CO_2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance

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List of Abbreviations

BNEF	**B**loomberg **N**ew **E**nergy **F**inance
DME	**D**imethyl **E**ther
ETS	**E**missions **T**rading **S**cheme
EU	**E**uropean **U**nion
IRR	**I**nternal **R**ate of **R**eturn
GHG	**G**reen**h**ouse **G**as
LCA	**L**ife **C**ycle **A**ssessment
MW	**M**ega**w**att
MW_e	**M**ega**w**att (electricity)
MW_f	**M**ega**w**att (fuel)
NPV	**N**et **P**resent **V**alue
NREL	**N**ational **R**enewable **E**nergy Laboratory
PEM	**P**roton **E**xchange **M**embrane
PtL	**P**ower **t**o **L**iquids
RED	**R**enewable **E**nergy **D**irective
SOEC	**S**olid **O**xide **E**lectrolyzer **C**ell
US	**U**nited **S**tates

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Chapter 1

Executive Summary

CO_2-based synthetic fuels are of increasing interest as a potential strategy to reduce petroleum consumption as well as greenhouse gas (GHG) emissions from the transportation sector. The most well-known example of CO_2-based synthetic fuels is power-to-liquids, or "electrofuels," which use captured CO_2 and electricity to produce drop-in diesel or gasoline, methanol, dimethyl ether (DME), or other fuels that can be used in vehicles, airplanes, or ships. Production of CO_2-based synthetic fuels has been very limited to date, but production could increase if policy support were available. In particular, the European Commission's proposal for a recast Renewable Energy Directive (RED II) includes CO_2-based synthetic fuels as an eligible pathway to meeting the 2030 target for renewable energy in transport. While there are two possible sources of CO_2 for synthetic fuels – direct capture from ambient air, and industrial waste gases – this study has focused on the latter, because the technology is judged to be at a higher state of readiness.

This study aims to improve our understanding of the potential contribution that CO_2-based synthetic fuels could make towards the European Union's (EU) climate mitigation goals. We project potential volumes of these fuels that could be produced in EU Member States based on a financial analysis and deployment model, taking into account technology readiness, potential subsidies or other policy support, and expected changes in renewable electricity prices. We then assess expected impacts of CO_2-based synthetic fuel production on electricity generation and consumption in the EU. We estimate the GHG intensity of CO_2-based synthetic fuels, including both direct emissions from synthesizing the fuels and indirect emissions resulting from increased demand for electricity from the grid. Lastly, we estimate the total GHG reductions that could potentially be achieved by CO_2-based synthetic fuels across the EU, compared to climate goals.

The potential production volumes and the potential for mitigating climate change, of CO_2-based synthetic fuels depend greatly on whether policy support is provided to these fuels, and if so, how much and what restrictions and accounting rules may be applied. We thus consider four policy scenarios with varying restrictions on the type of electricity that can be used to produce CO_2-based synthetic fuels:

- **Policy scenario 1: Excess renewable electricity only.** CO_2-based synthetic fuels are produced using only excess renewable electricity that would otherwise be unused or curtailed. Such excess electricity might not be available in future if there is strong investment in grid interconnections or storage solutions, but this scenario is designed to explore a potential situation where such solutions are not significantly developed.

- **Policy scenario 2: New renewable electricity installations only.** CO_2-based synthetic fuel facilities are connected to new renewable electricity installations that are independent from the grid. All electricity used in fuel production comes from these off-grid generators.

- **Policy scenario 3: Grid electricity without double counting.** Fuel producers use grid electricity but are required to have a contract with a renewable electricity producer. Fuel producers agree not to consume more electricity than the amount generated by the renewable electricity installation on an annual basis.

- **Policy scenario 4: Grid electricity with double counting of renewable energy** Fuel producers use grid electricity and count the national average renewable share of the grid towards the RED II. The amount of renewable electricity input to the fuel production process and the amount of energy in the fuel itself are both counted towards an overall EU renewable energy target in this scenario, but not in any of the others.

Within each scenario, we consider subsidy levels ranging from 0.50 € per litre to 1 €.50 per litre. While policy support may be provided in many different forms, such as financial incentives, procurement agreements, or capital grants, in this assessment we assumed a simple per litre subsidy.

An important consideration in understanding the role of CO_2-based synthetic fuels in climate policy is whether the production and use of these fuels is allowed to count towards more than one policy target (double counting across sectors). Double-counting of emissions reductions has in the past been used to help provide an advantage to nascent technologies (for example double counting of advanced biofuels in the 2020 RED), but carries high risks of leading to sub-optimal GHG reductions.

The EU has multiple climate mitigation policies aimed at different sectors, each with its own GHG reduction goals. The EU's overall climate benefits depend on the sum of GHG reductions achieved in each sector. GHG benefits from producing and using CO_2 based synthetic fuels do not arise from sequestering the CO_2, because that CO_2 is again emitted upon combustion in vehicles. Rather, CO_2 based synthetic fuels could deliver GHG benefits through displacing fossil petroleum that would otherwise be burned in vehicles, if the net carbon balance of the production process is less than that of fossil fuel.

However, if the GHG benefits from petroleum displacement by these fuels are allowed to count towards GHG reduction targets in multiple sectors simultaneously, the total sum of emission reductions achieved across sectors will be significantly lower than the stated goal. While this risk is minimal where the CO_2 is directly captured from the air, it is more significant where synthetic fuels are produced using CO_2 emitted from concentrated sources such as coal plants or steel mills.

In addition, and while outside the scope of an LCA, policymakers would also need to consider whether incentives to CO_2-based synthetic fuels would steer investments away from other, potentially more effective low-carbon solutions. This warrants further consideration but was beyond the scope of this report.

The risks of double counting

In our analysis, we did not look at synthetic fuels produced using direct air capture. We assumed that CO_2-based synthetic fuels are produced using fossil CO_2 emitted from concentrated sources such as coal plants or steel mills. For clarity, policymakers have two possible accounting options in this case:

- GHG reductions from synthetic fuels are attributed to the industrial sector, but these GHG reductions are NOT attributed to meeting transport or renewable energy goals.

- Synthetic fuels are treated as low-carbon and can be counted towards renewable energy and transport goals, but the GHG reductions are NOT attributed to the industrial sector.

However, it cannot be ruled out that policymakers try crediting GHG reductions from synthetic fuels to more than one sector. Allowing double counting goes counter to the principles of GHG accounting: it would mean that the industrial sector (or the transport sector) has a reduced commitment to provide GHG reductions through other measures, without actually providing any additional benefit. In a worst-case policy scenario, GHG reductions from the use of CO_2-based synthetic fuels could potentially count towards the RED II, the industrial sector in the EU Emissions Trading Scheme (ETS), and CO_2 standards for vehicles. For all scenarios, we present estimated GHG intensities in which CO_2-based synthetic fuels are counted towards only one sectoral target.

All renewable energy that counts towards the transport target in the RED II also counts towards the RED's overall renewable energy target. However, CO_2-based synthetic fuels are different from renewable fuels such as biofuels because they also utilize renewable electricity. If both the energy in the fuel and the renewable electricity input to the process are counted towards the renewable energy target, this would count the energy in these fuels twice towards the same target. This reduces the overall amount of renewable energy that is needed to meet the target. The Commission's proposal for the RED II does not allow this type of double counting; however, we include double counting of renewable energy in Scenario 4 because some stakeholders in the climate policy debate are pushing for this option and to highlight what the effect would be on lifecycle GHG performance.

Table 1.1 presents the main results of our analysis, including potential production volumes, GHG performance, and overall GHG reductions for each policy scenario in 2030. Percent GHG savings compared to petroleum transport fuels is also given; higher values indicate better climate performance, while negative values indicate CO_2-based synthetic fuels are worse for climate than petroleum fuels under some circumstances. If the emission reductions from CO_2-based synthetic fuels are counted in the transport sector, it is appropriate to compare the GHG intensity of these fuels to that of petroleum. However, if emission reductions are counted in the industrial sector, the GHG intensity of CO_2-based synthetic fuels could potentially be compared to that of the primary product in industry, for example coal-fired electricity. If we count the emission reductions from CO_2-based synthetic fuels towards a coal plant, we estimate that these fuels could reduce the GHG emissions from coal electricity by 10-33%, depending on scenario, for any electricity for which the CO_2 is utilized and as long as double-counting is avoided. There are a wide range of potential CO_2 sources, including production facilities for steel, chemicals, and cement, and this GHG comparison would vary with those sources.

Although the analysis is conducted on a national level, here we present results at the EU level. More detailed results are available in the main report. According to our analysis, CO_2-based synthetic fuel production is not likely to be viable in any EU Member State and in any policy scenario at subsidy levels below from 0.50 € per litre.

Policy scenario 1 performs well in terms of GHG performance, if double-counting across sectors is avoided, but is not expected to be economically viable. In Scenario 1, where only excess electricity is used, we expect no production to be cost viable at any of the subsidy levels we consider. This is because excess electricity is only available a small fraction of the time, and thus the fuel production facility would operate at very low capacity. It would not be possible to repay capital expenses for constructing the facility, even if the excess electricity were available at zero cost.

Policy scenario 2 performs well in terms of GHG performance, if double-counting is avoided, but would generate relatively low volumes even at the highest levels of subsidies considered here. In Scenario 2, where the fuel facility utilizes electricity from an off-grid renewable installation, some fuel

TABLE 1.1: 2030 volume projections and environmental parameters for CO_2-based synthetic fuels. **Note that the EU GHG emissions for the 1990 baseline do not include international aviation, land use, land use change and forestry. Green indicates the greatest potential contribution of each scenario to climate mitigation for the parameter indicated, followed by yellow and red.

Parameter	**Subsidy**	**Scenario 1:** Excess Electricity	**Scenario 2:** Off-Grid Renewables	**Scenario 3:** Renewable Electricity Contracts	**Scenario 4:** Grid Average Electricity
Production Volume, million litres	1.00 €/L	0	75	54	0
	1.50 €/L	0	403	413	0
Total GHG Reduction, million tonnes CO_2*e (% reduction from 1990 EU baseline***)	1.00 €/L	0	0.2 (0.004%)	0.1 (0.002%)	0
	1.50 €/L	0	1.2 (0.021%)	1.0 (0.018%)	0
GHG Intensity, gCO_2*e/MJ (% GHG reduction from petroleum baseline)*	—-	1 (99%)	12 (87%)	26 (72%)	66 (30%)

production is possible in EU Member States with high capacity for wind or solar. In these scenarios, the GHG reduction benefits for producing CO_2-based synthetic fuels are high as long as these benefits are only counted in one sector, because only additional renewable electricity is produced.

Policy scenario 3 performs relatively well in terms of GHG reductions, if double-counting is avoided, and has the potential to deliver the highest volumes in this analysis if very generous subsidies are provided, but is nonetheless incapable of reducing the EU's carbon footprint by more than 0.018%. Fuel production potential is highest in Scenario 3, where fuel producers enter a contract with a grid-connected renewable installation, because fuel production facilities can operate at greater capacity. In this scenario, the relative GHG benefits of the fuel are reduced because the fuel production facilities draw electricity continuously from the grid even when the contracted renewable installation is not operating, thus increasing the demand for other types of electricity generation at peak times, including generation from fossil fuels.

Policy scenario 4 is neither cost-viable, nor does it deliver the necessary GHG performance to comply with the RED II threshold. In Scenario 4, grid average electricity is used, but fuel producers can only claim the subsidy for the portion of that Member State's electricity mix that is renewable. In this case, no fuel production is cost viable because of the reduced subsidy amount. The GHG benefits for this scenario are poor in 2030 because the same renewable energy is allowed to count twice towards a renewable energy target, reducing the overall amount of new renewable energy that is produced. In all scenarios, the potential contribution of CO_2-based synthetic fuels to the EU's decarbonization goals is very modest when compared to baseline emissions in 1990.

From these results, we can draw a few key conclusions:

- **Emission reductions from CO_2-based synthetic fuels should be counted in one sector only. There should be no double counting of emission reductions across sectors.** Allowing double counting of emission reductions in both the transport and indus- trial sectors (or in both transport fuels and vehicles) results in poor climate outcomes, as the targeted emission reductions are not actually achieved in both sectors. If CO_2-based synthetic fuels are eligible to count towards GHG reduction goals in the industrial sector, these emission reductions will be undermined if the same fuel is allowed to count towards the RED II. Requiring CO_2-based synthetic fuels to be produced from CO_2 using direct air capture, rather than concentrated CO_2 sources such as coal plants, would ensure that double counting between the transport and industrial sectors would not occur, but this would substantially raise the cost of fuel production.

- **If GHG reductions are counted in the industrial sector, synthetic fuels should not be treated as low-carbon fuels within the context of the transport sector or within the context of renewable energy policy.**

- **If emission reductions are counted in the transport sector only, and not in the industrial sector, some pathways to CO_2-based synthetic fuels can offer significant GHG benefits compared to petroleum in 2030**, in most cases offering GHG savings above the 70% threshold in the Commission's proposal for the RED II. However, compared to the overall climate mitigation challenge, all synthetic fuels offer insignificant benefits. While some stakeholders are pushing for double-counting to be permitted, it should be noted that the GHG savings of the fuel would be eliminated.

- **CO_2-based synthetic fuels are not viable without high policy support.** In all scenarios, significant volumes are only achieved at subsidy levels of 1.00-1.50 € per litre or higher. This is roughly equivalent to 300-500 € per tonne CO_2e and is much greater than most, if not all, biofuel subsidies. Supporting significant roll-out of power-to-liquids is thus expected to require unprecedented levels of policy support in order to reduce the EU's CO_2 emissions by less than 0.2%. It seems likely that GHG reductions could be achieved in the transport and industry sectors at lower cost through other measures, and policymakers should consider the opportunity-cost of supporting synthetic fuels.

- **Even with very strong policy support, potential volumes of CO_2-based synthetic fuels are limited.** In the most favorable policy scenarios for the economics of power-to-liquids production with 1.50 € per litre subsidies (roughly equivalent to 500 € per tonne CO_2e reduction), around 400 million litres could be produced in 2030. This represents approximately 0.15% of total EU road transport fuel demand in 2030. CO_2-based synthetic fuels are not likely to make a significant contribution to the EU's overall decarbonization goals.

Chapter 2

CO_2-based synthetic fuels: Introduction

The European Union (EU) is entering a new phase in renewable energy policy, and with that may come a transition to new low carbon fuel technologies. In November, 2016, the European Commission released a proposal for a recast Renewable Energy Directive for the period 2021-2030 (RED II) that includes a 6.8% target for renewable energy in transport. Only advanced alternative fuels from non-food sources can qualify towards this target, and one of the types of fuels listed as eligible to count towards the target is "Renewable Fuels of Non-Biological Origin". This label is understood to refer to liquid fuels produced from renewable energy such as wind and solar, and these liquid fuels can take the form of hydrogen, hydrocarbons (examples are fossil diesel and petrol), or alcohols (methanol, ethanol, or dimethyl ether). Hydrocarbons and alcohols produced from renewable power sources such as wind, solar, and geothermal would use CO_2 as an input; for the purposes of this study, we refer to these types of fuels as "CO_2-based synthetic fuels". While various assessments are available on the potential for hydrogen fuel to be produced and used in fuel cell electric vehicles, little information is available about the potential for CO_2-based synthetic fuels to contribute towards the 6.8% transport target in the RED II proposal.

The expected environmental impacts of CO_2-based synthetic fuels are unclear. The greenhouse gas (GHG) performance of these fuels depends strongly on the type of electricity used in the fuel production process and whether that electricity would have been used for other purposes. To illustrate: if coal electricity is used to produce CO_2-based synthetic fuels, this would result in more coal combustion, and thus high CO_2 emissions, compared to if no CO_2-based synthetic fuels were produced. CO_2-based synthetic fuels produced from coal electricity would likely increase GHG emissions compared to fossil petroleum. In contrast, CO_2-based synthetic fuels produced from excess renewable electricity – for example, wind electricity produced during off-peak night-time hours that has no other use – could have a very low carbon footprint compared to petroleum [1] The RED II proposal requires that CO_2-based synthetic fuels be produced from renewable energy to qualify towards the transport target. However, this basic requirement could still lead to a number of different outcomes for the overall electricity supply and varying climate impacts. If renewable electricity that would otherwise be used in residential, industrial, and transport uses were diverted to producing CO_2-based synthetic fuels, indirect impacts on these other sectors could arise. Advanced biofuels are subject to a 70% GHG savings threshold to be eligible for the transport target in the RED II proposal, but the accounting rules are specified for CO_2-based synthetic fuels and other renewable fuels of non-biological origin in the Commission's RED II proposal are not clear.

Understanding the lifecycle GHG emissions of CO_2-based synthetic fuel production under various potential circumstances is necessary in developing clear eligibility and accounting requirements for these fuels. At the same time, understanding the potential GHG reductions that can be made from the production and usage of CO_2-based synthetic fuels in the EU will inform the degree to which other climate mitigation strategies are needed. This includes measures both within the transport sector – such as the promotion of other types of advanced alternative fuels, vehicle electrification, and vehicle efficiency improvements – as well as measures in industrial sectors, such as energy and resource efficiency, new product designs and processes, and carbon capture and storage (CCS) to reduce the carbon footprint of the EU's industrial activities.

2.1 Study Objectives

This study presents an analysis of potential volumes and environmental impacts of CO_2-based synthetic fuels. We seek to address the following areas:

- Potential volumes of CO_2-based synthetic fuels produced in 2030 and 2040
- Impact of CO_2-based synthetic fuels on renewable electricity production
- Availability and consumption of CO_2 from concentrated sources
- Lifecycle greenhouse gas impacts of CO_2-based synthetic fuels, including indirect emissions
- Overall contribution that CO_2-based synthetic fuels could make towards the EU's climate goals

This assessment focuses on fuel pathways that combine any of several electrolyzer technologies with several fuel synthesis stages. The electrolyzer technologies that are considered in this study are: *alkaline*, *proton exchange membrane (PEM)*, and *solid-oxide electrolyzers*. The output from each of these electrolyzers will be a concentrated stream of hydrogen gas as well as oxygen (the oxygen stream is not specifically used in the fuel synthesis stage). When introduced into a fuel synthesis system with a concentrated stream of CO_2 the hydrogen and carbon atoms can be upgraded into a range of hydrocarbon fuels. The three fuel synthesis systems considered in this study are: *Fischer-Tropsch*, *methanol synthesis-to-gasoline/diesel*, and a *direct dimethyl ether (DME) synthesis*. These technology combinations are currently the most developed CO_2-based synthetic fuel pathways available. This study only considers pathways that utilize inert waste CO_2, as opposed to energy-carrying waste gas, for example flue gas from steel production. The latter case has different economic and environmental considerations than the pathways included in this study. This study only assesses fuels produced using CO_2 from point sources, not from direct air capture.

We conduct a financial analysis of these CO_2-based synthetic fuel pathways, using data and projections at a national level in EU Member States. We consider capital expenses, electricity prices, other operating expenses, and potential policy support in determining where CO_2-based synthetic fuels might be economical in 2030 and 2040. We focus on solar and wind as renewable electricity sources. We conduct this analysis for four policy scenarios that reflect different eligibility and accounting requirements that could be imposed by policymakers. These scenarios are described in the next section. The projection for 2030 informs on the potential contribution CO_2-based synthetic fuels could make towards meeting the RED II targets, and we extend this analysis to 2040 to understand the longer-term impact that these fuels could have on the transport sector and the EU's climate goals.

The following chapters present the methodology and economic parameters used to project CO_2-based synthetic fuel volumes and the results of this analysis for each policy scenario, including consideration of the availability and consumption of CO_2. We then discuss the likely direct and indirect impacts of CO_2-based synthetic fuel production on electricity production and sources and evaluate the lifecycle GHG performance of these fuels in each policy scenario.

2.2 Scenarios

The production economics and environmental impacts of CO_2-based synthetic fuels depend on their eligibility and renewable energy accounting in policy. Here, we define four possible scenarios of how these fuels could be treated by European policy. These are scenarios that could be incorporated in RED II implementation or in any other renewable energy policy in the EU.

We analyze potential production volumes of CO_2-based synthetic fuels, impacts to renewable electricity, lifecycle GHG intensity, and overall potential GHG reductions in four policy scenarios:

- **Policy scenario 1: Excess renewable electricity only.** CO_2-based synthetic fuels are produced using only excess renewable electricity generation that would otherwise be unused or curtailed. In this scenario, facilities cease production when excess renewable electricity is not available.
- **Policy scenario 2: New renewable electricity installations only.** CO_2-based synthetic fuel facilities are connected to new renewable electricity installations that are independent from the grid. All electricity used in fuel production comes from these off-grid generators.
- **Policy scenario 3: Grid electricity without double counting.** Fuel producers use grid electricity but are required to have a contract with a renewable electricity producer. Fuel producers agree not to consume more electricity than is generated by the renewable electricity installation on an annual basis.
- **Policy scenario 4: Grid electricity with double counting allowed.** Fuel producers use grid electricity and count the national average renewable share of the grid towards the transport target. This amount of renewable electricity is double counted towards an overall EU renewable energy target

We assess a range of policy value from 0.50 - 1.50 € per litre diesel equivalent for CO_2-based synthetic fuels. There are few if any existing policies that actively support CO_2-based synthetic fuels with a defined policy value; policy support for CO_2-based synthetic fuels and other advanced alternative fuels are likely to increase to 2030 and 2040 (for example, the Commission's RED II proposal), and our estimate represents a rough expectation of what level of policy support may be possible. Many different types of alternative fuel support mechanisms exist (e.g. tax credits and exemptions, mandates with credit trading markets). For the purposes of this analysis, we assume that policy support is provided as a simple per litre subsidy.

Chapter 3

Economic Evaluation

This chapter is dedicated to the economic evaluation of various CO_2-based synthetic fuel pathways and begins by describing the methodology used to perform this evaluation. The pathways considered in this analysis include all possible combinations of electrolyzer technologies and fuel synthesis systems and are evaluated in all EU Member States for their economic feasiblity.

3.1 Basic Operation

The electrolyzers considered in this analysis are limited to alkaline water electrolyzers ("alkaline"), proton exchange membrane (PEM) electrolyzer cells (also referred to as "polymer electrolyte membrane"), and two variants of solid-oxide electrolyzer cells (steam and co-electrolysis) (SOECs). Alkaline water electrolysis is the most established technology of all the electrolyzers considered in this study. An alkaline system is operated by submerging two electrodes in a alkaline water solution, which are separted by a membrane, and apply a voltage. A hydroxide ion (OH^- is conducted from the cathode through the solution and across the membrane to the anode where it combines with electrons to release $O_{2]}$ gas; hydrogen gas is produced at the cathode. PEM and SOEC cells are similar to alkaline system, but the electrodes are not submerged in solution. Instead the streams of hydrogen and oxygen released from the reduction reaction are physically separated, making collection easier. Unlike the alkaline systems, PEM electrolytes conduct protons (H^+) through a polymer membrane (typically operated at 100^oC) and SOEC electrolytes conduct O^{2-} ions through a ceramic (solid oxide) material. Since SOECs use ceramic electrolytes they can be operated at a much higher temperature ($600 - 800^oC$), increasing their efficiency over other technologies.

The hydrogen produced from these reactions is then processed in the fuel synthesis process unit, with CO_2, to create short or long chain hydrocarbons (or, in some case an intermediate alcohol). In these systems the CO_2 must still be reduced into CO, but this reaction occurs in the fuel synthesis system. The co-electrolysis SOEC reduces both water and CO_2 in the same electrolysis unit to create streams of hydrogen and CO simultaneously, which are then used as feedstocks in the fuel synthesis system, to again, create hydrocarbon molecules. A generic system is summarized in Figure 3.1. Important parameters and economic assumptions for all of these subsystems are detailed in Section 3.4 while overall results being discussed in Section 3.5. Specific scenarios are detailed in Sections 3.5.1 to 3.5.4. The chapter concludes with a summary of all relevant findings.

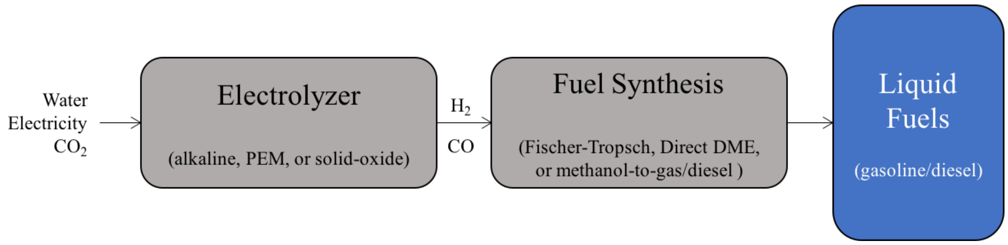

FIGURE 3.1: Model plant for the production of CO_2-based synthetic fuels.

3.2 Methodology

For purposes of this study, the two principle components of a CO_2-based synthetic fuel plant, the electrolyzer and the fuel synthesizer, are represented as an aggregate of many individual process units. In this way, an aggregate "conversion efficiency" parameter, as well as other parameters can be used to represent the operation of both the electrolyzer and fuel synthesis system. This level of aggregation is appropriate as the focus of this work is on the techno-economic aspects of CO_2-based synthetic fuels. As discussed in Section 2.1 this work considers a range of cash flows that would impact the overall viability of a CO_2-based synthetic fuel plant. These cash flows include: capital expenses, operations and maintenance, electrolyzer replacements, corporate taxes (rates are country specific), depreciation, feedstock costs (i.e., electricity and CO_2), revenue from fuel sales, and potential policy support.

This study performs the economic analysis from the perspective of a project developer (i.e., a company or companies that wish to build a CO_2-based synthetic fuel plant in Europe). The plant being considered is assumed to have a 30 year lifetime and is built over a period of 2 years. In order to effectively evaluate the overall investment attractiveness all cash flows are combined to calculate the net present value (NPV) as well as the internal rate of return (IRR); IRR is also sometimes referred to as the "hurdle rate." It is our assumption that a viable plant must have a postive NPV and a IRR of at least 15%. The IRR threshold assumed in this analysis is higher compared to more established technologies because it is assumed that investors would not invest in relatively new technologies without an expectation of high return to compensate for the risk. For comparison, the United States Energy Information Administration (EIA) uses a IRR threshold of 13% for new coal-to-liquids capital expansion projects (also considered risky) within their National Energy Modeling System (NEMS) assumptions [2].

Details of these assumptions are included in Section 3.4.

3.3 Literature Review

Academic research for CO_2-based synthetic fuels stretches back to 1977 where Steinberg et al. discussed synthetic methanol production from CO_2, water and nuclear fusion energy [3, 4, 5]. Steinberg and others were awarded early patents for some of the technologies involved (direct air capture of CO_2, electrolytic synthesis, etc...) [6, 7, 8, 9, 10, 11]. After this initial wave of interest there was a lull in the research products associated with CO_2-based synthetic fuels. These synthetic fuels were primarily being proposed as a low carbon alternative fuel but also as a way to store excess energy generated from nuclear power plants [12, 13, 14, 15, 16]. At the time of these studies the specific capital costs for nuclear power were lower than that of renewable technologies such as solar and wind. By the middle 2000s there was a renewed interest in researching the production of CO_2-based synthetic fuels but with a focus on using renewable energy as the main source of electricity for electrolysis; costs for renewable source of electricity (i.e., solar and wind) have decreased significantly. During this time there were advances in the efficiency and manufacture of solid oxide fuel cells that simultaneously helped in the technological advancement of solid-oxide electrolyzers (a solid oxide electrolyzer can be thought of as a solid oxide fuel cell run in reverse). While there are several electrolyzer technologies that are evaluated as part of this work, some of the most promising electrolyzer configurations are of the solid-oxide variety [17, 18, 19, 20, 21, 22, 23]. Laguna-Bercero et al. detail some of the recent advances in high temperature electrolysis using solid-oxide electrolyzers [24].

Until recently academic literature focused primarily on the physics/materials science aspects of electrolyzer technology, but as research has progressed, there has been a shift to focusing on techno-economic assessments of systems that can produce CO_2-based synthetic fuels. Very recently Brynolf et al. compiled and harmonized many of these different studies in order to aid in the overall economic assessment of the various technology pathways that are currently being discussed [25]. Original studies that were referenced by Brynolf et al. and used to generate investment cost estimates for electrolyzers are included for completeness [26, 27, 28, 29, 30, 31]. Original papers that were used to generate investment costs for liquid fuel synthesis are also included for completeness [32, 33, 34, 35].

In addition to presenting a harmonized summary of investment costs, Brynolf et al. also included an assessment of the electrolyzer conversion efficiencies (i.e., the electricity-to-hydrogen, η_{E2H}) for alkaline, PEM, and SOE (steam and co-electrolysis) units. Brynolf et al. also presented fuel synthesis conversion efficiencies (i.e., the hydrogen-to-fuel, η_{H2F}) for Fischer-Tropsch liquids, methanol, dimethyl ether (DME), gasoline, and methane. For detailed discussions of each of these technologies the interested reader is directed to the following references [18, 22, 23, 24, 28, 32, 33, 36, 37, 38, 39, 40, 41, 42]. This study focuses on fuel synthesis systems that could theoretically produce a gasoline/diesel-like fuel for automotive/truck applications; this study does not specifically address the production of aviation fuels. For the purposes of this study it is assumed that any electrolyzer can be paired with any fuel synthesis system; the overall plant conversion efficiency (electricity-to-fuel) is then $\eta_{plant} = (\eta_{E2H})(\eta_{H2F})$. Table 3.1 and 3.2 detail all of the necessary efficiencies used in this study. Note that both of these tables detail conversion efficiencies on an energy basis (as opposed to a volumetric basis). When calculating the volume of liquid fuels care must be taken to use proper conversions; DME, in particular has an energy density that is half that of traditional diesel fuels.

TABLE 3.1: Electrolyzer efficiencies (η_{E2H}) used in this study.

Parameter	**Value**	**Reference**
Alkaline Water	65%	[25]
PEM	62%	[25]
SOEC (steam)	77%	[25]
SOEC (co-electrolysis)	81%	[25]

TABLE 3.2: Fuel synthesis efficiencies (η_{H2F}) used in this study.

Parameter	**Value**	**Reference**
Direct-to-DME	80%	[25, 26, 34]
Fischer-Tropsch	73%	[25, 26, 34]
Methanol-to-gas/diesel	77%	[25, 26, 34]

3.4 Financial Model

This section details all of the necessary model parameters used to calculate the NPV and the IRR for a potential CO_2-based synthetic fuel plant. This section is organized by first describing the overall structural assumptions of the model, following this we present a detailed account of the parameters used to describe the electrolyzer and fuel synthesis subsystems, and finally we detail any necessary exogenous market parameters.

3.4.1 Fundamental Economic Parameters

Table 3.3 details the necessary economic parameters used in the calculation of NPV and IRR.

TABLE 3.3: Fundmental economic parameters for NPV and IRR calculations.

Parameter	**Value**	**Reference**
Plant Lifetime	30 years (no salvage value)	
Construction Time	2 years (75% initial capital in year 1, 25% in year 2)	
Inflation Rate	2%	
Depreciation Method	Straight Line	
Depreciation Rate	5%	
Operations & Maintenance	2% of initial capital costs/year	[25, 43]

3.4.2 Capital Costs

Capital costs for both the electrolyzer and the fuel synthesis units vary widely in the litreature as noted in Brynolf et al [25]. The capital costs used in this study are modeled such that they vary over time as well as with the size of the installed system. In order to represent economies of scale it is assumed that the capital costs for the fuel synthesis system scale through a power relationship represented by Equation 3.1. In this equation S is the capacity of the system and C is the capital cost of that system for the scaled system (S_o and C_o represent capacity and capital costs for the reference system). The parameter k is typically ≤ 1 and represents non-linear scaling behavior of the plant components (i.e., "economies of scale"). This study assumes that the fuel system scales as $k = 0.7$ following other studies that analyze capital costs for large chemical processing plants [25, 26, 32, 33, 34, 44]. This study also assumes that the electrolyzer is not subject to economies of scale (i.e., $k = 1$). Following Brynolf et al., it is assumed that as the size of the electrolyzer increases the project developer would simply build many parallel electrolyzer modules and that the necessary infrastructure to build out these parallel units would also scale linearly [25]. All other references values can be found in Table 3.4.

$$\frac{C}{C_o} = \left(\frac{S}{S_o}\right)^k \tag{3.1}$$

It is assumed that electrolyzers are still in the early to mid-levels of technology readiness, so their overall capital costs will decrease with time. For years not shown in Table 3.4 a simple linear interpolation assumption is used; beyond 2030 capital costs are held constant at the nominal 2030 rate. The fuel synthesis subsystem is assumed to be at commercial levels of technology readiness and so capital costs are held at a constant (in nominal terms) over the model time horizon. Note that the capital costs for the fuel synthesis parameters are cast in terms of fuel output.

TABLE 3.4: Reference capital costs for electrolyzers and fuel synthesis subsystems. All costs are reported in constant 2018 €.

Subsystem	**Parameter Value**	**Year**	**Reference**
Alkaline electrolyzer	$\frac{C_o}{S_o} = 1.1$ M€/MW$_e$	2018	[25]
Alkaline electrolyzer	$\frac{C_o}{S_o} = 0.7$ M€/MW$_e$	2030	[25]
PEM electrolyzer	$\frac{C_o}{S_o} = 2.4$ M€/MW$_e$	2018	[25]
PEM electrolyzer	$\frac{C_o}{S_o} = 0.8$ M€/MW$_e$	2030	[25]
Steam SOEC	$\frac{C_o}{S_o} = 0.6$ M€/MW$_e$	2018	[32]
Steam SOEC	$\frac{C_o}{S_o} = 0.6$ M€/MW$_e$	2030	[25]
Co-electrolysis SOEC	$\frac{C_o}{S_o} = 0.6$ M€/MW$_e$	2018	[32]
Co-electrolysis SOEC	$\frac{C_o}{S_o} = 0.6$ M€/MW$_e$	2030	[25]
Direct-to-DME	$C_o = 5$ M€	...	[25]
Direct-to-DME	$S_o = 5$ MW$_f$	...	[25]
Fischer-Tropsch	$C_o = 6.5$ M€	...	[25]
Fischer-Tropsch	$S_o = 5$ MW$_f$	...	[25]
Methanol-to-diesel	$C_o = 8.5$ M€	...	[25]
Methanol-to-diesel	$S_o = 5$ MW$_f$	...	[25]

The capital costs shown in Table 3.4 are for the initial capital costs of construction. The lifetime of electrolyzers is generally much shorter than the lifetime of CO_2-based synthetic fuel facilities, and this component must be replaced every several years. The capital costs in Table 3.4 do not include these electrolyzer replacement costs. Following Brynolf et al., these replacement costs are estimated to be 50% of the initial capital costs for alkaline, and solid oxide electrolyzer systems (SOEC), proton exchange membrane (PEM) replacement costs are slightly higher (60% of initial capital costs) [25]. The replacement cycle varies widely between different electrolyzer technology options, the values presented in Table 3.5 are mostly from Brynolf et al. but other references also detailed electrolyzer lifetimes [23, 25, 28, 45]. For years not listed in Table 3.5 a simple linear interpolation was used as a trend in electrolyzer lifetimes; the electrolyzer lifetime beyond 2030 was simply held constant at the 2030 value.

TABLE 3.5: Electrolyzer lifetime (years) before replacement is necessary.

Subsystem	**Lifetime**	**Year**
Alkaline electrolyzer	8 years	2018
Alkaline electrolyzer	11 years	2030
PEM electrolyzer	7 years	2018
PEM electrolyzer	9 years	2030
Steam SOEC	2 years	2018
Steam SOEC	8 years	2030
Co-electrolysis SOEC	2 years	2018
Co-electrolysis SOEC	8 years	2030

3.4.3 Feedstock Prices

Electricity

We use electricity price projections from the present to 2040 from Bloomberg New Energy Finance (BNEF). BNEF provides these projections by source for a limited number of EU Member States [46]. In this analysis, the price projections for Germany were utilized and extrapolated for other EU Member States [47]. These projections do not assume that national climate goals are met. Additionally, current policies such as subsidies are considered in projections until they expire, after which the subsidy does not influence price projections. Our electricity price estimates differ by scenario:

- **Scenario 1: Excess renewable electricity only:** We assumed an electricity price of zero.
- **Scenario 2: New renewable electricity installations only:** We utilized BNEF's projection of wholesale (without tax) wind and solar electricity prices for Germany. For other Member States, the electricity price based on BNEF's projection for Germany was adjusted for differences in solar and wind generation capacity by country. Country-level wind and solar generation capacities were obtained from JRC [48, 49].

  It was assumed that two-thirds of the total wholesale electricity prices for Germany relate to capital expenditures and one-third to operational expenditures. The capital expenditures were scaled (inversely) to the generation capacity for each country (for example, if country X has twice the wind generation potential as Germany, we estimated its wind capital expenditures would be half that of Germany's on a per *kWh* basis, while operational expenses on a per *kWh* basis would be the same across all Member States). For the hybrid renewable scenario (assuming a mix of wind and solar), the wholesale electricity price is represented as the weighted average of wind and solar.

- **Scenario 3: Grid electricity without double counting:** We estimated grid taxes and surcharges ("grid markup") as the proportional difference between historical base wholesale and large industrial prices by country, using data for 2012-2016 from BNEF. "Large industrial" reflects Eurostat's 70-150 GWh category. For a few countries, historical wholesale prices were not available, and so we applied the average value from the other EU countries. We then multiplied this grid markup factor by the projected solar and wind electricity prices in Scenario 2.
- **Scenario 4: Grid electricity with double counting allowed:** For Germany, we used BNEF's projection for grid electricity prices for the large industrial category. For the other countries, we applied the proportional change in the projected grid electricity prices for Germany in each year to the 2015 large industrial price in that country. In this scenario, only the average renewable fraction of the grid in each Member State is available for policy support; the assumed fuel subsidy was thus prorated by the renewable fraction for each Member State.

Renewable electricity prices for all scenarios were assumed to follow a -1% per year trend beyond 2040.

CO_2

In this analysis, it is assumed that all CO_2 used to produce synthetic fuels is purchased from concentrated CO_2 sources, such as coal plants or steel mills, rather than directly captured from the air. It has been assumed that the fuel production facility would purchase CO_2 from a concentrated stream at approximately 35 € per tonne [25]. Costs would likely be significantly greater using direct air capture, and so potential fuel production volumes would likely be lower (or required subsidies higher) than what we have presented if only direct air capture were used; some estimates show that the cost of direct air capture could vary between 20 €-950 € per tonne [25, 50].

3.4.4 Exogenous Market Prices

The primary output stream for any synthetic fuel production facility is transportation fuel, although there are some additional products (oxygen, waste heat, or possibly small amount of electricity) that may or may not have value. For this study it is assumed that a plant can only produce diesel fuel (or DME).

Diesel Fuel

For purposes of this study we assume that the synthetic fuel plant will only produce diesel fuel for consumption in Europe. It is also assumed that any diesel produced by a synthetic fuel plant would be sold at typical petroleum diesel market prices. The logic is that consumers will not be willing to pay a premium for synthetic diesel fuel if it is chemically identical to its petroleum fuel counterpart. Price projections for diesel fuel in the US are available out to 2040 from the EIA [51]. Since oil, and many refined products, are traded in global markets it has been assumed that the rate of increase in the US diesel price would mimic the same rate of increase in European markets as well, however their initial wholesale market prices will differ. For this analysis, the 2018 wholesale price for diesel fuel (before taxes) in Europe is assumed to be 0.54 € per litre. this price increases to approximately 0.80 € per litre by 2040 (in constant euro terms).

For those fuel pathways that produce DME as a final fuel it is assumed that DME can be sold for 50% the price of diesel fuel since is has roughly half the volumetric energy density of petroleum diesel fuel [39].

3.4.5 Deployment

The financial model described in Section 3.4 describes the financial situation for a single proposed plant in a given year (with a 30 year lifetime). This model does not encapsulate how plants would eventually be deployed within a specific timeframe. In order to project the deployment of CO_2-based synthetic fuel plants throughout Europe until 2040 the financial model was run for a wide range of possible plant sizes (1-1000 MW_e), locations, electrolyzer/fuel synthesis technology combinations, and deployment years (2018-2040). The raw data output from these simulations informs us on what types of CO_2-based synthetic fuel plants are financially feasible or infeasible based on their NPV and IRR. We expect that deployment of these technologies would also be constrained by the time required to construct plants and verify the technologies before further expansion occurs. Following Brynolf et al., Mathiesen et al., and Ridjan, it was assumed that large scale electrolyzers would not be commercially available until additional technology development and scale up had been achieved [25, 31, 52]. For purposes of this study, facilities using electrolyzers of any type that are larger than 100 MW_e were not considered to be available until 2030. A filtering algorithm was constructed with all of these market limitations in mind:

1. Remove plants that have NPV ≤ 0 and IRR $< 15\%$
2. Remove plants > 100MW$_e$ for the entire analysis period
3. For each technology type, a plant of < 50MW$_e$ must be built first as a “proof of concept”. A proof of concept plant must be built in each country in the EU (i.e., a proof of concept plant in Sweden is not considered to be sufficient to de-risk an investment in Spain). This filter is motivated by the fact that renewables have widely varying capacity factors by location. The size of the proof of concept plant is limited to ≤ 50MW$_e$, however, in the event that two (or more) of these small plants were found to meet the NPV and IRR criteria, the smallest plant is considered to be the “proof of concept” plant and is built first; subsequent plants are chosen to be of maximum size that meet the NPV and IRR criteria.
4. There is a 4 year lag before another plant of a specific technology type can be built again. This lag gives the developer time to construct and start ramping up production. 1. This dynamic simulates how an investor might evaluate risk when considering whether to continue investing in subsequent plants using a certain technology. These subsequent plants are chosen to be of maximum size that meet the NPV and IRR criteria.

3.5 Results

The following subsections detail results from each of the scenarios specified in Chapter 1. Results presented in the Chapter 1 only considered the larger of the wind and solar scenarios (specifically for Scenario 2 & 3) because we believe investment opportunities would likely be too limited to support the combined potential of wind and solar across all EU Member States.

3.5.1 Policy Scenario 1

As discussed previously, Scenario 1 models a situation where excess renewable energy from the grid would need to be shed. This situation could arise when demand is out of sync with the generation of renewable electricity. For example, solar power might be at peak production in the middle of the day, but demand for electricity is lower (compared to a morning or evening peak). This excess solar energy could be made available to a synthetic fuel plant, but only for a short period of time per day. In order to model this scenario we assume that this excess electricity is available for 4 hours per day (capacity factor of 16%) at zero cost to the fuel producer. This small capacity factor severely limits revenue from the sale of fuel as well as additional revenue from the assumed policy support. It is not possible to repay capital expenses with a reasonable rate of return. If, somehow, investors would be willing to accept a lower IRR (indicating that the projects are not considered as risky) it may be possible to identify a plant with a positive NPV. However, this plant will still require our highest assumed levels of policy support (1.50 € per litre). Given our assumed IRR threshold, we find no production of CO_2-based synthetic fuel would be viable in this scenario.

3.5.2 Policy Scenario 2

Scenario 2 models a situation where the CO_2-based synthetic fuel facility utilizes electricity from an off-grid renewable installation. Since the electrical generator is located off-grid, the price of electricity for the CO_2-based synthetic fuel facility is lower by approximately 50% because there are no associated transmission and distribution costs and taxes that must also be paid. This lower electricity cost does enable some CO_2-based synthetic fuel production, however this production is limited by the capacity factors for the technologies considered in this study (solar and wind). As an extension, a scenario was also modeled where a hybrid solar/wind generator was used to increase the effective capacity factor of the CO_2-based synthetic fuel plant. This scenario does not specify the size of the renewable generation installation as it is assumed to be owned by another company; the CO_2-based synthetic fuel facility simply enters into a power purchase agreement for electricity generated. The effective capacity factors used in this study are shown in Appendix C.

Production of CO_2-based synthetic fuels is predicted under all different generation scenarios (solar, wind and hybrid), however, the production of these fuels depends on significant policy support. Figure 3.2 shows projected volumes of CO_2-based synthetic fuels aggregated for the EU if these facilities used electricity generated from solar (PV) generators. The minimum level of policy support necessary to incentivize these fuels was found to be 1.25 € per litre. The maximum fuel production (with a level of policy support of 1.50 € per litre) was approximately 210 million litres by 2040; production falls to approximately 125 million litres with a policy support of 1.25 € per litre.

Figure 3.3 shows projected volumes of CO_2-based synthetic fuels aggregated for the EU if these facilities used electricity generated from wind resources; the minimum policy support necessary for these fuels is 0.75 € per litre. The minimum policy support necessary to produce CO2-based synthetic fuels anywhere in the EU is lower than in the solar analysis because for a subset of countries, in particular Sweden, the wind capacity factor is significantly higher than the solar capacity factor. In fact, Sweden is the only country in

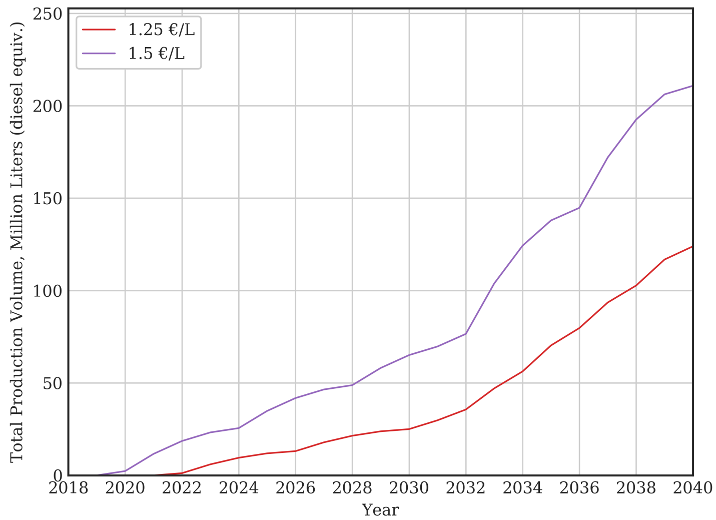

FIGURE 3.2: Production of CO_2-based synthetic fuels in **Scenario 2** from **solar-only generation** in **Europe**.

which CO2-based synthetic fuel production is projected to occur. The higher capacity factor enables more revenue to be generated from fuel sales but also from policy support. The maximum fuel production (with a policy support of 1.50 € per litre) was approximately 800 million litres by 2040; with a policy support of 0.75 € per litre the maximum production falls to approximately 200 million litres by 2040.

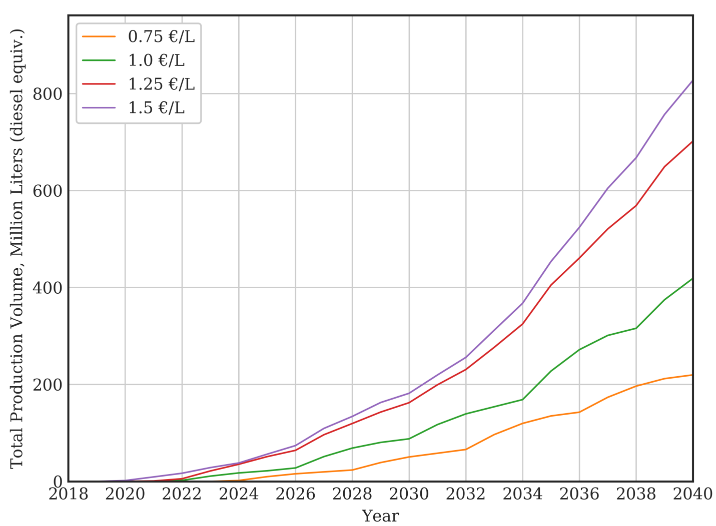

FIGURE 3.3: Production of CO_2-based synthetic fuels in **Scenario 2** from **wind-only generation** in **Europe**.

Figure 3.4 shows projected volumes of CO_2-based synthetic fuels aggregated for the EU if these facilities used electricity generated from a combination of solar/hybrid resources; the minimum policy support necessary for these fuels is 0.75 € per litre. The additional increase in the effective capacity factor from using a hybrid generator enables other Member States to produce CO_2-based synthetic fuels. Specifically, Greece, Italy, Portugal, and Spain are also projected to produce CO_2-based synthetic fuels but only at the highest levels of policy support considered in this analysis (e.g. Portugal is project to produce roughly 60 million litres of CO_2-based synthetic fuel in 2040 at a policy support of 1.00 € per litre). Sweden was still seen as the most attractive location for CO_2-based synthetic fuel. The maximum fuel production (with a policy support of 1.50 € per litre) was approximately 1.6 billion litres by 2040 for all EU Member States; with a policy support of 0.75 € per litre the maximum production falls to approximately 250 million litres by 2040.

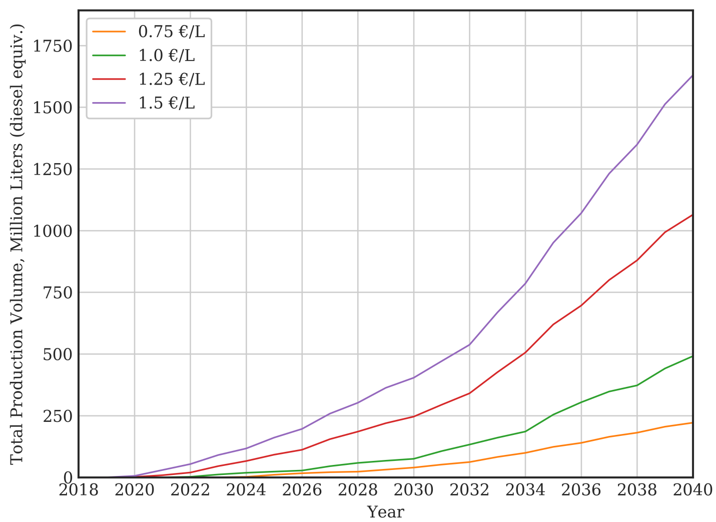

FIGURE 3.4: Production of CO_2-based synthetic fuels in **Scenario 2** from **hybrid generation** in **Europe**.

3.5.3 Policy Scenario 3

Scenario 3 models a situation where the CO_2-based synthetic fuel facility utilizes electricity from the grid, while arranging purchase contracts with a grid-connected renewable electricity source. These grid connected CO_2-based synthetic fuel facilities are able to operate with an effective capacity factor of 0.95, much higher than an off-grid renewable energy generator even in the most favorable situations. However, the electricity price paid by the CO_2-based synthetic fuel facility is much higher because transmission and distribution charges and taxes must also be included. The higher capacity factor more than compensates for the higher electricity prices, and fuel production in Scenario 3 is projected to be larger than in Scenario 2 for solar installations with significant policy support.

Figure 3.5 shows projected volumes of CO_2-based synthetic fuels aggregated for the EU for facilities contracted for solar energy but connected to the grid for delivery. As in Scenario 2 the minimum policy support necessary for these fuels is 0.75 € per litre. However, at the highest levels of policy support (1.50 € per litre) the projected production across all EU Member States was approximately 6.6 billion litres by 2040. With a policy support of 1.25 € per litre the production of CO_2-based synthetic fuels fell to just 3.4 billion litres by 2040 and to just 450 million litres at a policy support of 0.75 € per litre.

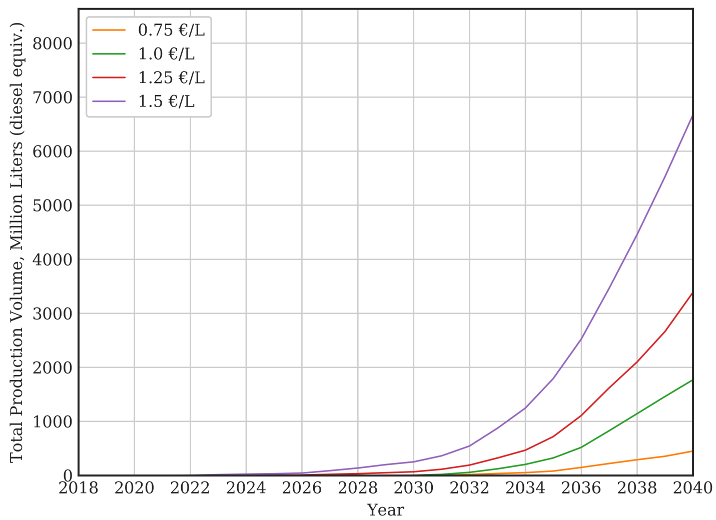

FIGURE 3.5: Production of CO_2-based synthetic fuels in **Scenario 3** from **solar-only generation** in **Europe**.

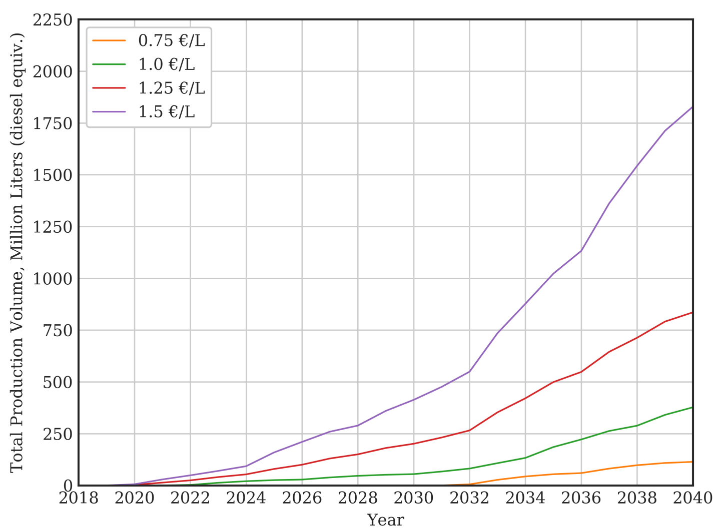

FIGURE 3.6: Production of CO_2-based synthetic fuels in **Scenario 3** from **wind-only generation** in **Europe**.

Figure 3.6 shows projected volumes of CO_2-based synthetic fuels aggregated for the EU for facilities contracted for wind energy but connected to the grid for delivery. Projected production of CO_2-based synthetic fuels was approximately 2.5x larger than that in Scenario 2 with a policy support of 1.50 € per litre. Production levels for the other subsidy scenarios are slightly less that those volumes projected in Scenario 2. The drop in production can be attributed to the higher price of electricity. Even though the capacity factor in Scenario 3 is larger than in Scenario 2 there were countries (such as Sweden) where the wind capacity factor was already quite high (see Appendix C) and the electricity costs were much less than in Scenario 3.

3.5.4 Policy Scenario 4

Scenario 4 models a situation where grid average electricity is used, but fuel producers can only claim the subsidy for the portion of that Member State's electricity mix that is renewable. Effectively, this scales down the amount of the policy support that the facility is able to draw as revenue. The fraction of renewable energy on the grid increased from roughly 38% in 2018 to 100% by 2060 in our analysis. Data from BNEF indicated that there will be a decrease in grid aver- age electricity prices as more and more renewables are integrated. In Scenario 4 the grid average prices were also assumed to follow a -1% per year trend beyond 2040. Even though grid prices may continue to fall in the future, the widespread expansion of renewables did not occur soon enough to incentivize the production of CO_2-based synthetic fuels before 2040. A much more aggressive price reduction of -3%/year was also investigated to test the sensitivity of the results to this modeling assumption. Under this assumption one 30 million litre/year solid oxide electrolyzer plant in Sweden producing DME was found to have a positive NPV and an IRR of >15%. This plant did not reach its full production capacity until 2040.

3.5.5 CO_2 Sources

The amount of CO_2 needed to produce the estimated volumes of CO_2-based synthetic fuel presented along with the projected availability of CO_2 from concentrated sources to check whether the availability of concentrated CO_2 could potentially constrain fuel production.

Data on CO_2 generation was collected from large point sources (including power, iron and steel, refineries, and others) in 16 EU Member States from the International Energy Agency (IEA) [53]. The data was adjusted by applying expected rates of CO_2 emission reduction from 2004 to 2030 and 2040 for the power generation sector (42% in 2030 and 54% in 2040) and the industrial sector (40% in 2030 and 56% in 2040) from the European Commission's EU Reference Scenario [54].

Expected CO_2 generation from large point sources in 2030 and 2040 greatly exceeds the amount of CO_2 that would be consumed by the volumes of CO_2-based synthetic fuel that have been projected (Table 3.6). For example, our analysis shows that in Sweden, one of the EU Member States with the highest potential to produce CO_2-synthetic fuels, up to 878 million litres could be viably produced in 2040 given favorable policy conditions; but this is much less than the theoretical maximum amount of fuel that could be supplied using CO_2 from point sources, at 1.9 billion litres in 2040.

TABLE 3.6: Projected availability of CO_2 from large point sources in EU Member States and theoretical maximum production of CO_2-based synthetic fuel from these sources in 2030 and 2040.

EU Member State	**2030** Total annual CO_2 production (million tonnes)	**2030** Theoretical max fuel production (billion litres)	**2040** Total annual CO_2 production (million tonnes)	**2040** Theoretical max fuel production (billion litres)
Austria	12.9	2.8	9.7	2.1
Belgium	31	6.9	23.2	5.1
Denmark	19.4	4.3	15	3.3
Finland	14.3	3.1	11	2.4
France	89.4	19.8	65.2	14.4
Germany	295.2	65.2	225.8	49.9
Greece	36.4	8	27.9	6.2
Ireland	8.1	1.8	6.3	1.4
Italy	87.5	19.3	66.5	14.7
Luxembourg	1.3	0.3	1	0.2
Malta	0	0	0	0
Netherlands	50.9	11.2	38.6	8.5
Portugal	17	3.8	13	2.9
Spain	64.7	14.3	49.4	10.9
Sweden	11.3	2.5	8.6	1.9
UK	157	34.7	120.1	26.5

3.6 Summary of Results

This study investigated four different scenarios in which the production of CO2-based synthetic fuels might be supported by policy. While the details may differ, there is one common theme that runs through all the results: synthetic fuels are expensive to produce given current and projected grid prices and will likely not be produced unless there is an unprecedented level of policy support. Even when including technology improvements and other cost reductions, the economics of these plants remain challenging. Under most of the scenarios investigated the primary cost for these facilities was the purchase of electricity (roughly 45-60% of the total net present costs), while capital expenditures totaled approximately 15- 30% of total net present costs. Unless petroleum fuel prices increase dramatically (and unexpectedly) the sales price of the fuel outputs will not even cover the variable costs associated with the electricity input alone, and these plants will remain reliant on government support.

Chapter 4

Environmental Impacts

The purpose of this section is to assess the greenhouse gas (GHG) impact of CO_2-based synthetic fuels in the EU through the use of a life-cycle assessment (LCA). In our analysis, we focus on synthetic diesel, although the GHG impact is likely to be very similar for other types of CO_2-based synthetic fuels. We evaluate both the attributional process emissions (i.e., direct emissions) associated with manufacturing CO_2-based synthetic fuel diesel fuel and the consequential emissions resulting from incremental electricity demand to support that fuel production. By incorporating a scenario- based analysis of electricity production in response to new CO_2-based synthetic fuel demand, our goal is to better understand how differences in the eligibility of electricity used to power electrolysis impacts the life-cycle emissions of CO_2-based synthetic fuel. Our scope includes the following life-cycle stages:

- **Carbon capture:** For the purposes of this study, we assume that carbon dioxide (CO_2) or carbon monoxide collection occurs at a point source such as a power plant or steel mill. Other options can include direct air capture (DAC) powered by either natural gas or waste heat [55].
- **Electrolysis:** Electricity generated from a variety of sources is used to separate hydrogen (H_2) from water (H_2O). We assess the upstream emissions associated with electricity production and attribute it to the CO_2-based synthetic fuel process, though the scope and composition of this life-cycle phase changes depending on the scenario chosen.
- **Fischer-Tropsch Processing:** A syngas consisting of carbon monoxide (CO) and hydrogen (H_2) is converted into hydrocarbons in the presence of a catalyst.
- **Combustion:** This includes the combustion of the finished fuel at point-of-use.

We assume that the additional electricity demand for CO_2-based synthetic fuel production in scenarios 2, 3, and 4 generates demand for new electricity generation capacity. To fully capture the emissions associated with the construction of new electricity generation capacity, we utilize levelized emission factors for electricity generation based on National Renewable Energy Laboratory's harmonization analysis of existing published LCA data [56]. These emission factors include both ongoing combustion emissions as well as one-time, construction and infrastructure emissions that are amortized over the expected lifetime of the power plant. Particularly in the case of renewables, incorporating upstream infrastructure emissions changes our understanding of their emissions and their contribution to the carbon intensity of CO_2-based synthetic fuel systems.

4.1 Methodology

4.1.1 Direct Emissions

The direct emissions for this analysis occur from the operation of the CO_2-based synthetic fuel facility, inclusive of carbon-capture, electrolysis, FT processing, and final combustion. Other research groups, JEC and LBP, estimate that at the site of fuel processing and conversion, very little emissions are generated [55, 57]. Together, operation emissions comprise approximately 1 gram of CO_2-equivalents (1 gCO_2e) per MJ of finished synthetic diesel fuel.

The direct emissions from the system are relatively low because the combustion of the finished fuel is offset by the upstream carbon capture. Because we assume that the CO_2-based synthetic fuel process is nominally powered through renewable energy, we do not include combustion emissions from electricity generation as direct emissions for the purposes of our analysis.

DAC provides another option for obtaining the carbon feedstock for CO_2-based synthetic fuel fuels; however, this method requires additional infrastructure and is more energy intensive than obtaining carbon from a point source. Powering DAC through natural gas can significantly raise the process emissions for CO_2-based synthetic fuel, though DAC powered by waste heat would almost entirely eliminate this source of emissions, reducing DAC emissions close to the level of point-source carbon capture [55].

4.1.2 Indirect Emissions

Indirect emissions attributable to the CO_2-based synthetic fuel process include upstream emissions for the construction and operation of new electricity generation capacity. Expansion of electricity demand for CO_2-based synthetic fuel is assumed to trigger a complementary expansion in generation capacity to meet that demand. The composition of this power generation, as well as the scope and magnitude of these emissions vary according to the region assessed as well as the choice of scenario. Our analysis utilizes median electricity emission factors for a variety of electricity sources estimated by the U.S. National Renewable Energy Laboratory (NREL) in support of the IPCC [56]. NREL's LCA grid harmonization study draws upon a wide variety of LCA literature on electricity generation and adjusts the results to use consistent methodologies and assumptions for each technology—notably, NREL attributes one-time, construction emissions for new power plants and amortizes them over the lifetime of the facility. This methodological decision is critical to understanding the impact of new electricity generation that could be required as a result of CO_2-based synthetic fuel production.

No indirect emissions are estimated for Scenario 1 (grid excess) because no new renewable electricity generation is required. For Scenario 2 (new off-grid renewable electricity installations), the construction of new renewable electricity installations that directly power CO_2-based synthetic fuel facilities is included in our estimate of indirect emissions. For Scenario 3 (grid electricity, contract with a renewable electricity provider), much of the electricity used by the fuel facility is assumed to be sourced from that provider, and for this portion we include construction emissions. However, in Scenario 3, because the fuel producer draws electricity from the grid, we assume that it operates at all times, regardless of whether its contracted renewable electricity producer is currently generating at near or full capacity. For example, if the fuel producer contracts with a solar electricity generator, other types of electricity will supply the fuel producer at night when the solar generator is not operating. We include an estimate of the indirect emissions attributable to stable power demand, with more detail below. In Scenario 4 (grid electricity, double counting renewable energy), we assume that use of electricity from the grid results in increased generation from new electricity installations elsewhere, and include the emissions associated with construction of those new installations installations and emissions from generating electricity at these installations.

Table 4.1 presents the emission factors for electricity production estimated by NREL [56]. It is evident that fossil fuel combustion has at least one order of magnitude higher emissions than most sources of renewable electricity and nuclear power. The life-cycle of renewable electricity sources is dominated by the construction emissions; however, even after accounting for these emissions, the total amount of GHG emissions from using these sources of electricity are still relatively small. For this analysis, we supplemented the NREL results with ICCT's assessment of emissions from stationary biomass combustion (i.e., biopower) in the EU, due to strong regional variation in biopower emissions based on feedstock choice [58]. Here, biopower is assumed to be a mix of roundwood and short-rotation coppice combustion and includes land-use change emissions. Solar generation is an average of photovoltaic and concentrated solar power. To assess the impact of upstream emissions from electricity generation on CO_2-based synthetic fuel, we use an assumption of 1.90 MJ of electricity per MJ of finished fuel for CO_2-based synthetic fuel production from concentrated CO_2 from Schmidt et al. [1].

TABLE 4.1: Levelized Emission Factors for Electricity Generation [56, 58].

Generator	**Emission Factor (gCO_2e/MJ)**
Biopower	63.6
Solar (average)	9.4
Geothermal	12.5
Hydropower	1.1
Wind	3.3
Nuclear	4.4
Natural Gas	130.3
Oil	233.3
Coal	278.1

The intermittency of some sources of renewable electricity, such as wind and solar, creates some uncertainty in projecting the impact of increased renewable electricity on the grid. In Scenario 3, a CO_2-based synthetic fuel facility is anticipated to require a consistent, steady supply of electricity, whereas intermittent renewables can either over- or under-produce relative to that demand depending on local conditions. To an extent, the impact of intermittency is mitigated through load smoothing, which refers to the effective smoothing out of short-term intermittency of an individual unit through the distribution of renewable energy across a wider geographic region, allowing generators to dispatch power across that wider region to make up for localized shortfalls in supply. EIA demonstrates that to an extent, wind and solar generation have somewhat complementary daily cycles, though peak solar electricity generation during midday displaces more valuable, peak electricity than wind power does [59].

To account for contracts with a renewable electricity generator that produces electricity intermittently in Scenario 3, we first assume that load smoothing partially counteract periods of insufficient electricity generation by the contracted electricity generator. Electricity production in excess of facility power demand during peak production times would likely offset other, more emissions-intensive sources of electricity even if it was not being used by the CO_2-based synthetic fuel facility, thereby compensating for periods of under-production. Turconi et al. demonstrates that as wind power generation as a share of overall electricity increases, the cycling emissions from baseload generation increase accordingly (though this effect is mitigated through the installation of energy storage) [60]. Fripp estimates that the emissions associated with maintaining spinning reserves of excess flexible natural gas plants and dispatching fast-starting natural gas plants are still substantially lower than the amount of fossil fuel electricity offset by wind power, estimating that wind still offsets 94% of natural gas emissions after accounting for this effect [61]. Based on the results from Fripp, we attribute 6% of the difference between the levelized emission factors for natural gas and wind power to the emissions from renewable electricity in this scenario.

In Scenarios 2 and 3, we assume that renewable energy used in CO_2-based synthetic fuel is largely additional to what would otherwise have been produced. In Scenario 4, grid average electricity is used, and the renewable fraction used in CO_2-based synthetic fuel is counted twice towards the renewable energy target in the RED II. CO_2-based synthetic fuel production thus displaces some amount of renewable electricity that otherwise would have been used in non-fuel applications, and there is no policy requirement that any resulting new electricity production to meet overall grid demand will be renewable. We thus assume that new electricity production resulting from CO_2-based synthetic fuel in Scenario 4 will simply represent the composition of all new electricity installations built in the year in question. We thus estimate the likely composition of Europe's electricity generation in 2030 and 2040. We utilize a market projection from Bloomberg New Energy Finance, which breaks out the mix of electricity sources in France, Germany, Italy, the United Kingdom, and the rest of the EU ("Other Europe") based on projected costs and existing energy policies. To estimate the emissions impact of new renewable electricity production in 2030 or 2040, we estimate the composition of new electricity installations in that year. We start by comparing total electricity generation by source and by country in the year in question (e.g. 2030) with total electricity generation in the preceding years (averaged over 2027-2029). We then account for expected retirements for each type of electricity source using data on typical facility lifetimes [62, 63, 64, 65].

In this example, the difference between the projected electricity mix in 2030 and the mix in 2027-2029 (subtracting expected retirements) is thus interpreted as the mix of new electricity installations in 2030. We find that this is generally a mix of both conventional and renewable technologies, but that a greater share of new electricity installations are expected to be renewable in 2040 compared to 2030. We assumed that the GHG intensity of CO_2-based synthetic fuel in Scenario 4 could not be lower than that for Scenario 3 because high deployment of new renewable electricity installations will likely result in greater use of spinning reserves, such as natural gas, than projected by Bloomberg New Energy Finance.

LBP estimates that the infrastructure-related emissions for constructing a CO_2-based synthetic fuel facility to be approximately 3 gCO_2e/MJ [55]. However, we do not factor in this source of emissions into our final assessment in order to maintain consistency with life-cycle assessments for other liquid fuels.

4.2 Estimated GHG Intensities

Tables 4.2 and 4.3 present our estimated GHG intensities for CO_2-based synthetic fuel in France, Germany, Italy, UK, and Other Europe in 2030 and 2040 for each of the scenarios. We present both GHG intensities in gCO_2e/MJ and percent GHG reduction compared to fossil petroleum (94 gCO_2e/MJ from RED II). The

EU average GHG intensity represents the weighted average by total national electricity production. We find that the emissions associated with CO_2-based synthetic fuel production varied significantly across scenarios, demonstrating that constraints on the source of electricity for electrolysis strongly impact the final emissions associated with the fuel.

TABLE 4.2: Life-Cycle Emissions for CO_2-based synthetic fuel if GHG reductions are counted in one sector only, by Country (gCO_2e/MJ) in 2030 (percent GHG reduction compared to petroleum fuels).

2030 Emissions	**France**	**Germany**	**Italy**	**UK**	**Other EU**	**EU Average**
Scenario 1	1 (99%)	1 (99%)	1 (99%)	1 (99%)	1 (99%)	1 (99%)
Scenario 2	14 (85%)	11 (89%)	19 (80%)	10 (89%)	11 (89%)	12 (87%)
Scenario 3	29 (70%)	25 (73%)	33 (65%)	25 (74%)	25 (73%)	26 (72%)
Scenario 4	29 (70%)	119 (-26%)	143 (-52%)	30 (68%)	111 (-18%)	66 (30%)

TABLE 4.3: Life-Cycle Emissions for CO_2-based synthetic fuel if GHG reductions are counted in one sector only, by Country (gCO_2e/MJ) in 2040 (percent GHG reduction compared to petroleum fuels.)

2040 Emissions	**France**	**Germany**	**Italy**	**UK**	**Other EU**	**EU Average**
Scenario 1	1 (99%)	1 (99%)	1 (99%)	1 (99%)	1 (99%)	1 (99%)
Scenario 2	10 (89%)	16 (83%)	17 (82%)	10 (90%)	10 (89%)	12 (87%)
Scenario 3	25 (74%)	31 (67%)	31 (67%)	24 (74%)	25 (74%)	26 (72%)
Scenario 4	25 (74%)	42 (56%)	31 (67%)	24 (74%)	25 (74%)	26 (72%)

Differences between Member States are mainly due to differences in the overall renewable fraction of the electricity mix. The main factors leading to differences in GHG intensities between scenarios are:

- **Policy scenario 1: Excess renewable electricity only.** CO_2-based synthetic fuels are produced using only excess renewable electricity generation that would otherwise be unused or curtailed. Therefore, no new electricity installations are built or operated as a result of CO_2-based synthetic fuel demand. There are thus no upstream or indirect emissions from electricity. Only direct emissions from CO_2-based synthetic fuel production are included, and these are very low. In this scenario, the renewable energy used in CO_2-based synthetic fuel is allowed to count only once towards the renewable energy target, and thus we assume no change in the amount of renewable electricity needed to meet the remainder of the target; the effect on the overall renewable energy target is the same as if biofuels were used (note: here we assume that CO_2-based synthetic fuel counts towards the renewable energy target on the basis of the energy in the fuel, which differs from the treatment in the Commission's RED II proposal).

- **Policy scenario 2: New renewable electricity installations only.** CO_2-based synthetic fuel facilities are connected to new renewable electricity installations that are independent from the grid. All electricity used in fuel production comes from these off-grid generators. Because these facilities are off-grid, they are assumed to be completely additional to the electricity that would otherwise be used in non-fuel uses. Emissions from constructing these off-grid renewable installations is included, but there are no indirect emissions from impacting the grid. As in Scenario 1, the renewable energy used in CO_2-based synthetic fuel counts only once towards the renewable energy target, and there is therefore no effect on the total amount of renewable electricity used in non-fuel uses.

- **Policy scenario 3: Grid electricity with renewables contracts.** Fuel producers use grid electricity but are required to have a contract with a renewable electricity producer. Fuel producers agree not to consume more electricity than is generated by the renewable electricity installation on an annual basis. As in Scenarios 1 and 2, because there is no double counting of the renewable energy in the fuel, any diversion of renewable electricity from existing installations should result in new installations built elsewhere to meet the target. However, because the consumption of electricity at the CO_2-based synthetic fuel facility is not matched to renewable electricity generation in real time, CO_2-based synthetic fuel production worsens grid balancing problems and results in a small increase in natural gas. The emissions from increased use of natural gas result in a higher GHG intensity compared to Scenario 2.

- **Policy scenario 4: Grid average electricity.** Fuel producers use grid electricity and count the national average renewable share of the grid towards the RED II. The amount of renewable electricity input to the fuel production process and the amount of energy in the fuel itself are both counted towards an overall EU renewable energy target. New electricity generation must be constructed and operated as a result of increased demand for electricity by CO_2-based synthetic fuel, but because there is no policy requirement that this new electricity be renewable, new construction simply reflects the grid-average marginal electricity source mix resulting from economics and grid balancing needs. Some of this new electricity generation is renewable and some fossil. The fossil component greatly increases the GHG intensity in some Member States and years, while having little effect in other cases if the grid in that country is already mostly moving towards renewables.

If the emission reductions from CO_2-based synthetic fuels are counted in the transport sector, it is appropriate to compare the GHG intensity of these fuels to that of petroleum, although petroleum might not be the only competitor to CO_2-based synthetic fuels. However, if emission reductions are counted in the industrial sector, the GHG intensity of CO_2-based synthetic fuels could potentially be compared to that of the primary product in industry, for example coal-fired electricity or steel. If we count the emission reductions from CO_2-based synthetic fuels towards a coal plant, these fuels could reduce the GHG emissions from coal electricity by 10-33%, depending on scenario, for any electricity for which the CO_2 is utilized and as long as double-counting is not taking place.

The Environmental Risks of Double Counting

One important consideration in policy implementation is whether emission reductions from CO_2-based synthetic fuels is allowed to count towards multiple targets (double counting). GHG benefits from producing and using CO_2-based synthetic fuels do not arise from sequestering the CO_2, because that CO_2 is again emitted upon combustion in vehicles. Rather, CO_2-based synthetic fuels can deliver GHG benefits through displacing fossil petroleum that would otherwise be consumed in vehicles. Whether the GHG benefits from petroleum displacement by these fuels are allowed to "double count" towards multiple policy goals can greatly change our understanding of the overall environmental impacts of these fuels. Double counting refers to a situation in which an attribute of the fuel (e.g. GHG reductions or renewable energy consumption) counts towards two different policies. For example, the GHG emissions from one litre of CO_2-based synthetic fuel could contribute towards fulfilling the emissions reductions obligation of a steel mill towards the EU Emissions Trading Scheme (ETS); at the same time, the GHG emissions from that same litre of fuel count towards a fuel supplier's obligation under the energy in transport target in the recast Renewable Energy Directive (RED II). In this example, allowing CO_2-based synthetic fuel to count towards the RED II would not result in any additional emission reductions, because that same fuel would still be produced and used even in the absence of the RED II in order to fulfill the steel mill's ETS obligation. If double counting is prevented, only one sector could claim the emission reductions from CO_2-based synthetic fuel. If a fuel supplier claims these emission reductions towards the RED II, the steel mill would not be able to claim the same emission reductions towards its ETS obligation. In this case, the steel mill must achieve emission reductions elsewhere, for example through carbon capture and storage (CCS). The overall environmental benefits of using CO_2-based synthetic fuel are thus only possible if double counting is prevented, and each sector is required to achieve its intended GHG emission and renewable energy consumption goals.

If double counting is allowed across sectors, the overall climate impact is actually worse than using petroleum. If CO_2-based synthetic fuels are allowed to count in both the industrial sector and the transport sector, then a similar amount of CO_2 reductions will be avoided in the second sector. Double counting in the industrial sector and transport sector would add 74 gCO_2e/MJ to all estimated GHG intensities shown in Tables 4.2 and 4.3 compared to single counting in the transport sector. The net GHG intensities would thus range from 74 to 140 gCO_2e/MJ in 2030 and from 75 to 100 gCO_2e/MJ in 2040 for the EU on average.

Another type of double counting could occur if the renewable energy used to make CO_2-based synthetic fuels is counted twice towards renewable energy targets in the EU. All renewable energy that counts towards the transport target in the RED II also counts towards the overall renewable energy target in the RED II; the overall renewable energy target is crafted with an expectation of a certain amount of biofuels and other renewable transport fuels. However, CO_2-based synthetic fuels are different from other types of renewable fuels (such as biofuels) because they also utilize renewable electricity. If both the energy in the fuel and the renewable electricity input to the process are counted towards the renewable energy target, this would count the energy in these fuels twice towards the same target. This reduces the overall amount of renewable energy that is needed to meet the target. The Commission's RED II proposal does not allow this type of double counting; it states that only the amount of renewable electricity input to the fuel production process can be counted towards the overall renewable energy target, and not also the energy in the fuel. However, this treatment is substantially different from the way other types of renewable fuels are counted in the RED II. Because there are substantial conversion losses in the production of CO_2-based synthetic fuels, the amount of energy in the final fuel is lower than the amount of energy input to the process. This treatment allows CO_2-based synthetic fuels to count more towards the overall renewable energy target on paper than the amount that is actually used, without providing any additional climate benefit over a similarly performing biofuel. As a result, a lower total amount of renewable electricity is used in the EU, and thus a lower amount of fossil fuels is displaced, compared to a scenario where the transport target is met with biofuels instead of CO_2-based synthetic fuels. While not double counting the energy in CO_2-based synthetic fuels, the Commission's proposal treatment effectively "over counts" this energy compared to other types of renewable fuel. However, we do not attempt to quantitatively assess the impact of this treatment on the GHG performance of CO_2-based synthetic fuels in this study.

4.3 Potential contribution of CO_2-based synthetic fuels to climate mitigation goals in the EU

Here, we combine our results for potential production volumes of CO_2-based synthetic fuels with our estimated GHG intensities to estimate what impact these fuels could potentially have on overall GHG emissions and petroleum displacement in the EU. To estimate total GHG reductions, we multiply volumes in each scenario by the GHG intensity, and subtract this amount of GHG emissions from the amount that would be emitted by the equivalent amount of petroleum fuels (assuming a GHG intensity of 94 gCO_2e/MJ for the fossil fuel comparator in the RED II). We then compare this with total GHG emissions in the EU in 1990, a year commonly used as a climate policy baseline, excluding emissions from international aviation and LULUCF [66]. To estimate the potential contribution of CO_2-based synthetic fuels to petroleum displacement, we compare potential volumes to projected total road fuel consumption in the EU in the Commission's reference scenario [54]. For Scenarios 2 and 3, where both wind and solar power are considered, we estimate overall GHG and petroleum displacement impacts for whichever type of renewable electricity generation would support greater volumes of CO_2-based synthetic fuels. These results are presented in Table 4.4 and 4.5 for two subsidy levels: 1.00 € and 1.50 € per litre.

TABLE 4.4: Total potential GHG reduction of CO_2-based synthetic fuels, counted in one sector only (million tonnes CO_2e) (% of total EU GHG emissions in 1990, excluding international aviation and land use, land use change and forestry).

in Year	Subsidy	Scenario 1: Excess Electricity	Scenario 2: Off-Grid Renewables	Scenario 3: Renewable Electricity Contracts	Scenario 4: Grid Average Electricity
2030	1.00 €/L	0	0.2 (0.004%)	0.1 (0.002%)	0
2030	1.50 €/L	0	1.2 (0.021%)	1.0 (0.018%)	0
2040	1.00 €/L	0	0.5 (0.009%)	4.3 (0.076%)	0
2040	1.50 €/L	0	4.8 (0.084%)	16.3 (0.29%)	0

TABLE 4.5: Potential fraction of total EU road fuel consumption that could be displaced by CO_2-based synthetic fuels.

in Year	Subsidy	Scenario 1: Excess Electricity	Scenario 2: Off-Grid Renewables	Scenario 3: Renewable Electricity Contracts	Scenario 4: Grid Average Electricity
2030	1.00 €/L	0%	0.03%	0.02%	0%
2030	1.50 €/L	0%	0.15%	0.15%	0%
2040	1.00 €/L	0%	0.06%	0.65%	0%
2040	1.50 €/L	0%	0.60%	2.46%	0%

Chapter 5

Final Conclusions

In this study, we assessed the potential role for CO_2-based synthetic fuels to contribute to climate mitigation in the EU to 2040. We estimated potential volumes of these fuels that could be realistically produced in the EU under a variety of policy scenarios and subsidy levels. We estimated the lifecycle GHG intensity of these fuels, taking into account both direct production emissions and indirect emissions from the effects CO_2-based synthetic fuel production would have on electricity markets. From our results, we can draw a few key conclusions:

- **Emission reductions from CO_2-based synthetic fuels should be counted in one sector only. There should be no double counting.** Allowing double counting of emission reductions in both the transport and indus- trial sectors (or in both transport fuels and vehicles) results in poor climate outcomes, as the targeted emission reductions are not actually achieved in both sectors. If CO_2-based synthetic fuels are eligible to count towards GHG reduction goals in the industrial sector, these emission reductions will be undermined if the same fuel is allowed to count towards the RED II. Requiring CO_2-based synthetic fuels to be produced from CO_2 using direct air capture, rather than concentrated CO_2 sources such as coal plants, would ensure that double counting between the transport and industrial sectors would not occur, but this would substantially raise the cost of fuel production.

- **If GHG reductions are counted in the industrial sector, synthetic fuels should not be treated as low-carbon fuels within the context of the transport sector or within the context of renewable energy policy.**

- **If emission reductions are counted in the transport sector only, and not in the industrial sector, some pathways to CO_2-based synthetic fuels offer significant GHG benefits compared to petroleum**, in most cases offering GHG savings above the 70% threshold in the Commission's proposal for the RED II. However, compared to the overall climate mitigation challenge, all synthetic fuels offer insignificant benefits. While some stakeholders are pushing for double-counting to be permitted, it should be noted that the GHG savings of the fuel would be eliminated.

- **CO_2-based synthetic fuels are not viable without high policy support.** In all scenarios, significant volumes are only achieved at subsidy levels of 1.00-1.50 € per litre or higher. This is roughly equivalent to 300-500 € per tonne CO_2e and is much greater than most, if not all, biofuel subsidies. Supporting significant roll-out of power-to-liquids is thus expected to require unprecedented levels of policy support in order to reduce the EU's CO_2 emissions by less than 0.2%. It seems likely that

GHG reductions could be achieved in the transport and industry sectors at lower cost through other measures, and policymakers should consider the opportunity-cost of supporting synthetic fuels.

- **Even with very strong policy support, potential volumes of CO_2-based synthetic fuels are limited.** In the most favorable policy scenarios for the economics of power-to-liquids production with 1.50 € per litre subsidies (roughly equivalent to 500 € per tonne CO_2e reduction), around 400 million litres could be produced in 2030. This represents approximately 0.15% of total EU road transport fuel demand in 2030. CO_2-based synthetic fuels are not likely to make a significant contribution to the EU's overall decarbonization goals.

Appendix A

Policy Scenario 2: Country specific production

The following graphs break out production of CO_2-based synthetic fuels by country if powered by three different renewable energy generator configurations: solar-only, wind-only, and a hybrid solar/wind generator.

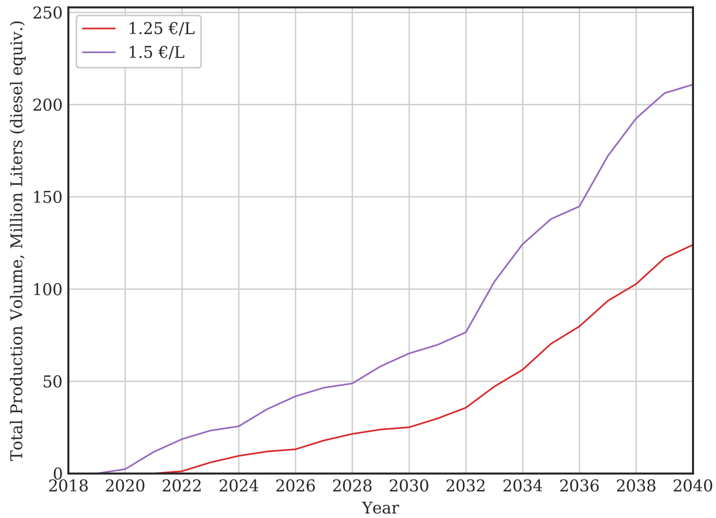

FIGURE A.1: Production of CO_2-based synthetic fuels from **solar-only generation** in **Portugal**.

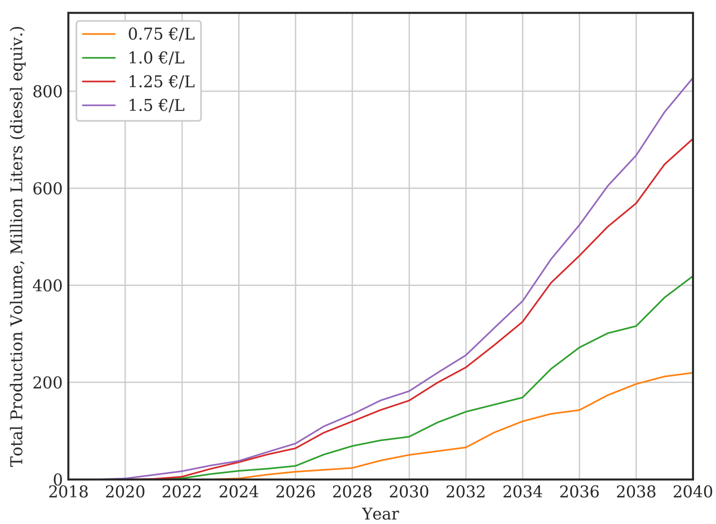

FIGURE A.2: Production of CO_2-based synthetic fuels from **wind-only generation** in **Sweden**.

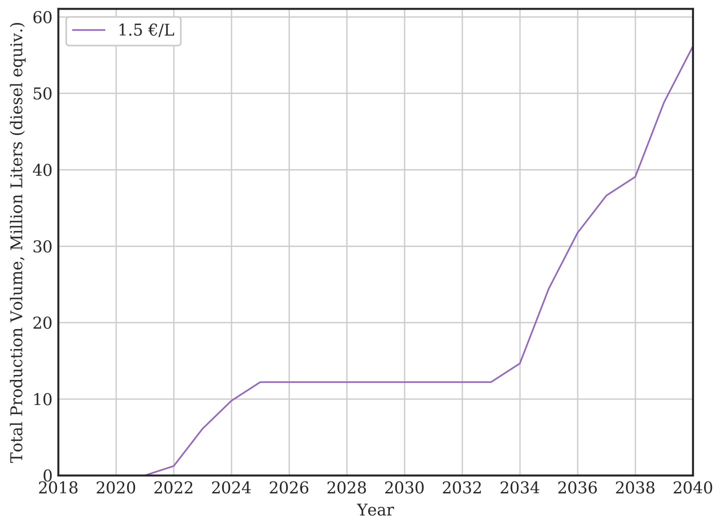

FIGURE A.3: Production of CO_2-based synthetic fuels from **hybrid generation** in **Greece**.

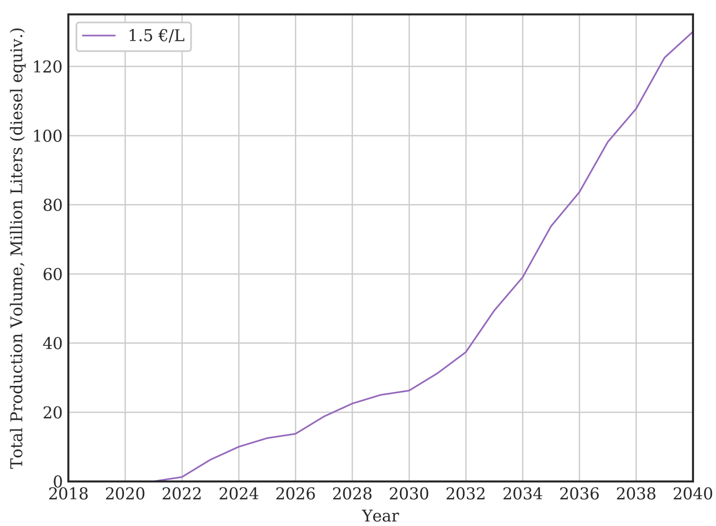

FIGURE A.4: Production of CO_2-based synthetic fuels from **hybrid generation** in **Italy**.

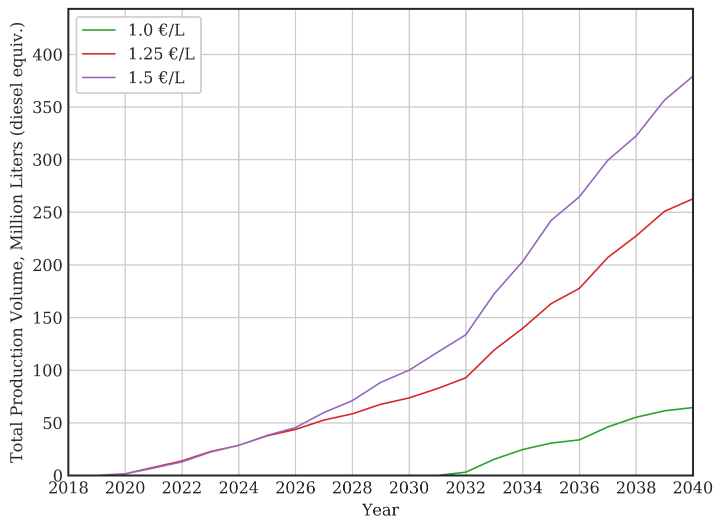

FIGURE A.5: Production of CO_2-based synthetic fuels from **hybrid generation** in **Portugal**.

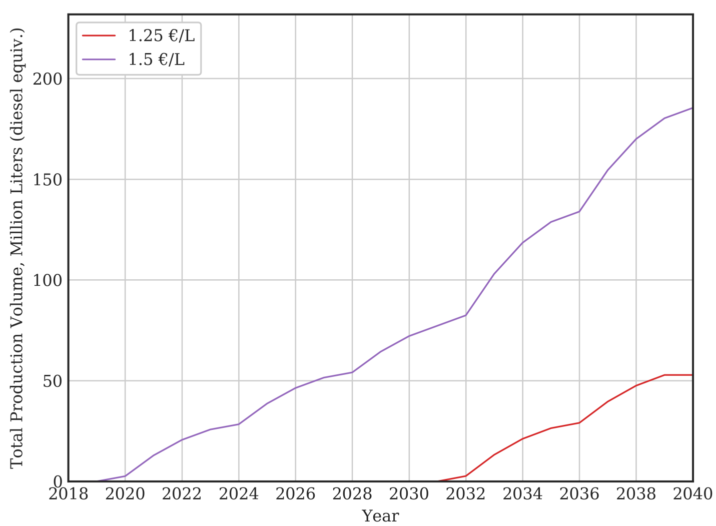

FIGURE A.6: Production of CO_2-based synthetic fuels from **hybrid generation** in **Spain**.

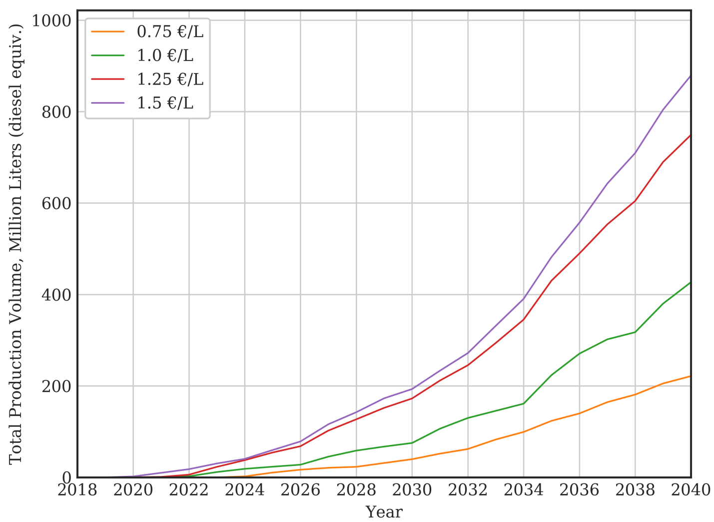

FIGURE A.7: Production of CO_2-based synthetic fuels from **hybrid generation** in **Sweden**.

Appendix B

Policy Scenario 3: Country specific production

The following graphs break out production of CO_2-based synthetic fuels by country if powered by two different renewable energy generator configurations: solar-only and wind-only. In this scenario CO_2-based synthetic fuel producers draw electricity from the grid and thus increase their operation capacity factors compared to plants that are directly connected to off-grid renewable energy generators, however they must hold renewable energy contracts to account for their total energy drawn from the grid. Note that the ramping of production in some countries is slightly slower in a higher subsidy scenario due to assumptions made in the deployment model; maximum production capacity for larger subsidy scenarios is always larger than lower levels of support. Future research is necessary to refine these details.

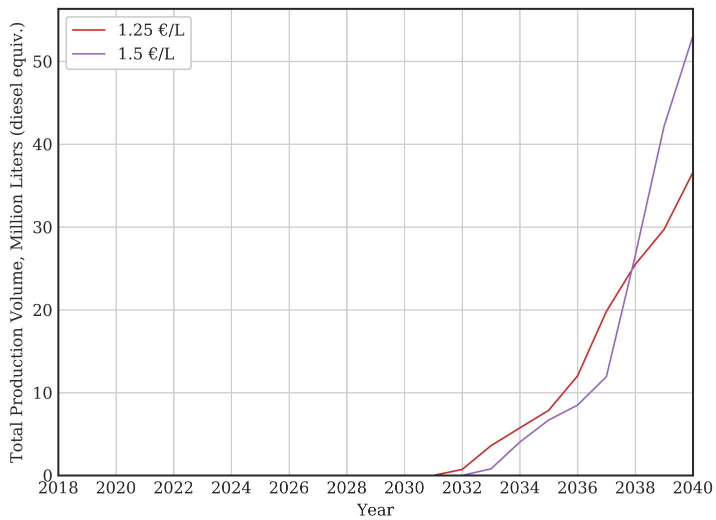

FIGURE B.1: Production of CO_2-based synthetic fuels from **solar generation** in **Austria**.

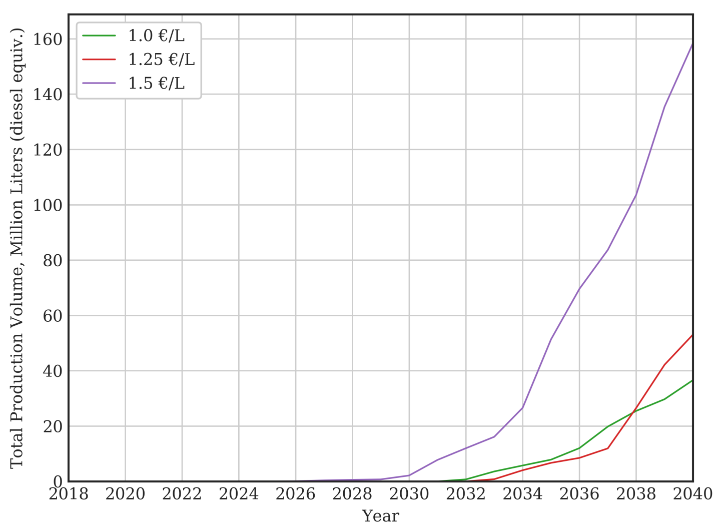

FIGURE B.2: Production of CO_2-based synthetic fuels from **solar generation** in **Belgium**.

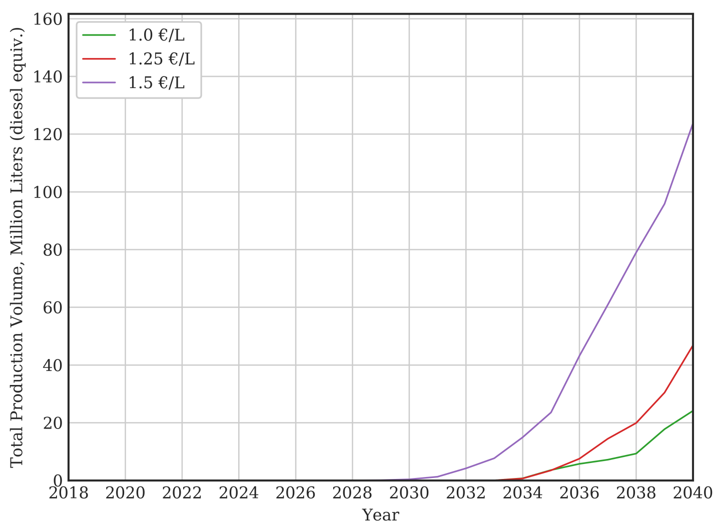

FIGURE B.3: Production of CO_2-based synthetic fuels from **solar generation** in **Bulgaria**.

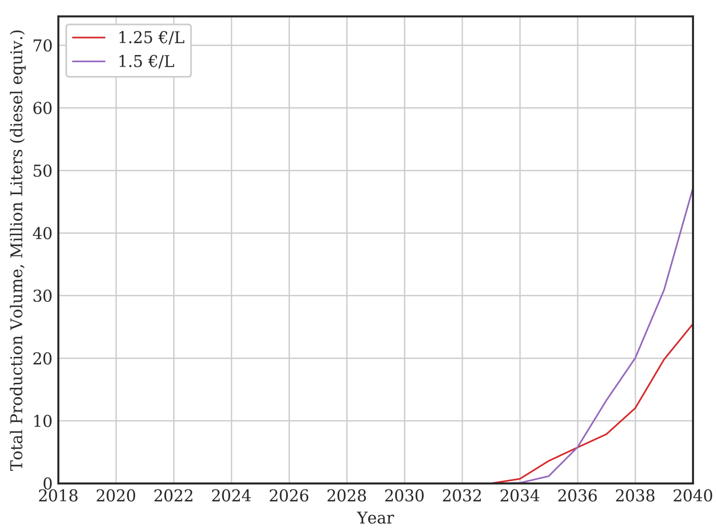

FIGURE B.4: Production of CO_2-based synthetic fuels from **solar generation** in **Cyprus**.

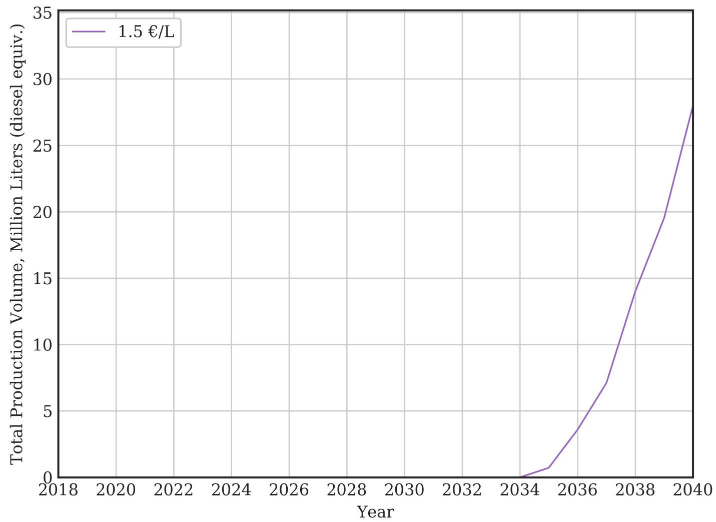

FIGURE B.5: Production of CO_2-based synthetic fuels from **solar generation** in **Czech Republic**.

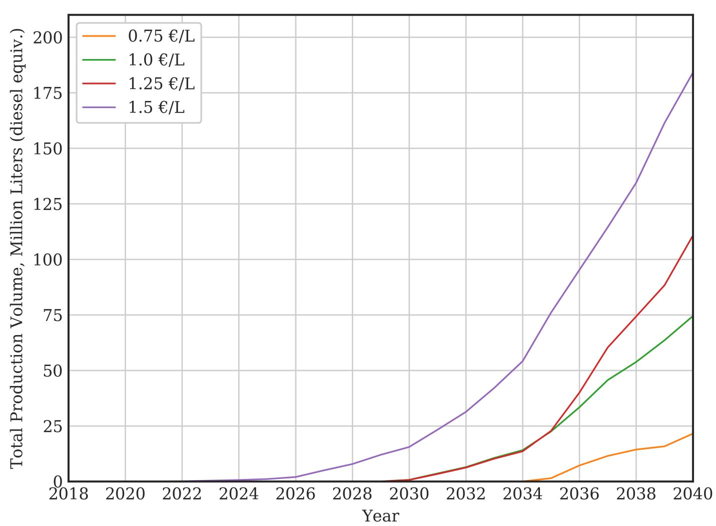

FIGURE B.6: Production of CO_2-based synthetic fuels from **solar generation** in **France**.

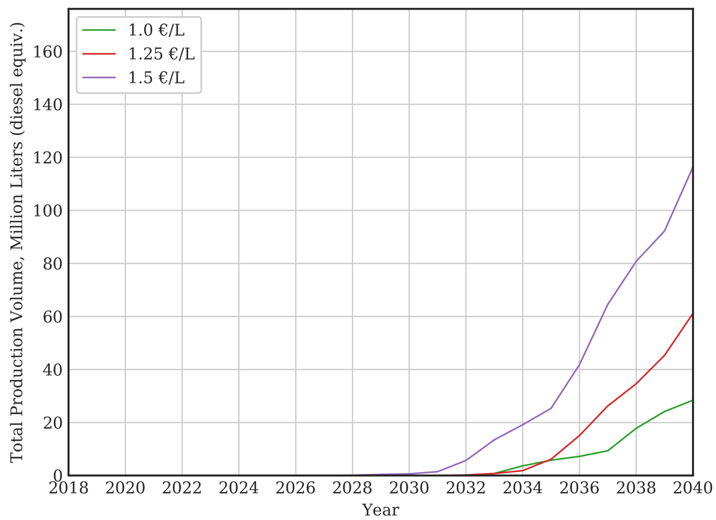

FIGURE B.7: Production of CO_2-based synthetic fuels from **solar generation** in **Greece**.

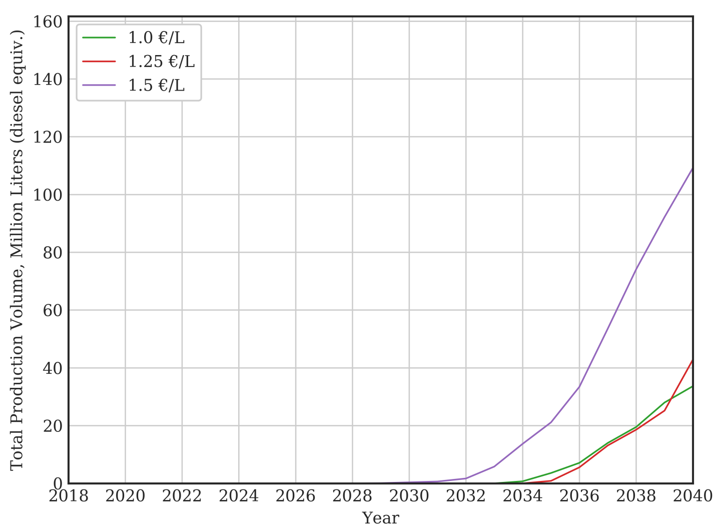

FIGURE B.8: Production of CO_2-based synthetic fuels from **solar generation** in **Hungary**.

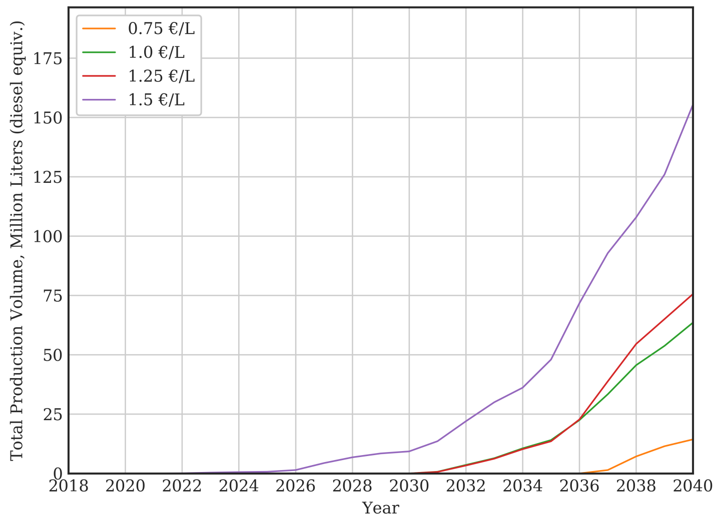

FIGURE B.9: Production of CO_2-based synthetic fuels from **solar generation** in **Italy**.

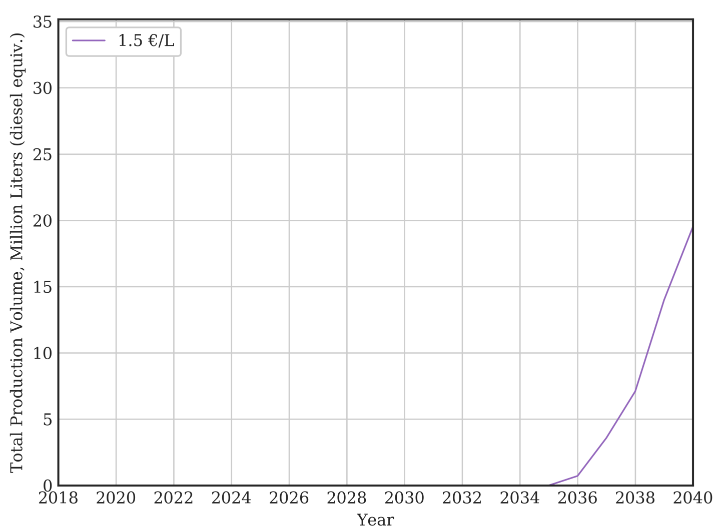

FIGURE B.10: Production of CO_2-based synthetic fuels from **solar generation** in **Luxembourg**.

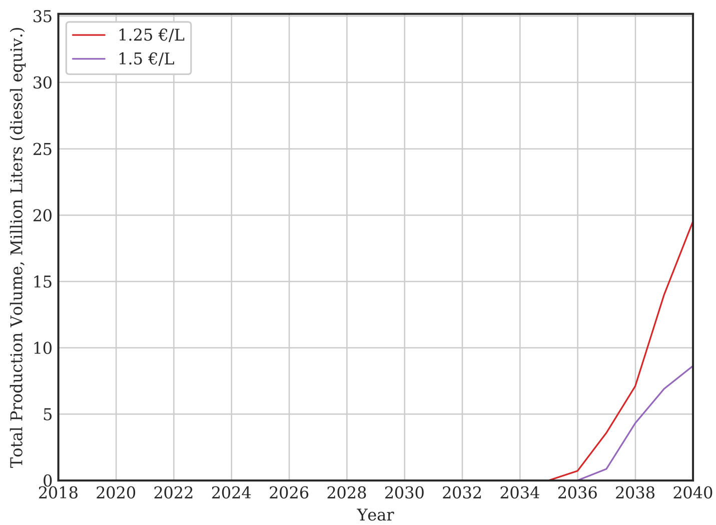

FIGURE B.11: Production of CO_2-based synthetic fuels from **solar generation** in **Malta**.

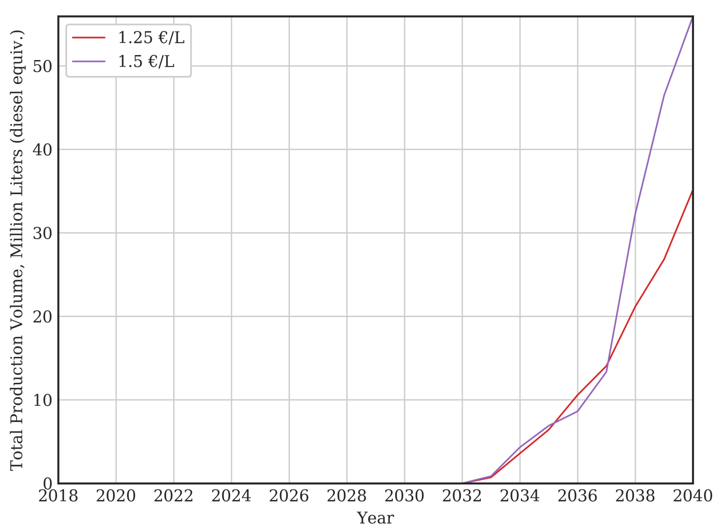

FIGURE B.12: Production of CO_2-based synthetic fuels from **solar generation** in **Poland**.

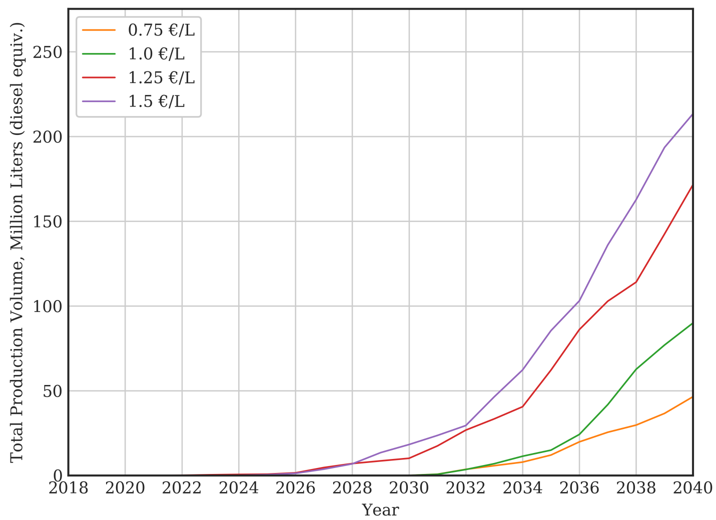

FIGURE B.13: Production of CO_2-based synthetic fuels from **solar generation** in **Portugal**.

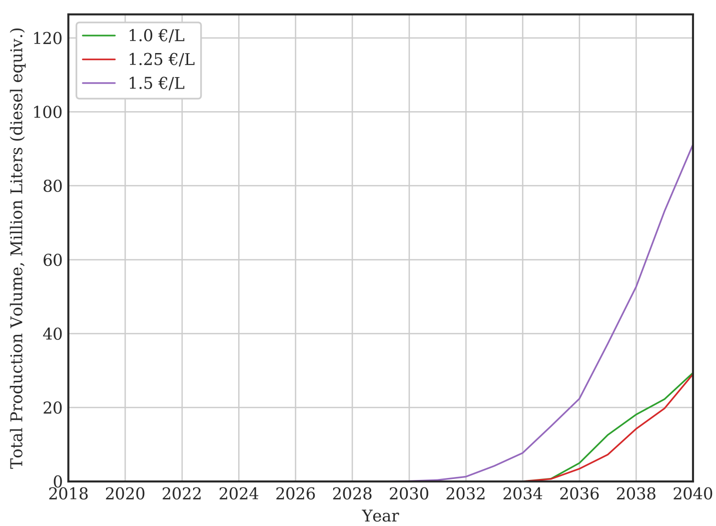

FIGURE B.14: Production of CO_2-based synthetic fuels from **solar generation** in **Romania**.

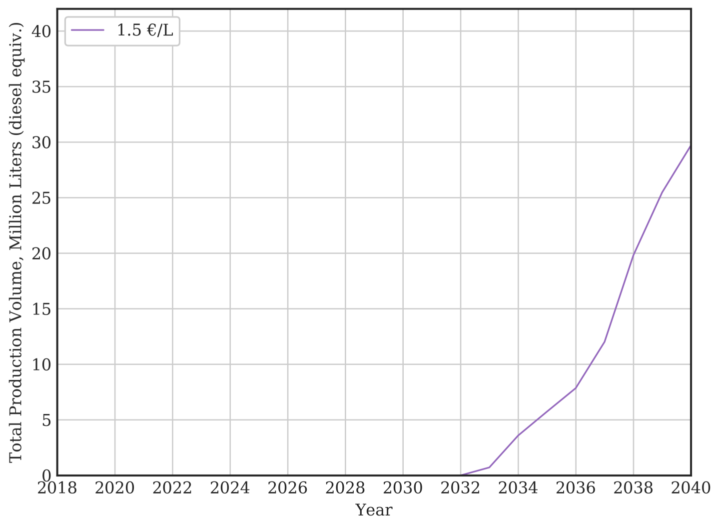

FIGURE B.15: Production of CO_2-based synthetic fuels from **solar generation** in **Slovakia**.

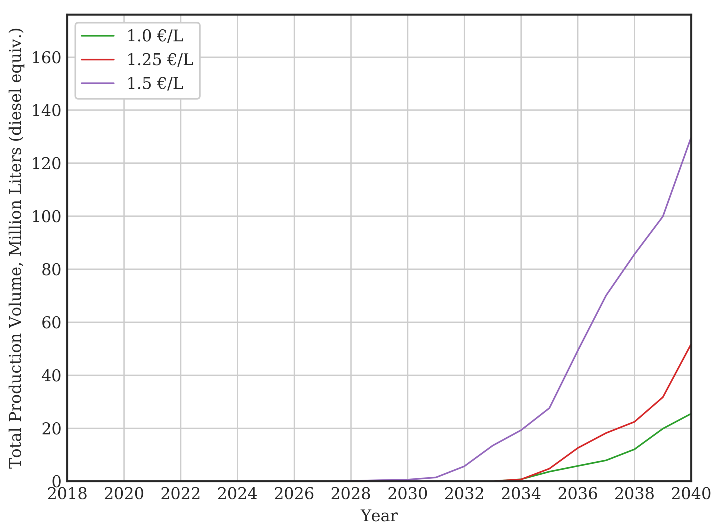

FIGURE B.16: Production of CO_2-based synthetic fuels from **solar generation** in **Slovenia**.

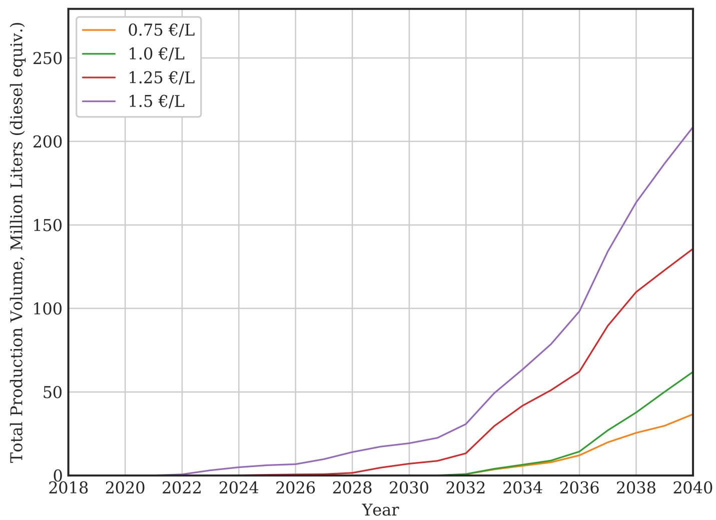

FIGURE B.17: Production of CO_2-based synthetic fuels from **solar generation** in **Spain**.

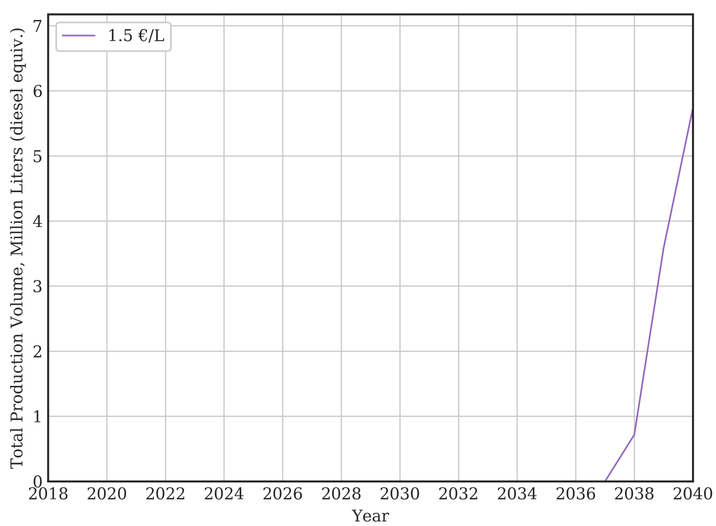

FIGURE B.18: Production of CO_2-based synthetic fuels from **solar generation** in **Sweden**.

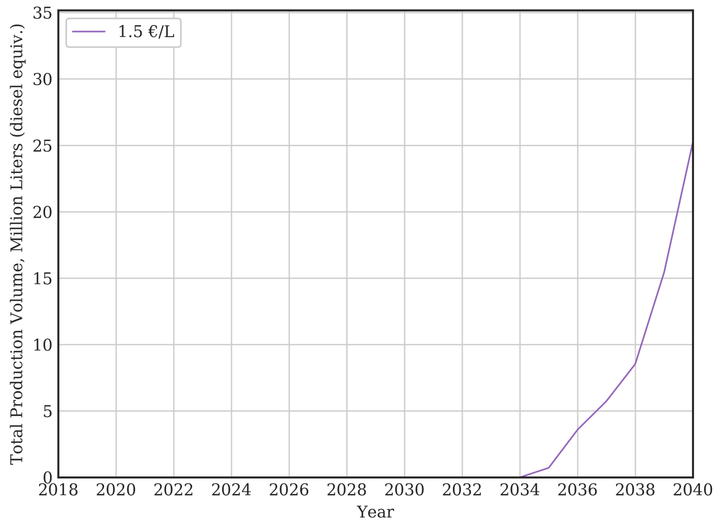

FIGURE B.19: Production of CO_2-based synthetic fuels from **solar generation** in **United Kingdom**.

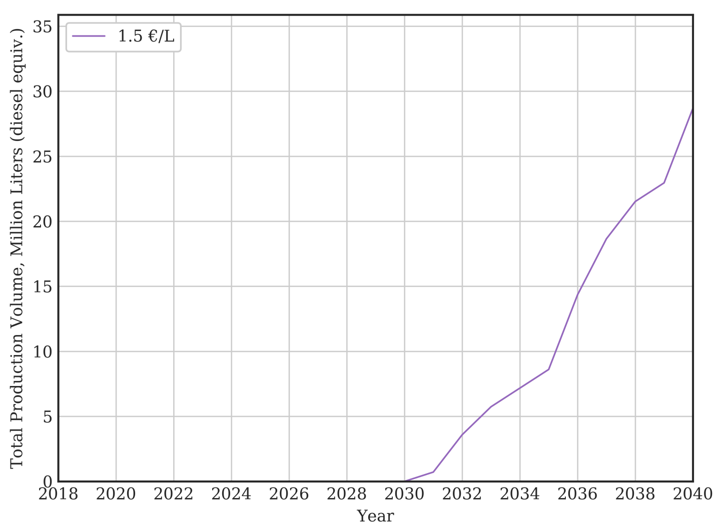

FIGURE B.20: Production of CO_2-based synthetic fuels from **wind generation** in **Finland**.

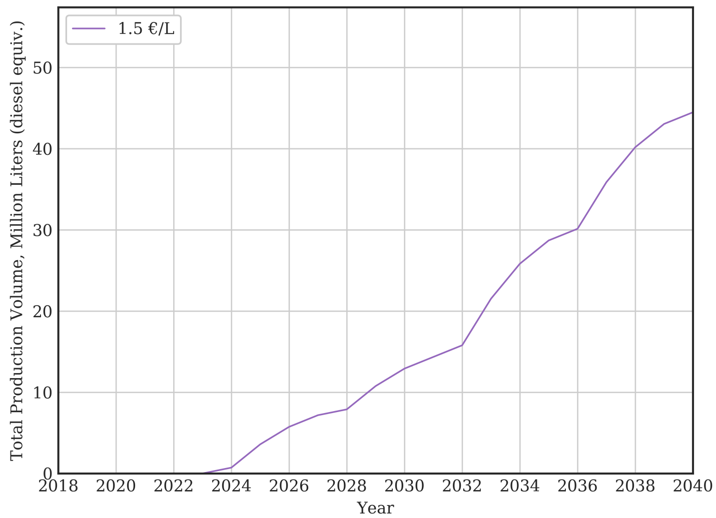

FIGURE B.21: Production of CO_2-based synthetic fuels from **wind generation** in **Italy**.

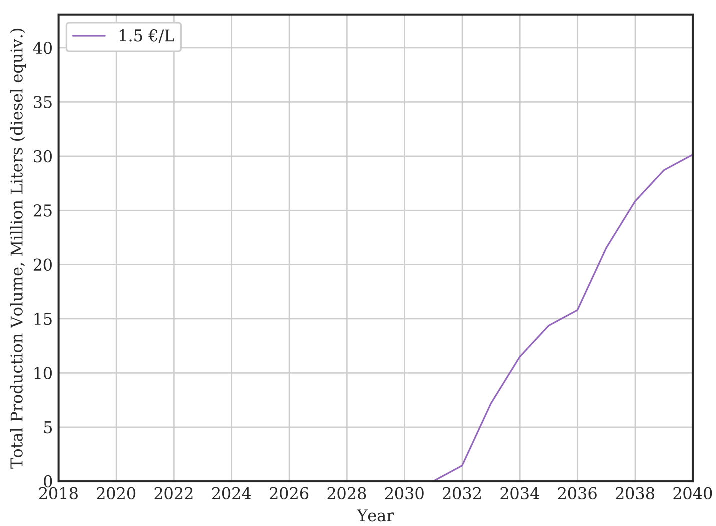

FIGURE B.22: Production of CO_2-based synthetic fuels from **wind generation** in **Netherlands**.

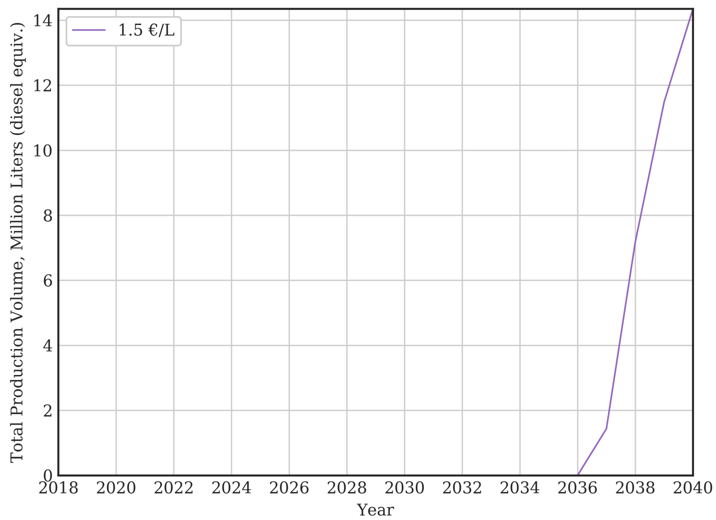

FIGURE B.23: Production of CO_2-based synthetic fuels from **wind generation** in **Poland**.

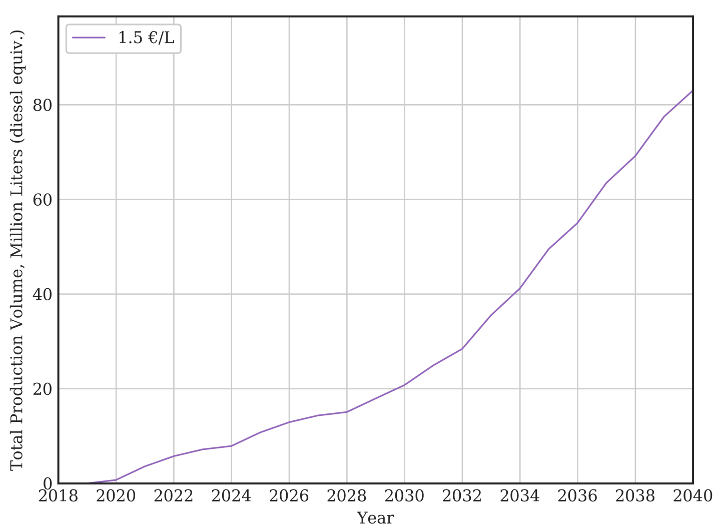

FIGURE B.24: Production of CO_2-based synthetic fuels from **wind generation** in **Finland**.

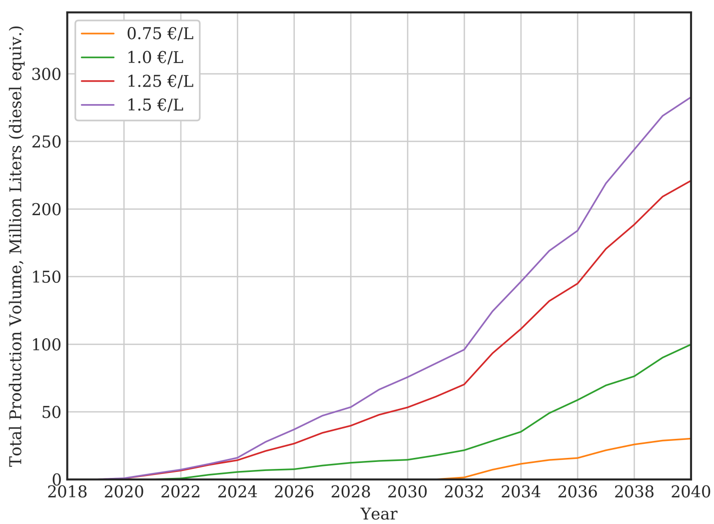

FIGURE B.25: Production of CO_2-based synthetic fuels from **wind generation** in **Sweden**.

Appendix C

Country specific capacity factors (renewable energy generators) used in Policy Scenario 2 & 3

TABLE C.1: Capacity factors for different off-grid renewable generators used in this study [48, 49].

Country	**Solar**	**Wind**	**Hybrid**
Austria	0.22	0.27	0.38
Belgium	0.16	0.12	0.22
Bulgaria	0.24	0.16	0.32
Cyprus	0.18	0.17	0.27
Czech Republic	0.17	0.13	0.23
Denmark	0.14	0.28	0.35
Estonia	0.08	0.2	0.24
Finland	0.06	0.25	0.28
France	0.23	0.22	0.34
Germany	0.15	0.23	0.3
Greece	0.32	0.21	0.42
Hungary	0.24	0.21	0.34
Ireland	0.11	0.17	0.22
Italy	0.25	0.31	0.43
Latvia	0.09	0.15	0.19
Lithuania	0.09	0.17	0.21
Luxembourg	0.15	0.23	0.3
Malta	0.16	0.13	0.23
Netherlands	0.04	0.26	0.28
Poland	0.13	0.25	0.31
Portugal	0.41	0.24	0.53
Romania	0.25	0.19	0.34
Slovakia	0.21	0.16	0.29
Slovenia	0.15	0.27	0.34
Spain	0.33	0.25	0.46
Sweden	0.08	0.69	0.73
UK	0.13	0.18	0.24

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