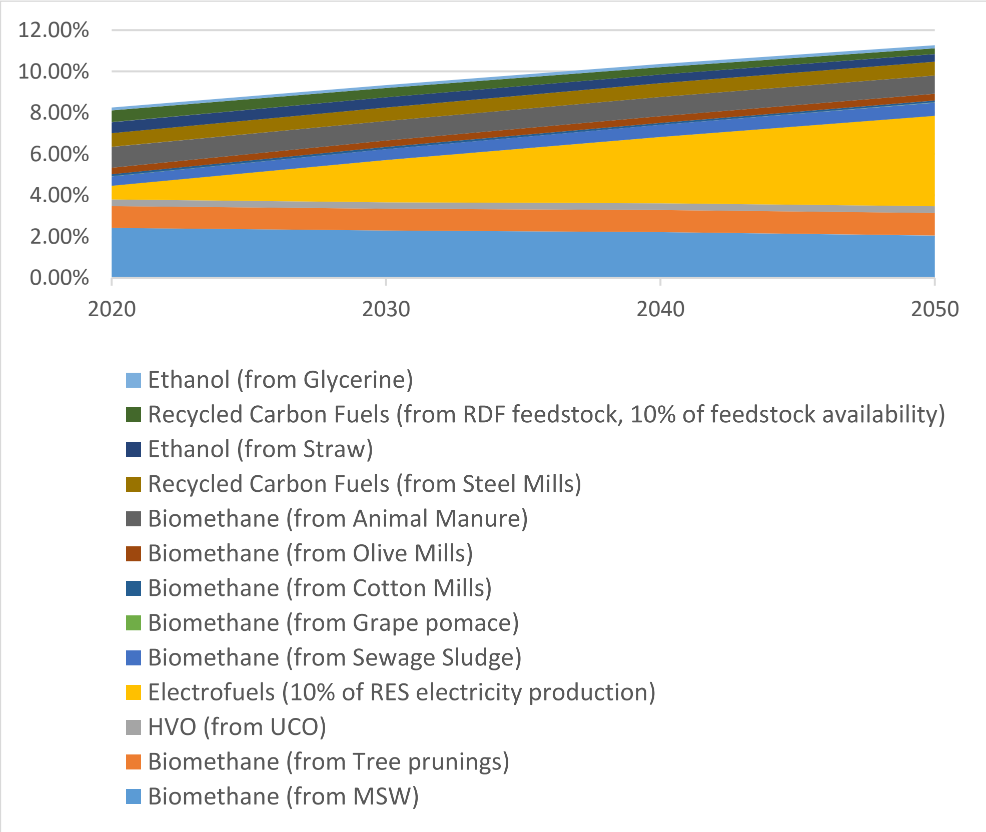

Figure 2 Technical share of new fuels and technologies in final energy for transport.

4. Discussion

4.1 Technical potential

The results show that the technical energy availability of the fuels covered in this study is just sufficient for Greece to reach its 2030 target of at least an 8.2% share of advanced biofuels in the final consumption of RES energy in the transport sector. However, it also shows that these advanced fuels and technologies are unable to cover the majority of the energy consumed in Greece's transport sector and that a significant amount of the 19% target for RES in the transport sector by 2030 will have to come from other sources, such as battery powered vehicles. Similarly, for the Long-Term Strategy for 2050 targets, 21% of the total energy consumed in the transport sector needs to come from biofuels [49]. Our analysis indicates that if all feedstocks covered in this study (excluding non-biomass feedstocks) are used to produce advanced fuels, then this would cover around 5.9% of Greece's annual energy consumption for transport in 2050. If we consider that conventional biofuels could contribute around 6% of the total energy used in transport, this suggests that, in order to reach the 21% share, at least 9% of the total energy consumed in the Greek transport sector needs to come from imported biofuels.

In addition, it is important to highlight that certain feedstocks are geographically spread throughout Greece and do not exist in adequate densities to support the development of certain advanced biofuel refineries. For instance, regarding the production of lignocellulosic ethanol, our feedstock analysis shows that straw-based ethanol is technically not feasible in Greece. This is because our feedstock estimates show that the actual technical capacity of straw for the whole of Greece is 0.2 million tonnes in 2020. According to our predictions, no area within a 50 km radius in Greece, even in the main cereal-producing regions, will have enough straw feedstock capacity for the establishment of a medium sized ethanol plant (which has a feedstock capacity of 150,000–250,000 tonnes). Similarly, our feedstock analysis shows that it is unlikely that there will be enough technical availability for the production of wood-based ethanol in any area in Greece as it is unlikely to reach over 0.1 million tonnes even in the main olive and fruit producing areas in Greece.

By contrast, regarding the production of biomethane, our feedstock analysis illustrates that there is significant potential. This is mainly because biomethane plants can operate commercially at a much smaller scale; plants at a scale of 50,000 and 100,000 tonnes of feedstock are viable in multiple places across Greece, and in a few instances, even larger plants are viable. Potential examples include biomethane plants running on MSW, for instance, the main urban areas around Attica and Thessaloniki, which have an annual feedstock availability of 0.71 and 0.35 million tonnes respectively; smaller urban areas like Attica and Thessaloniki, which already produce biogas from sewage sludge; as well as plants running on livestock manure in Macedonia or on olive mill wastes in Ilia and Messina in the Peloponnese, and Heraklion in Crete. Similarly, our feedstock analysis indicates that producing biomethane from the prunings of olive and fruit trees is possible in a number of areas around Greece, in particular Heraklion, Messina and Ilia where our estimates show an availability of over 0.1 million tonnes.

Regarding HVO, our research and discussions with Elinverd and Hellenic Petroleum show that the majority of UCO is already collected and used in Greece, and to a large extent used in the biodiesel industry. Although it is theoretically possible to shift production to HVO, this would conflict with the significant investments and notable amounts of greenhouse gas savings produced by the biodiesel industry. However, the potential collection of UCO from households would significantly increase the amount of UCO available, which could be used in HVO production.

Regarding feedstocks for the production of electrofuels and recycled carbon fuels, our feedstock analysis suggests that plants are technically possible next to the main petroleum refining and iron and steel production centres. For instance, plants would be feasible next to the largest industrial complexes in the country, such as the Corinthos and Aspropirgos refineries. As the emissions trading system enters its fourth stage and the annual reductions in CO_2 allowances decreases by 2.2% per year [58], it is likely that the price of emitting carbon will increase and place significant costs on industrial CO_2 emitters. Based on this, we expect steady decreases in CO_2 emissions from petroleum refineries and stable emissions with regards to steel and iron sectors due to the increased demand for iron and steel as the Greek economy recovers cancels out the reductions in emissions expected due to increases in the price of carbon.

Table 6 Promising technology–feedstock combinations for Greece.

Technology–feedstock combination*	**2020**	**2030**	**2040**	**2050**	**Comments**
Bioethanol–straw					High TRL, high costs, lack of available feedstock
Bioethano–tree Prunings					High TRL, high costs
Biomethane–biomass fraction of MSW					High TRL, high costs even with low feedstock costs
Biomethane–tree Prunings					High TRL, high technology costs, high costs of feedstock
Biomethane–animal manure					High TRL, high technology costs, high costs of feedstock
Biomethane–sewage sludge					High TRL, high technology costs, biogas is already produced from sewage sludge
HVO–UCO					High TRL, competing uses for UCO
Electrofuels–CO_2					Low TRL but progress expected due to large research and investment initiatives Promising for Greece due to large renewable energy (solar, wind) potential
Recycled Carbon Fuels–CO_2					Low TRL, uncertainty over costs of production, analysis suggests that it will be economically competitive at a higher carbon price
Recycled Carbon Fuels–RDF/Plastics					Low TRL, uncertainty over costs of production

Notes: Dark grey suggests that the technology-feedstock combination is not currently achievable even with economic support. Light grey suggests that the technology-feedstock combination is achievable and competitive in instances with economic support. Diagonal pattern suggests that the technology-feedstock combination is achievable and competitive with economic support.

4.2 Achievable potential

The achievable potential is based on whether the associated biofuel production is economically viable and whether there is sufficient biofuel feedstock within the technical feedstock area in the long run. Paris (2021) finds that none of these fuels will be cost competitive in the long run in Greece without economic support and with medium to low fossil fuel prices [7]. However, our results regarding the technical potential depicted in the present paper suggest that there are various promising feedstock–technology combinations that could be achievable in Greece with some policy support. Table 6 illustrates our interpretation of when these technology feedstock combinations can be available with economic support.

The most promising technology–feedstock combination we identify is biomethane production from the biomass fraction of MSW, which is likely to have possibilities in Greece by 2030, due to its high technology readiness level (TRL) and large amounts of available feedstocks in various places, especially around the main urban centres. The technology was considered relatively expensive compared to natural gas until the recent war in Ukraine and associated rise in the price of natural gas. At current EU gas prices in October 2022, biomethane from a range of feedstocks, especially the biomass fraction of MSW, is likely to be cost-competitive with natural gas. However, for the required sustained investments to be made for biomethane production, it will require for the price of natural gas to remain high in the long run. If the price of natural gas falls back closer to previous levels, then the production of biomethane will require levels of economic support. For instance, Paris *et al*. (2021) shows that, with a cost of natural gas similar to levels experienced in 2020–2021, a tipping fee of 21 euros per tonne in 2030 would make biomethane economically cost competitive with natural gas [7]. We identify that the production of biomethane using feedstocks other than the biomass fraction of MSW has possibilities in Greece by 2040. We also identify that the HVO-UCO fuel feedstock combination is likely to have possibilities in Greece around 2030 due to its high TRL, however, this assumes that other sources of UCO, mainly from households, will become available by then. Additionally, we expect electrofuel production to be possible by 2040 due to improvements in TRL, increases in the availability of electricity from RES and reductions in the cost of electricity from RES. The most likely location of these plants would be close to the largest industrial complexes around Corinth and Aspropirgos. We also expect that recycled carbon fuels that draw CO_2 from steel mills have possibilities by 2030 if the current commercial trials are effective and their estimated cost predictions are relatively accurate and supported by a rise in carbon prices. Similarly, we expect that recycled carbon fuels from RDF/plastics have potential by 2030 if current commercial trials are effective and their estimated cost predictions are relatively accurate and supported by an effective tipping fee. Lignocellulosic ethanol from straw is not achievable in Greece in the long run due to a lack of adequate amounts of feedstock in a specific geographic area in Greece.

In practice, collecting a large amount of feedstock for biofuel production faces an array of practical difficulties including farmer cooperation and logistical challenges. The collection of agricultural feedstocks is dependent on farmer cooperation and farmer incentives. Based on the results of relevant farmer surveys that have been conducted in Greece and across the EU, it is unlikely that all farmers will be easily convinced to participate in the processes of biofuel feedstock collection and will need to be supported by effective education and extension processes [59]. This feeds into wider farmer education for the bioeconomy and policy incentives towards a circular economy. It appears that considerable efforts are being made in this direction, and in recent years various higher education and vocational education training institutes have developed interdisciplinary bioeconomy approaches including sustainable feedstock management and bioenergy into education programs in Greece [60,61].

Similarly, large scale local biofuel production will require the collection, storage, processing and transport of large amounts of biomass within specific geographic areas. Mitkidis *et al*. (2018) highlight the potential in Greece for using existing infrastructure for the collection of agricultural feedstock, which could be possible in the main agricultural areas [10]. Areas where appropriate feedstocks will need to be effectively combined and where there are large feedstock availabilities can benefit from significant economies of scale. However, as has been indicated by multiple studies, it is clear that, in order to effectively collect large amounts of feedstocks across Greece, considerable investments in new logistical and infrastructural capabilities will need to be made, especially in the harder to reach areas [10,11,62]. In addition, it is unclear what the real costs of feedstock collection and storage are in specific areas, which is an important area of future research and a prerequisite for development of the biofuel market.

Beyond the scope of this assessment, it is important to highlight a few other technologies that may be promising for Greece. There is a new technology by VERBIO for biomethane production from straw (capacity: 40,000 tonnes of straw)—a plant on this scale would be feasible in Larissa or Thessaloniki. A pilot plant using this technology-feedstock combination is currently in operation in Germany [63]. Furthermore, it is important to highlight that there are various commercial biogas electricity plants in operation across Greece. They benefit from an attractive feed-in tariff for biogas electricity production—the utilisation of some of the feedstock potentials identified in this study for the production of biogas for electricity could support Greece in reaching its RES targets. These combined heat and power plants that run on biogas could provide a more attractive alternative for biomethane production.

5. Conclusions

This study on the local availability of feedstocks and associated advanced technologies for the Greek transport sector suggests that the biomass fraction of MSW, the biomass fraction of industrial waste, animal manure and sewage sludge, tree prunings, CO_2 feedstocks from industrial sources and RDF/plastics are potential feedstocks for the production of renewable fuels and gases for the transport sector. We find that there is sufficient technical feedstock availability for Greece to reach its medium-term targets on the production and use of these advanced fuels. We find that if the total technical energy contribution of the fuels covered in this study (excluding recycled carbon fuels from petroleum refineries) are considered then this could equate to 7% in 2020, 8.2% in 2030, 9.3% in 2040 and 10.3% in 2050 of the total energy consumed in the transport sector.

Several technology-feedstock combinations for the production of advanced biofuels are possible in Greece in the long run. Our findings suggest that the most promising technology-feedstock combination for Greece by 2030 is biomethane from the biomass fraction of MSW. By 2040 biomethane produced from various other feedstocks are also expected to become possible. HVO could have possibilities in Greece by 2030 if additional feedstock value chains are developed. Electrofuels are shown to become achievable around 2040 while Recycled carbon fuels and RDF fuels could be achievable around 2030 with some economic support and continued technological development.

It is likely that in the medium term the energy used in the Greek transport sector will be composed of a mixture of conventional fossil fuels, traditional biofuels, advanced biofuels, electrofuels and battery powered vehicles. At current trajectories it appears that road transport will in the long term be dominated by battery powered vehicles. However, it is likely that the maritime and aviation sectors will need to rely on high density fuels for which the fuels covered in this study are extremely relevant.

Ethics Statement

Not applicable.

Availability of Data and Material

The authors confirm that the data supporting the findings of this study are available within the article.

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Competing Interests

George Papadakis is a member of the Editorial Board of this journal Green Energy and Sustainability. The other authors, Bas Paris, Rainer Janssen and Dominik Rutz have declared that no competing interests exist. All the authors were not involved in the journal's review of or decisions related to this manuscript.

Author Contributions

Conceptualization, Bas Paris, George Papadakis, Rainer Janssen and Dominik Rutz; methodology, Bas Paris; validation, Bas Paris, George Papadakis, Rainer Janssen and Dominik Rutz; formal analysis, Bas Paris, George Papadakis and Rainer Janssen; investigation, Bas Paris, George Papadakis and Rainer Janssen; data curation, Bas Paris, George Papadakis, Rainer Janssen; writing—original draft preparation, Bas Paris; writing—review and editing, Bas Paris, George Papadakis, Rainer Janssen and Dominik Rutz; visualization, Bas Paris, George Papadakis, Rainer Janssen; supervision, George Papadakis and Rainer Janssen; project administration, Rainer Janssen; funding acquisition, Bas Paris, George Papadakis, Rainer Janssen and Dominik Rutz. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

CRES	Centre for Renewable Energy Sources and Saving
HVO	Hydrotreated vegetable oil
LNG	Liquified natural gas
MSW	Municipal solid waste
NECP	National Energy and Climate Plan
RDF	Refuse derived fuels
RED II	The Recast Renewable Energy Directive 2018/2001
RES	Renewable energy sources
TRL	Technology readiness level
UCO	Used cooking oil

Units and Conversion Table

EJ	Exajoule
ktoe	Kilotonnes of oil equivalent
kWh	Kilowatt hour
toe	Tonne of oil equivalent
€/t	Euro per tonne
€/kWh	Euro per kilowatt hour
€/MWh	Euro per megawatt hour
€/bbl	Euro per barrel
1 m^3 diesel	0.98 toe
1 m^3 petrol	0.86 toe
1 m^3 bioethanol	0.51 toe
1 m^3 biomethane	0.00086 toe
1 toe	11.63 MWh
1 m^3 natural gas	0.01055 MWh

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