

Sustainable Aviation Fuel

Production and Use

Edited by Leonard Uchejim Okonye,
Chike George Okoye-Chine, Kabir Opeyemi Otun
and Jianwei Ren

ROYAL SOCIETY
OF CHEMISTRY

Sustainable Aviation Fuel
Production and Use

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Hardback ISBN: 978-1-83767-568-5
EPUB ISBN: 978-1-83767-873-0
PDF ISBN: 978-1-83767-872-3

A catalogue record for this book is available from the British Library

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Dedication

This book is dedicated to our families, mentors, and colleagues, whose support and encouragement make our work possible. It is also dedicated to the global community of researchers, engineers, and policymakers striving to advance sustainable aviation. May this work serve as a contribution toward a future where innovation, collaboration, and responsibility allow flight and sustainability to coexist in harmony, for the benefit of generations to come.

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Foreword

The aviation industry stands at a crossroads. As global air travel continues to increase, the sector faces mounting pressure to reduce its carbon footprint and meet ambitious climate targets. Sustainable aviation fuel (SAF) has emerged as one of the most promising solutions—a transformative innovation capable of shifting aviation from an environmental challenge to a leader in the fight against climate change. However, despite its potential, widespread adoption of SAF faces significant technical, economic, and policy hurdles.

This book, *Sustainable Aviation Fuel: Production and Use*, arrives at a critical moment. It serves as an authoritative and comprehensive resource for academics, industry professionals, policymakers, and stakeholders committed to decarbonizing aviation. Drawing on the latest research, cutting-edge technologies, and practical insights, the authors offer an in-depth exploration of SAF production pathways—from electrochemical synthesis to biomass-to-liquid processes. In addition to production technologies, the book addresses essential factors such as feedstock selection, techno-economic feasibility, environmental impact assessments, and market dynamics.

What sets this work apart is its ability to seamlessly integrate scientific rigor with practical guidance, offering a clear roadmap through the complexities of SAF production and commercialization. Beyond its depth and breadth, this book serves as a clarion call for innovation, collaboration, and the large-scale implementation of sustainable solutions that will shape the future of aviation.

As we navigate through its pages, it becomes clear that achieving sustainability in aviation is not just a technical challenge but a collective responsibility. This book is both a guide and a call to action—urging us to rethink how we power the future of flight and how we balance our desire for global connectivity with our duty to protect the planet.

Professor Diane Hildebrandt

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Preface

The aviation industry is at a critical stage, facing increasing pressure to reduce its environmental impact and lower its carbon footprint. The problem of reducing greenhouse gas emissions is becoming an increasingly urgent one as the number of people flying across the world continues to increase. Sustainable aviation fuel (SAF) has emerged as a possible approach to solve this dilemma by providing a realistic road to considerably cut emissions while preserving operating efficiency. This is a solution that has emerged as a serious possibility.

A complete investigation of the technology used for the manufacture of sustainable aviation fuel (SAF), the selection of feedstock, and the significant obstacles and possibilities involved in the commercialization of SAF are presented in this book, which is titled "*Sustainable Aviation Fuel: Production and Use*". It highlights how SAF can contribute to a more sustainable future for aviation by incorporating the latest research and technological advancements in the air transportation sector. In this book, the difficulties and possibilities of SAF production and commercialization are also discussed, highlighting the significance of sustainability, environmental concerns, and stakeholder cooperation. Additionally, this book explores the complex regulatory frameworks, market perspectives, and life cycle assessments that are essential for the successful adoption and integration of SAF.

The motivation for writing this book stems from the urgent need to accelerate the transition to environmentally friendly energy solutions in the aviation industry since aviation has a big impact on both air pollution and greenhouse gas emissions. As academics and professionals dedicated to developing and advancing clean energy technologies, we recognize the significant changes needed in the aviation fuel landscape. This transformation calls for collaboration, creativity, and the exchange of knowledge.

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This book aims to promote knowledge sharing, stimulate innovation, and contribute to the transformation of the aviation industry into one that is greener and more sustainable. Academics, business leaders, legislators, and interested parties dedicated to increasing SAF output and making aviation more sustainable can find great value in this book.

We would like to express our heartfelt gratitude to colleagues and collaborators who have generously shared their insights and expertise in this volume.

Leonard Uchejim Okonye
Chike George Okoye-Chine
Kabir Opeyemi Otun
Jianwei Ren

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CHAPTER 13

Life Cycle Assessment (LCA) of Sustainable Aviation Fuel

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13.1 Introduction

The aviation sector currently contributes around 2.5% (4% including non-CO_2 impacts) of global energy related emissions and has developed at a faster rate compared with rail, road or shipping.[1–3] In 2022, the aviation industry produced over 800 Mt CO_2 (80% of emissions are pre-pandemic).[4] Currently, improvements in energy efficiency have unfortunately not been enough to counter sustained growth in this sector. Sustainable aviation fuel (SAF) pathways provide different results in terms of their environmental footprint depending upon the feedstocks and production processes involved. Life Cycle Assessment (LCA) is the primary tool for assessing the carbon footprint of SAF pathways throughout the supply chain, with the aim of making SAF pathways completely transparent.[5]

The full traditional LCA of SAF pathways are often referred to by studies in the aviation sector as "Well-to-Wake (WtWa)". A significant number of

Sustainable Aviation Fuel: Production and Use
Edited by Leonard Uchejim Okonye, Chike George Okoye-Chine, Kabir Opeyemi Otun and Jianwei Ren
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Published by the Royal Society of Chemistry, www.rsc.org

pathways discussed in the earlier chapters are all affected by their supply chains. LCA studies within the SAF literature feature contrasting configurations which need to be uncovered and thus the purpose of this chapter is to provide a thorough review of the SAF literature for the purposes of interpretation – the most important phase of the LCA. Allocation approaches which still represent one of the most controversial phases of the LCA can cause confusion when assessing the performance of SAF co-products.[6–9]

Provided that LCA is performed according to recommended guidance and standards are followed, LCA will be able to deliver a high level of SAF benchmarking throughout the different pathways and feedstocks. Greenhouse gas (GHG) emissions can be estimated across the full SAF life cycle. The purpose of this chapter is therefore to understand how LCA is configured for all SAF pathways available as well as the potential integration with other forms of industry such as CO_2 utilization and carbon removal. Certain types of technologies applied to SAF that are claiming to be carbon neutral or net zero may not necessarily be sustainable, particularly when comparing against their total emissions footprint. LCA as a tool has been a very useful method for comparing the performance of SAFs against other similar pathways and other fuel products that are produced during the whole process. As well as simply exploring global warming potentials normalized to CO_2, it is also important to explore the impact of other environmental midpoint impact categories that take a wider look at the impact of SAF fuels upon the environment. Such categories can include acidification, ozone depletion and eutrophication. By taking other categories into account, it is possible to identify major environmental impacts beyond the traditional global warming lens as well as different spheres. Relative differences when adjusting the system boundary or even updated emission factors may allow for new perspectives and deeper investigations although these environmental categories are rarely used in the overall SAF literature.

A variety of different methodological issues are present within the SAF literature and consist of a series of common themes. These may include data availability and quality, functional unit definition as well as spatial and temporal availability.[10–12] A variety of different types of LCA have been applied where some have included economic assessments that have been carried out using market allocation for example. This was conducted using various types of marginal data through attributional or consequential LCA. Social and economic factors also exist when concerning the production of SAF. See Chapter 15 for a review of techno-economic literature applied to SAF fuels.

System boundaries are also important when carrying out an LCA of SAF fuels.[13] For the majority of the LCA studies that have been carried out across disciplines, it is widely accepted that there are four specific types of system boundary. These system boundaries (see Figure 13.1) consist of Well-to-Wake (WtWa), Well-to-Pump (WtP), Well-to-Gate (WtG) and Gate-to-Gate (GtG).[5]

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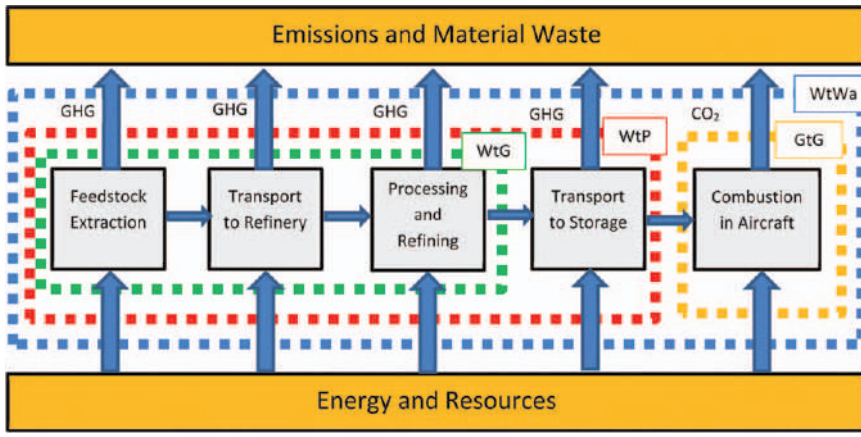


Figure 13.1 Typical system boundaries for LCA of SAF showing different stages of the life cycle. Reproduced from ref. 13, https://doi.org/10.1039/C9SE00788A, under the terms of the CC BY 3.0 license, http://creativecommons.org/licenses/by/3.0/.

A great deal of uncertainty arises when comparing different variations of the four system boundaries compared with the rest of the literature. Throughout the definition of the system boundary, the allocation methods are performed depending upon the definition of the functional unit. Allocation is necessary to ensure that co-products are clearly separated and assessed depending on either displacement/system expansion, economic, energy and mass. There are significant challenges in assessing the performance of SAF fuels during the operational/combustion phase mainly due to the wide variation in different types of aircraft, flight paths covered, and total distances accumulated. These types of studies are covered elsewhere within the literature.[14–18]

This chapter aims to provide an all-round perspective of the LCA literature that is dedicated to SAF and is therefore non-exhaustive, covering only significant studies within the SAF community so that major advances can be highlighted. Variations in the key LCA types, as well as feedstocks, process pathways and uncertainty associated with LCA are discussed.[19–29] Identification of emission hotspots relating to SAF production is critically highlighted within the discussions.

Section 13.2 looks at the inventory analysis phase of SAF including the types of data to be collected, some information on the types of software available for conducting such studies including but not limited to algorithms and databases. Section 13.3 explores some significant results from the LCA pathways. Comparing traditional forms of jet fuel as a baseline (Jet A1), this is compared across the literature and crucially, highlighting potential scaling issues and availability. Section 13.4 provides some summative conclusions on the current state of the art, and how the field will look in the short to long term. Future work to be addressed is also discussed.

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13.2 Data Requirements, Tools and Useful Resources

Data collection is very important for SAF studies depending upon the LCA configuration that is being deployed. LCA configurations for SAF studies can for example be grouped into two key configurations: Attributional and Consequential.[7,30,31] While attributional allows for assessing the performance of pathways from a historical perspective, consequential allows for exploratory counterfactual analysis against the baselines that were estimated using the former. Also, attributional approaches are fixated on the system boundary and cannot assess the indirect impacts that are commonly associated with SAF fuels. Only direct impacts based upon the input (raw materials) and output (combustion of the jet fuel) are included. Consequential has the capacity to include not just the direct impacts of SAF fuels but can also consider indirect cause and effect feedback loops of the fuel production system. System dynamic modelling is important for consequential LCA assessment and its decision making process, with many tools allowing the observer to see a visual representation of the cause and effect feedback loops that determine how the LCA is calculated over time, often based on a simplification of the real production system.[32–35]

For SAF, functional units play a prominent role like all other LCA studies.[36] In these scenarios, the FU provides specific normalization metrics for the liquid SAF fuel products focusing on the functions of the product compared with the physical mass allocation approach. Liquid fuel is usually normalized on an energy based allocation approach in the form of embodied Megajoules (MJ) or Gigajoules (GJ) in the form of $g\,CO_2e$ per MJ^{-1} and $kg\,CO_2e$ per GJ^{-1} respectively.[37,38] For liquid fuel products the FU must be able to compare different product categories without bias, allocation once again is dependent on whether an attributional or consequential LCA approach is being applied. Allocation is based upon a specified fixed timeframe while consequential decision making is based upon the scale of consequence of the counterfactual. One important issue with SAF and a continuing parallel issue with the LCA methodology in general is that linear attributional studies do not consider time and as such this will cause considerable confusion due to the fact that technological advancements and innovations will slowly improve the efficiency of the product over time. Emission timing should therefore be taken into account so that results can provide greater clarity as to what happens to the product over reasonable durations due to improvements in the product system.[12,39] As one example new emerging technologies provide more stability and are more energy efficient which will ultimately have an impact on the LCA results. Such time horizons should not only equal the project lifespan but should also deploy multiple counterfactual analysis that shows how such improvements can change over time.[12] Currently, no methods provide the appropriate value selection, and RFS2 analysis in terms of land use emissions would traditionally set the fuel production lifespan to around 30 years with an appropriate yield being

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retained. Global Warming Potentials (GWP) traditionally provide assessment periods of over 100 years; however, these may not be accurate approaches depending upon the assessment. Assessments of GWP over 20 years for SAF may be preferable due to more than one type of emission being released post-combustion from the wake of the aircraft. Other impact assessment categories besides GWP are important for truly assessing the environmental component of the SAF life cycle, particularly the burden of cost. The reality is that SAF projects could either fail quickly, freeing up land (if using biomass) for other applications such as bioenergy with carbon capture and storage (BECCS)[40] or such land will be used for multiple purposes, including SAF. Land sequestration through CO_2 removal addresses other challenges as well. One specific approach was introduced in terms of a time shock rather than spreading environmental burdens equally across the time boundary. Consequential approaches appear to offer a more detailed understanding of these one off events.[41,42]

In terms of process efficiency, a variety of different pathways are dependent on the type of technology that is currently being utilized. The emissions depend on the process efficiency of the SAF pathway which is determined by the type of technology being used compared with the production of fuel. In addition, it is the refinery itself which exhibits its own efficiency that is considered a priority in most of the studies that are available. Allocation methods are also important and form a controversial part of the LCA methodology, particularly when SAFs are involved. The four most popular approaches described by the literature are (1) mass allocation, (2) energy allocation, (3) economic allocation and (4) displacement which can also be referred to as either system expansion or substitution.[43] The latter methods are heavily involved in consequential LCA as they deal with the creation of different counterfactual scenarios that offer an alternative to the SAF baseline, which is the conventional Jet-A1 pathway provided by crude oil.[37,44] By using only one of the allocation methods that are described here, the results of the SAF LCA will become drastically different due to the fact that emissions are allocated differently depending upon the frame of reference, be it mass, energy monetary *etc.*

Energy allocation for instance, focuses on the energy content of the feedstock and is most suitable for comparing different fuel types.[45–47] A requirement of the EU renewable energy directive is to perform energy allocation and is ultimately easy to apply, and possibly the most relevant method to carry out upon assessing the performance of SAF technologies mainly due to the largely contrasting nature of feedstocks. The lower heating value (LHV) tends to be used particularly in terms of pre-production in the EU and North America prefers to use the higher heating value (HHV). HHV includes additional products within the process including water vaporization heat in terms of post-production to assess the overall energy content. Due to the fact that the fuel is used primarily to provide energy, deploying this energy allocation method appears to be the most logical choice in such cases.

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Mass allocation in terms of SAF although easy to perform in a conventional sense, would not be appropriate in most cases when assessing the energy. This allocation method appears to be at its strongest when assessing a small amount of product that is produced as a byproduct of the SAF fuel fraction.[44] In the case that such a co-product substitute cannot be found the fourth allocation method should be applied.[37] Indeed, it would be rare to use such a method in order to assess liquid fuel products unless there is some form of displacement analysis that is carried out from the perspective of a mass-based allocation approach.

Market based allocation approaches differ from mass and energy allocation in that they can operate from the standpoint of linear and non-linear assessments. For example, parameters that affect the production of SAF fuel may not consist of linear data but could in fact also comprise non-linear data which can be projected forward through time.[38,48] In this approach, market dynamics influence the production of SAF fuel and its co-products resulting in emissions that are distributed according to the fuel selling price.[49] As demand from SAF fuel production increases over time *via* demand, the price and ultimately emission factors of the fuel will also increase. As supply increases steadily to compensate for demand, the co-products of the SAF production process will fall which will result in the main SAF product being allocated higher emissions. Ultimately, the SAF alternative to kerosene overall provides the necessary driving force of the SAF pathway and the emissions that the market based allocation method applies.[50] The reality of the situation is market dynamics are unstable and it can be quite challenging to accurately predict and this approach exhibits the highest levels of uncertainty, therefore a large degree of uncertainty analysis and scenario exploration is required to determine acceptable levels of accuracy in allocating emissions to the SAF process in relation to the price of oil.[51–53]

Displacement/system expansion approaches entail assessing the potential co-products for opportunities and is a requirement of the U.S. renewable fuel standard.[54] It is one of the most preferred choices in terms of assessing the sustainability of SAF fuels as the feedstocks that are under scrutiny. The co-products that are codeveloped alongside the SAF fuel is compared with the baseline of conventional aviation and then discounted to the appropriate fuel product. In order words, it's a form of credit which can be used to acknowledge the fact that other fuel products that are being produced can end up being more sustainable when grouped together. One example for this kind of approach is if CO_2 is being used to produce chemical products, the emissions that would have been released would offset by the amount of CO_2 that is used in the SAF production process. Essentially, this is a form of offsetting. Carrying out this approach can be troublesome, as there may be issues in using a suitable displaced product to perform the discounting. The total impact of the emissions needs to be assessed and finally, the appropriate displacement ratio must be applied.[55] Assessing the counterfactual in terms of land use can also be problematic, as there is usually a reasonable lack of clarity of how land use emissions impact the system, based upon the

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type of SAF biomass feedstocks being used. This is particularly the case when comparing 1st generation biomass with 2nd generation. Ultimately, product allocations do not have a singular correct approach, and care must be taken to produce a comparative analysis of more than one allocation so that they results can be included within the sensitivity analysis. This is of course dependent on the SAF fuel and production pathway in question. SAF feedstocks should be assessed individually. There is an ongoing dialogue between academics and industry in terms of how to provide key guidance when carrying out the displacement approaches for SAF.[13,56]

13.3 Selected LCA Pathways

13.3.1 Waste Biomass Pathways

Biomass sequesters CO_2 from the atmosphere and utilizing it as feedstock can significantly reduce carbon emissions arising from aviation fuel. Biomass feedstocks can be classified as either 1st generation, 2nd generation or 3rd generation. 1st generation feedstocks are derived from edible food crops and vegetable oils. Contentious issues relating to land use change (LUC) and feedstock availability due to competition with food production pose a limitation to their use for SAF production. 2nd generation feedstocks are derived from non-food crops and can be classified as oil-based (*e.g.* camelina, jatropha, used cooking oil), lignocellulosic (*e.g.* miscanthus, switchgrass, corn stover, forest residues) or waste materials such as municipal solid waste. 3rd generation feedstocks consist of algae/microalgae. They require minimal land use, exhibit exceptional capacity to absorb carbon, thrive in diverse environments (*e.g.* wastewater, open ponds), and offer potentially high yields due to faster growth rates. Biomass derived fuels are estimated to cut GHG emissions by about 80% compared to conventional jet fuel.[5,57]

The GHG emissions from biomass based SAF is dependent on certain factors such as choice of feedstock, type of conversion process/technology, material and emission from energy inputs during farming operations, variation in LCA procedure including scope and system boundary, allocation methods for co-products and life cycle impact assessment (LCIA) methods. The geographical origin of the data used for the analysis and the inclusion/exclusion of land use change (LUC) can also have a profound impact on the LCA results. Algal- and oil-based feedstocks are typically processed through HEFA/HRJ and HTL pathways while lignocellulosic biomass can be used to produce SAF *via* FT synthesis, hydroprocessed depolymerized cellulosic jet (HDCJ) or lignin-to-jet (LTJ). Bio-based jet fuel can also be produced *via* STJ and APR pathways.

A comprehensive WtWa LCA of SAF produced from 2nd generation feedstocks covers (i) feedstock/crop cultivation, (ii) pre-processing/pre-treatment and transportation, (iii) feedstock conversion, (iv) bio jet fuel transportation, and (v) bio-jet-fuel use/combustion. The following section analyses LCA studies for 2nd generation feedstock through different pathways and how

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variation in the processes as well as the LCA methodology contribute towards emissions. The integration of models such as the Greenhous Gases Regulated Emissions, and Energy Use in Transportation (GREET) into the LCA framework also helps in evaluating sustainability of the technology.

Li & Mupondwa[58] performed a WtWa LCA of Camelina oil using the HRJ pathway encompassing cultivation of camelina plant, oil extraction, conversion to SAF, and the final step of fuel use/combustion in aircrafts (as shown in Figure 13.2). The input raw materials to the fuel conversion step include processed camelina oil, hydrogen, natural gas, steam, cooling water and electricity. The overall GHG emissions from HRJ pathway falls between 3.06–31.01 g CO_2 eq per MJ with seed yield greatly influencing LCA results and contributing about 28–46% when high yield seeds are used. This denotes a decrease of 65–96% GHG emissions in comparison to conventional jet fuel.

Similar to the study by Li & Mupondwa which used system expansion, the LCA studies by Shonnard *et al.*[59] applied energy allocation to the HEFA/HRJ pathway with a resultant GHG impact of 22.36 g CO_2 eq per MJ. The largest contributor to GHG emissions is the feedstock production while the smallest contributor is feedstock transportation with emissions arising from rail transport. A scenario analysis using mass and displacement allocation further reduces this to 20.18 and −17.08 g CO_2 eq per MJ respectively. The resultant low and negative values are due to the attribution of more emissions to co-products and the use of less GHG intensive fuels to satisfy the energy needs of the process.

The LCA study of Jatropha for producing SAF conducted by Bailis & Baka[60] indicates a decrease of about 55% (40 g CO_2 eq per MJ) compared to conventional jet fuel production emissions for a 20 year lifetime without direct land use change. A sensitivity analysis of seed yield shows a relatively small variation in GHG emissions between 42 and 39 g CO_2 eq per MJ for lower yield and higher yield respectively while a lifetime of 30 years reduces the net GHG emissions to 37 g CO_2 eq per MJ. Implementing mass allocation to account for co-products further reduces this to 33 g CO_2 eq per MJ.

For the HEFA pathway, the life cycle GHG emissions from the production of bio-jet- fuel from used cooking oil (yellow grease) is dominated by the fuel conversion process according to a study by Seber *et al.*[61] Using an energy-based allocation method, the low, baseline and high emissions were reported to be 16.8, 19.4 and 21.4 g CO_2 eq per MJ respectively. A comparison with conventional jet fuel as a benchmark indicates a decrease in climate change impact of about 78% for the baseline scenario.

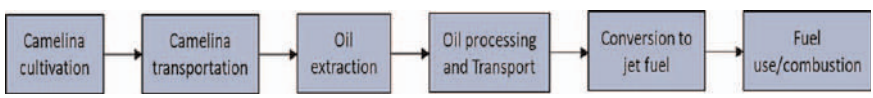


Figure 13.2 Process flow diagram for Camelina HRJ production. Reproduced from ref. 58 with permission from the Royal Society of Chemistry.

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The conversion of syngas to SAF *via* gasification/FT synthesis offers great potential for emissions reduction in the aviation sector. The feedstock undergoes processing 5 stages to produce SAF as shown in Figure 13.3.[62]

Using lignocellulosic biomass yields very low GHG emissions particularly during the feedstock cultivation and harvest.[63] Also excess steam from FT synthesis can be used to generate electricity and thus reduces the energy penalty of the process. Emissions arise from fertilizer use during biomass cultivation with noticeable variation in results obtained for different allocation methods. For instance, in the analysis by de Jong *et al.*[64] the biomass FT pathway shows remarkably low GHG intensity of 9, 10, 13 and 6 g CO_2 eq per MJ for willow, poplar, corn stover and forest residues respectively when energy allocation is implemented. For the same types of biomass, the GHG intensity reduces to −7, −6, −3 and −10 g CO_2 eq per MJ when co-product allocation is handled using the displacement method. For forest residue, Almena *et al.*[65] integrated carbon capture and storage with FT synthesis in their analysis leading to a further reduction of the GHG emissions to −20 g CO_2 eq per MJ.

The production of drop-in fuels from 2nd generation biomass through advanced fermentation (AF) faces some technical challenges including variation in composition of feedstock, feedstock quality and efficiency of the AF process, all of which affect the LCA approach. In addition, Staples *et al.*[66] also noted that the pre-treatment technology, utility requirements, allocation method, conversion efficiency, and post-processing requirements results in variation in the GHG intensity. Another key factor to consider for the AF pathway is emissions associated with direct LUC, which could increase the GHG footprint of the process. For instance, the analyses by Staples *et al.*[66] shows that the GHG footprint without and with LUC emissions are 37.4 and 40.3 g CO_2 eq per MJ respectively for switchgrass feedstock.

Sugar-to-jet (STJ) fuel can be produced *via* biological or catalytic conversion with both routes involving pre-treatment and enzymatic hydrolysis of feedstocks followed by further processing to jet fuel.[67] From a WtWa perspective, the LCA of the STJ pathway using 2nd generation biomass includes

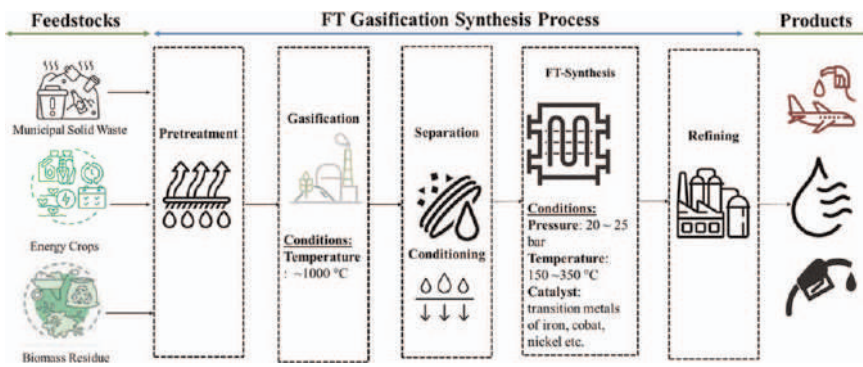


Figure 13.3 Gasification/FT process for producing SAF. Reproduced from ref. 62 with permission from the Royal Society of Chemistry.

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feedstock cultivation and collection, feedstock transport, STJ fuel production, transportation and use/combustion. The GHG intensity of the catalytic conversion process is highly influenced by the source of hydrogen for catalytic upgrading while biological conversion is impacted by the amount of CO_2 absorbed by the biomass feedstock. This is evident in the WtWa study by Han *et al.*[68] for corn stover feedstock. Their analysis illustrates that using hydrogen from biomass gasification and steam methane reforming (SMR) result in overall GHG emissions of 24.6 and 61.3 g CO_2 eq per MJ respectively. When biological conversion is applied, this was estimated to be 35 g CO_2 eq per MJ with CO_2 emissions arising from combustion of fossil fuels, particularly natural gas contributing the largest share of emissions.

For the ATJ pathway, biomass feedstock can be converted into SAF through biochemical or thermochemical processes using ethanol or isobutanol as intermediates. SAF derived from alcohol undergoes the conversion process of dehydration, oligomerization, and hydrogenation as shown in Figure 13.4.[62]

The efficiency of the conversion process is a key consideration in assessing the LCA of the ATJ pathway. Prior to conversion, the biomass feedstock is pre-treated by steam explosion or enzymatic hydrolysis to enhance the conversion efficiency.[69] The GHG emissions vary depending on the feedstock choice, alcohol intermediate and conversion process with most LCA studies focusing on the ethanol route due to advanced technological maturity of ethanol production and feedstock availability. Noticeable variations are also observed for the allocation method applied in the LCA. For instance, using corn stover as the feedstock, Han *et al.*[68] estimates the WtWa GHG emissions for ethanol-to-jet production *via* biochemical conversion to be 23 g CO_2 eq per MJ when energy allocation is applied. On the other hand, using mass allocation, Pierobon *et al.*[70] estimates GHG intensity of 29.6 g CO_2 eq per MJ for residual woody biomass as feedstock while system expansion yields 34 g CO_2 eq per MJ. This further emphasizes the role of the allocation method used in LCA.

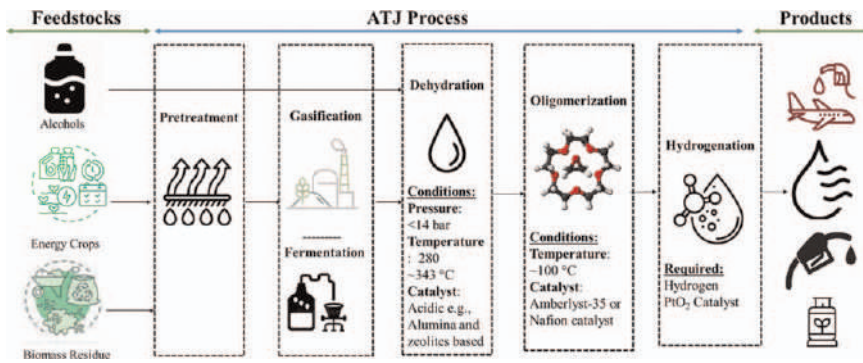


Figure 13.4 Alcohol-to-jet pathway for SAF. Reproduced from ref. 62 with permission from the Royal Society of Chemistry.

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13.3.2 Third Generation Biomass

SAFs derived from third-generation biomass feedstocks, particularly algae and microalgae, are emerging as viable alternatives to conventional fossil fuels. These biofuels offer distinct advantages, such as reduced competition with food resources and lower land use requirements, making them appealing in the context of a global push for sustainability.[71] However, a comprehensive understanding of their environmental impacts is essential for evaluating their potential role in a decarbonized aviation sector. This section examines the current landscape of LCA studies related to third-generation biomass feedstocks, focusing on their methodologies, findings, pathways, and implications for the sustainability of SAF. Third-generation biomass feedstocks primarily encompass microalgae, which can be cultivated in different systems, such as closed photobioreactors, open ponds, and even integrated systems that utilize wastewater. Microalgae are characterized by their rapid growth rates and high lipid contents, which can be converted into biofuels. Unlike first- and second-generation biofuels, which rely on food crops or agricultural residues, third-generation biofuels have the potential to mitigate land-use conflicts and minimize food security concerns.[72] The energy density of algal biofuels is also favorable compared to traditional biomass sources, positioning them as promising candidates for jet fuel production.[73]

Several pathways have been developed for converting microalgae into aviation fuels, each offering distinct advantages and challenges. The Hydroprocessed Esters and Fatty Acids (HEFA) pathway is one of the most promising, involving the extraction of lipids from algae followed by hydroprocessing to produce hydrocarbons; while commercially viable, it requires substantial energy inputs for lipid extraction and processing.[74] Alternatively, Fischer–Tropsch Synthesis (FTS) employs gasification of biomass to generate synthetic hydrocarbons, but its energy-intensive nature can lead to higher emissions compared to HEFA.[75] Pyrolysis, which thermally decomposes organic material to produce bio-oil, biochar, and syngas, can yield high outputs but may necessitate further refining to improve bio-oil quality. Hydrothermal liquefaction (HTL) is notable for its ability to convert wet algal biomass directly into crude oil-like substances under high pressure and temperature, effectively reducing drying energy costs, although it requires significant energy inputs. Anaerobic digestion transforms algal biomass into biogas, primarily methane, which, while not directly yielding aviation fuel, produces nutrient-rich digestate that can enhance agricultural sustainability. Lastly, transesterification—a process commonly applied to oilseed crops—can also be utilized for algal oils to produce biodiesel, providing another pathway for aviation fuel production. Each of these pathways presents unique opportunities and challenges that impact the overall sustainability of algal biofuels.[76]

The variability in GHG emissions associated with third-generation biofuels is significant and can be attributed to several factors. Different studies

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report a wide range of emissions outcomes, reflecting disparities in methodologies, cultivation conditions, and assumptions regarding energy inputs. The choice of cultivation system—open ponds *versus* closed photobioreactors—can dramatically impact both the efficiency of biomass production and the associated emissions.[77] Closed systems generally yield higher productivity but require more energy and infrastructure investment, leading to trade-offs between efficiency and emissions. The role of nitrous oxide (N_2O) emissions in algae cultivation has become a focal point of LCA studies. While algae are often touted for their low N_2O emissions compared to terrestrial crops, the production processes can still emit N_2O, especially when nutrient management practices are suboptimal. This discrepancy emphasizes the need for careful monitoring and optimization of cultivation practices to minimize emissions.[78]

The methodologies employed in LCA studies also contribute to variability in GHG assessments. Allocation methods—how emissions are distributed among different outputs—can lead to divergent results. Some studies utilize mass allocation, while others employ energy allocation or economic allocation, each yielding different emissions profiles. The lack of consensus on the most appropriate allocation method complicates comparisons between studies and hinders the establishment of clear sustainability benchmarks. The energy inputs required for microalgae cultivation are another critical aspect of LCA.[79] While the potential for carbon capture during algal growth presents a pathway for reducing net emissions, the energy demands for cultivation, harvesting, and processing can offset these benefits. For instance, energy-intensive processes such as dewatering and lipid extraction can significantly increase the overall energy footprint of algal biofuels.[80,81] Studies indicate that the energy balance of algal biofuels can be negative in certain cultivation scenarios, meaning that the energy expended in production may exceed the energy contained in the fuel produced. Moreover, the reliance on fossil fuel-derived inputs for energy can exacerbate the environmental impacts associated with algal biofuels. If energy used in cultivation is sourced from conventional power plants, the benefits of using algae as a carbon sink may be undermined.[82,83] Conversely, integrating renewable energy sources into algae cultivation could enhance the sustainability of these systems, but this transition presents its own challenges, such as the availability and cost of renewable energy.[84]

Water consumption and land use are additional critical factors in the sustainability assessment of third-generation biofuels. Algal cultivation systems can require significant quantities of water, particularly in regions with limited water resources. The type of water source—whether freshwater, seawater, or treated wastewater—also plays a crucial role in determining the environmental impacts. Studies have shown that using wastewater for algae cultivation can reduce the need for fertilizers while simultaneously addressing water treatment challenges, but this approach may introduce contaminants that could affect biomass quality.[85,86] Land footprint is another essential consideration. While algae can be cultivated in non-arable

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land, the physical footprint of large-scale cultivation facilities may still pose challenges in terms of land use conflicts and ecosystem impacts. The siting of algal production facilities should be carefully evaluated to minimize biodiversity loss and other ecological impacts, underscoring the need for spatial planning in the deployment of algal biofuel technologies.[87]

A growing number of LCA studies provide insights into the environmental performance of algae-derived fuels compared to conventional fossil fuels and other biofuels. For instance, a comparative LCA of various biofuel pathways highlighted that while algal biofuels show promise in terms of GHG reductions, their economic viability remains a significant barrier. In many cases, algal biofuels exhibit higher costs per unit of energy produced than their fossil counterparts, necessitating supportive policies and investment to make them competitive. The variability in results based on local conditions further complicates the assessment of algal biofuels.[88] The environmental performance can differ significantly depending on factors such as climate, feedstock availability, and technological infrastructure. Therefore, region-specific LCAs are essential for understanding the potential impacts and benefits of deploying algae-based fuels in different contexts.[89] To enhance the reliability and relevance of LCA studies on third-generation biofuels, several research needs must be addressed. There is a pressing need for standardized methodologies that can be widely adopted to ensure comparability across studies. Developing a robust framework for LCA that accounts for regional variations and technology differences will be crucial in advancing the understanding of algal biofuels sustainability. More comprehensive data collection efforts are also required to fill knowledge gaps related to emissions, energy inputs, and resource utilization in algal cultivation. Long-term field studies that monitor the environmental impacts of algal production systems under real-world conditions can provide valuable insights for LCA. In addition, integrating economic considerations into LCA frameworks will be essential for understanding the trade-offs between environmental impacts and economic viability. As the demand for sustainable fuels increases, a holistic approach that balances environmental, economic, and social dimensions will be key to advancing the deployment of third-generation biofuels in the aviation sector.

13.3.3 Carbon Dioxide Removal (CDR) and Aviation/Power to X/Hydrogen

Hydrogen (H_2), the epitome of zero carbon fuels, has begun to cement its way into many Net Zero and CDR strategies, especially in terms of decarbonizing transportation, be that domestic vehicles or aviation. In terms of volumetric energy density, H_2 (8.4 MJ m^{-3}) is far lower than other low/zero carbon options such as ammonia, methanol and ethanol, 13.6 MJ m^{-3}, 15.9 MJ m^{-3} and 21.6 MJ m^{-3}, respectively.[90] However, the gravimetric energy density of H_2 (120 MJ kg^{-1}) far exceeds that of the other low carbon options

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by a large amount. Hydrogen also outperforms conventional kerosene in terms of gravimetric energy density by 2.77×, where the standard fuel boasts 43.2 MJ kg^{-1}.[90]

Siddiqui and Dincer documented that for a passenger aircraft, hydrogen exhibited higher environmental performance (global warming potential, GWP) in comparison with liquefied natural gas, 1 kg CO_2 eq per ton per km *vs.* 0.82 kg CO_2 eq per ton per km.[91] However, through its higher operation performance, the production of liquid hydrogen as an energy carrier and its associated storage poses a technical challenge due to its low volumetric energy density, even in a liquid phase.[92] Some of the physical properties of liquid hydrogen *vs.* conventional aviation kerosene is shown in Table 13.1.

Hydrogen must be cryogenically stored due its boiling point (20.35 K) and the impracticalities of gaseous storage. This does pose considerations in terms of appropriate storage to avoid leakage and minimize additional weight to the fuselage and wing structure.[92] However, some increased weight is necessary to include insulation to limit heat leaks, while ensuring sufficient ventilation is in place for the pressurized fuel. This being said, the additional infrastructure to handle cryogenics is beneficial in terms of engine efficiency due to intercooling and the fuel's ability to act as an engine heat sink.

Although the positives for H_2 are clearly demonstrated in terms of carbon reduction at the point of use, there is a carbon bill (cost of carbon removal per kg of H_2 produced) associated with production which fluctuates variably as one would expect if using non-renewables or energy derived from renewable sources. Although in terms of monetization, where endpoint LCA emissions costs are added to the levelized cost of H_2 production from routes such as gasification (biomass and coal, brown H_2), steam methane reforming (SMR, grey H_2), methane pyrolysis (turquoise H_2) and electrolysis powered by renewable means (wind, solar and nuclear, green H_2), it is suggested that SMR with CCS, blue H_2 has the lowest monetized cost.[73,88] Table 13.2 is adapted from Weidner *et al.*,[93] focusing on the last five years which reviews a range of future-oriented LCA directed towards hydrogen sustainability, and its role in carbon reduction, specifically for electrolysis (powered by either the grid, solar or wind sources) and SMR production routes.

Table 13.1 Properties of liquid hydrogen *vs.* conventional kerosene. Adapted from ref. 92, https://doi.org/10.1007/s13272-022-00627-w, under the terms of the CC BY 4.0 license, https://creativecommons.org/licenses/by/4.0/.

Properties, nominal composition	Hydrogen, LN_2	Kerosene, $CH_{1.93}$
Liquid density[a] (g cm^{-3})	0.071	0.811
Boiling point at 1 atm (K)	20.27	440–539
Specific heat (J (g^{-1} K^{-1}))	9.69	1.98
Specific energy (kJ g^{-1})	120	42.8

[a] For hydrogen at the boiling point, for kerosene at 283 K.

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Table 13.2 Review of previous studies investigating hydrogen sustainability using either future-oriented LCA or contextualized results utilizing blue or green hydrogen.

Study	Relevant details	Findings	Ref.
Future-oriented LCA, green H_2	LCA for SMR and electrolysis powered by wind, changing efficiency and cell lifespan for years 2020, 2030 and 2050	• SMR 11.2–9.5 kg CO_2 per kg H_2 • Electrolysis powered by wind 0.4–0.3 kg CO_2 per kg H_2 (2020–2050)	98
Grey and green H_2, contextualization	LCA and economic assessment of solar and fossil technologies with climate abatement costs	• SMR 10.5 kg CO_2 per kg H_2 • Wind-solar ~3.5 kg CO_2 per kg • H_2 (~800 $ per t CO_2 *vs.* SMR)	99
Future-oriented LCA, green H_2	Optimization of technology mix between SMR, electrolysis powered by the grid and biomass gasification Reduction in investment costs and renewable penetration increases up to 2050	For a given increase in demand, the peak of SMR production in 2032 with a strong increase of wind energy fed to the grid until 100% in 2048	100
Blue and green H_2, contextualization	LCA of multiple H_2 production technologies with monetization of externalities	Total cost of H_2 production: • SMR 5.5 $ per kg H_2, SMR + CCS 4.7 $ per kg H_2, • Electrolysis powered by wind ~6.5 $ per kg H_2, • Electrolysis powered by solar ~12 $ per kg H_2,	101
Future-oriented LCA, green H_2	LCA with estimation of future parameters (*e.g.* lifetime, metal density)	• Relative comparison between electrolysis powered by wind and SMR, kg CO_2 eq ~10× lower • Mineral/water depletion 50× and 3× higher, respectively	102
Future-oriented LCA, blue and green H_2	GWP analysis of blue hydrogen at varying methane leakage rates for different technologies	Break-even with green hydrogen at around 0.5% leakage rate (high capture rate), lowest emissions from blue hydrogen ~2.5 kg CO_2 per kg H_2 (0% leakage rate)	103
Future-oriented LCA, blue and green H_2	LCA for blue (56% and 90% capture rate) and green (electrolysis powered by wind and solar) and electrolysis powered by the grid for 2030 and 2050 (efficiency increase)	• Blue H_2 (90%) with ~4 kg CO_2 per kg H_2, • Electrolysis powered by solar drops from 5 kg to 4 kg CO_2 per kg H_2 • Electrolysis powered by on/offshore wind is 2 kg and 1 kg CO_2 per kg H_2, respectively	104
Future-oriented LCA, green H_2	Prospective LCA for electrolysis powered by the grid with changes to background processes (based on IMAGE) for 2030 and 2050 (higher efficiency, cell lifetime and material demand)	• Electrolysis powered by the grid in an ideal scenario, drops between current to 2050 from 68.1 kg to 5.5 kg CO_2 per kg H_2 • Resource depletion increases by factor 2	105

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13.3.4 Power-to-liquid Pathways

Alternative feedstocks for the production of SAF *via* the PtL approach combines hydrogen production from renewable energy through water electrolysis, CO_2 capture and hydrocarbon synthesis *via* Fischer–Tropsch (FT) or methanol (MeOH) synthesis and conversion. Presently, the FT pathway meets the ASTM standard and is certified while the methanol pathway is not. The FT reaction is exothermic and the high temperature heat generated can be incorporated into the process (Schmidt *et al.*, 2018), thereby reducing electricity demand.[94] The typical process flow for the PtL pathway is shown in Figure 13.1. To achieve low GHG emissions, the co-location within proximity to the CO_2 source and low carbon electricity is required at a large scale as seen in Figure 13.5.

The hydrogen produced *via* water electrolysis is combined with CO_2 to obtain syngas which is further processed to produce jet fuel. The CO_2 can be sourced from industrial sources (*e.g.* power plants, steel production, cement plants), or direct air capture (DAC) in the long term. Rojas–Michaga *et al.* conducted a Well-to-Wake analysis for a PtL FT synthesis SAF system in the UK.[95] Their analysis incorporated a low-temperature solid sorbent DAC system to supply the CO_2 required for syngas production [*via* reverse water gas shift (RWGS) reaction] and alkaline electrolysis (AE) for hydrogen production. Their findings estimated a GWP of 21.43 g CO_2 eq per MJ for the PtL derived SAF with offshore wind providing the electricity required for electrolysis. This represents a 76% reduction in GHG emissions relative to conventional jet fuel and is in line with the emissions limit approved by the renewable fuel standard (RFS) for SAF. The greatest contributor to GHG emissions for the PtL process is the production of green hydrogen which accounts for about 78% of emissions. A similar study by Micheli *et al.* showed that onshore wind energy combined with LT DAC and solid oxide electrolyzer cells (SOEC) yielded the least emissions for PtL based SAF.[96] Waste heat from the FT synthesis is utilized for preheating the CO_2 for the

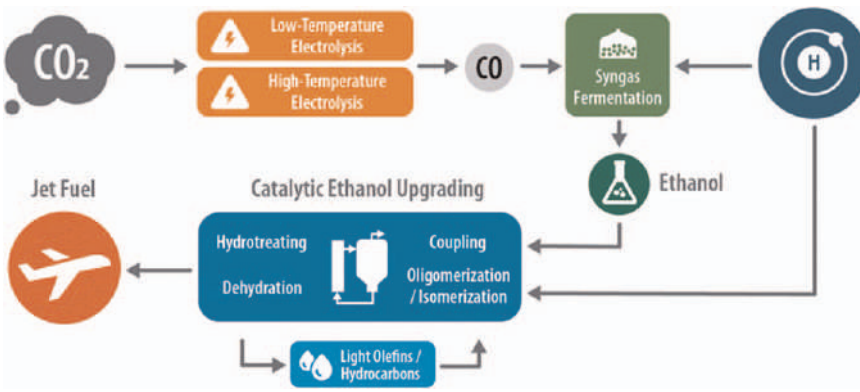


Figure 13.5 Process flow for the PtL pathway. Reproduced from ref. 106 with permission from the Royal Society of Chemistry.

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RWGS reaction and satisfying thermal energy requirements for the DAC unit resulting in improved process efficiency. Using electricity from PV instead of onshore wind increases the overall GHG from 9.35 g CO_2 eq per MJ to 28.6 g CO_2 eq per MJ. It is evident from these studies that both hydrogen and CO_2 production are critical factors that determine the sustainability of the PtL process. PV electricity from solar energy, which is abundantly available, can be integrated into existing infrastructure and is a promising alternative for producing SAF. The use of PV electricity and DAC for PtL through the FT pathway was investigated by van der Giesen *et al.* to ascertain the cumulative energy demand (CED) and GHG emissions.[97] Some of the surplus heat from the FT process is used in the RWGS reactor to produce syngas leading to a reduction in electrical energy demand. Their work showed that although the GHG emission (30 g CO_2 eq per MJ) is significantly lower than for conventional jet fuel, hydrogen production *via* alkaline electrolysis required 2 MJ/MJ which is equivalent to 87% CED for the process. This result is within the range of GWP reported by (Micheli *et al.*, 2022) and Rojas–Michaga *et al.*[95,96]

13.4 Conclusion

Over the past 15 years, there have been significant advances in terms of LCA studies applied to SAFs. As more pathways are being explored, it remains imperative to assess the sustainable performance of jet fuels not just from CO_2 related emissions but also non-CO_2 impacts. It remains extremely difficult to compare various LCA studies with other SAF pathways, mainly due to the vastly different configurations of the LCA boundary, allocation methods and data collection methods. Allocation methods remain controversial and offer conflicting results. Biomass remains one of the most important feedstocks, and its coverage by the literature confirms this. What is also interesting is the process integration of CDR and power-to-X pathways which will most likely become more prominent due to scaling up of technologies such as DAC and other approaches. Ultimately, what has become clearer is that the LCA approach towards assessing the sustainability of sustainable aviation fuels has not been fully realized yet, with a lack of implementation of other characterization factors. This is something that needs to be addressed through future research.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council and the Natural Environment Research Council EP/S023763/1, the EPSRC Centre for Doctoral Training in Offshore Wind Energy.

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