University of Strathclyde Engineering

Department of Mechanical and Aerospace Engineering

Feasibility of Synthetic Fuels from Renewable Sources as Part of the UK Energy System

Author: Duncan Hambrey

Supervisor: Dr Paul Tuohy

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Duncan Hambrey Date: 25/08/17

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Abstract

As the need for renewable solutions to the world's energy demands becomes more and more important, many efforts are being made towards producing energy in a clean manner. One area which is not yet seeing the improvements being made in other sectors is transport. Demand continues to rise quickly while technology has struggled to keep up.

Electric battery cars and plug-in hybrids are showing plenty of promise, however, not everybody will be able to afford a new one and performance is still lagging behind fossil fuel cars – meaning it will be many years before they become ubiquitous. Until then, synthetic fuels produced using renewable energy could provide a solution.

This thesis systematically reviews potential pathways to synthetic fuel integration within a UK energy system, inspired by research from the University of Aalborg. This research imagines a potential future energy system in Denmark with all energy sectors connected and 100% renewable energy.

Using modelling the modelling software EnergyPLAN, simulations were run and results were collected. These results culminated in drawing several conclusions.

It was seen that synthetic fuels could lead to substantial reductions to carbon dioxide emissions without requiring extortionate investment. Additionally, the possibility of using these fuels as a vessel for energy storage is an attractive opportunity. While these were positive findings, it was noted that the sheer quantity of additional electricity or energy from biomass required for large-scale fuel synthesis was infeasible in the UK in the near future. The best-performing fuel in the modelling phase was synthetic jet fuel. Higher efficiencies in the production, coupled with the fact that electrification of aviation remains a very distant possibility, means that synthetic paraffinic kerosene or other synthetic jet fuels could be an integral fuel of the future.

The effectiveness of synthetic fuels depends largely on the rest of a country's energy system and the UK was not deemed appropriate for synthetic fuels on a large scale. In some countries they will play an important part until electric vehicle technology has matured.

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Nomenclature

CHP – Combined Heat and Power

CCR – Carbon Capture & Recycling

CCS – Carbon Capture and Storage

Electrofuel – synthetic fuel produced using renewable electricity

FT – Fischer-Tropsch

GHG – Greenhouse Gas

Mt – Million tonnes

NO_X – Nitrous Oxides

PES – Primary Energy Supply

RES – Renewable Energy Supply

SOEC – Solid Oxide Electrolyser Cell

SO_X – Sulphurous oxides

SPK – Synthetic Paraffinic Kerosene

Syngas – Synthesis gas

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1. Introduction

1.1. Background and Context

Transport constitutes a huge part of everyday life for many people and is extremely important to modern society. There are concerns that the ever-increasing demand for transport is unsustainable unless solutions are found to reduce the emissions posing a threat to the environment. The electrification of the transport sector is an exciting and important push towards a sustainable future. It will reduce environmental impacts from vehicles considerably and already steady progress is being made to achieve this. However, most of the current fleet of vehicles used in the majority of countries are unsuitable for hydrogen fuel cells or electric batteries. Additionally, it is too expensive for many people to invest in a new electric model. This calls for a solution in the meantime to prevent rising pollution from transport which is damaging for the environment and human health. Some chemical combustion products, such as carbon dioxide and methane are more detrimental to the environment in terms of climate change. However, Sulphurous and nitrous oxides have a greater effect on the health and wellbeing of humans.

One possible means of reducing emissions and creating a sustainable transport sector is through the use of synthetic fuels. These are hydrocarbon fuels with similar properties to conventional fossil fuels such as petrol and diesel, although in this case they are produced from a renewable source. This means that infrastructure and existing vehicles would not need altered significantly and emissions could be greatly reduced. Until recently, the gasification of coal and other carbon-based feedstocks has been used to create synthetic gas capable of being processed further into a synthetic fuel. Now, the possibility of using renewable electricity and captured carbon is beginning to become a reality. Figure 1 gives an idea of potential pathways to clean and renewable alternative fuels. [1] These different pathways and fuels will be discussed and explained throughout the literature review.

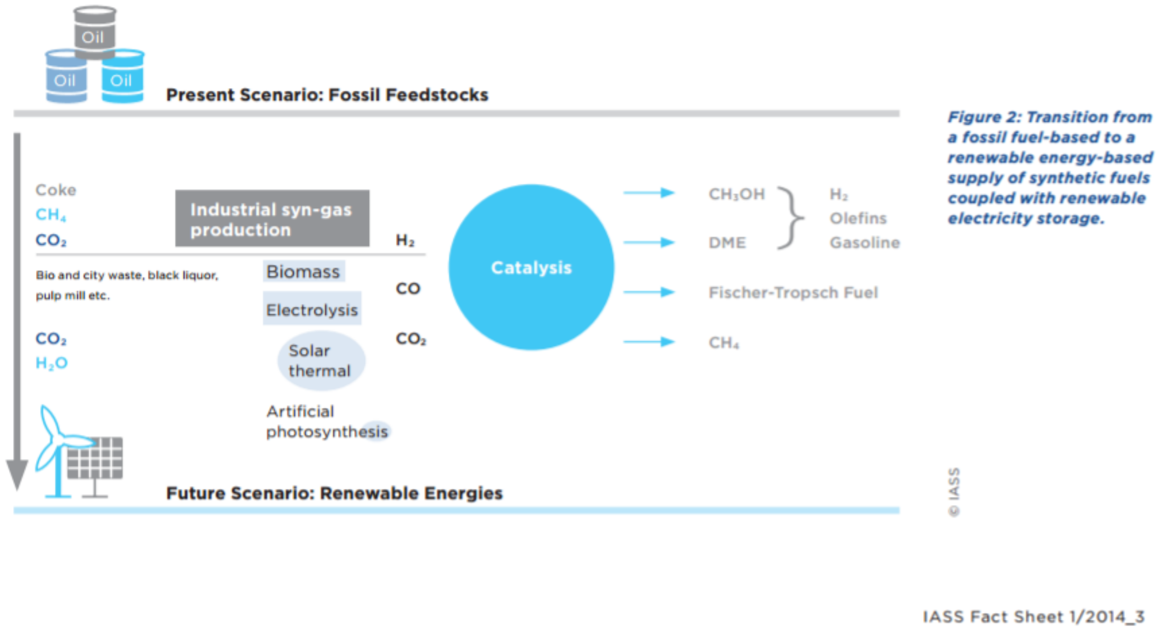


Figure 1 - Potential pathways to synthetic fuels

Synthetic fuels can often be integrated for use in existing engines and so can provide a solution to the high emissions we currently produce. They can not only be implemented within the transport sector, but also as sources of heat or electricity. The versatility of some of these fuels leads to many possibilities and uses.

Biofuels from renewable sources are already in use in several countries, usually in the form of an ethanol or methanol fuel blend with petrol or diesel. Use in fuel blends could be an option for synthetic fuels, although many synthetically produced hydrocarbon fuels are capable of acting as a pure fuel without the need for blending.

There is already a wide range of potential synthetic fuels which have been proven in land, sea, and air travel. This thesis will examine the effects of these fuels when implemented on a national scale and will evaluate their feasibility.

1.2. Project Aim

This project started with the main aim:

"To investigate the feasibility of synthetic transport fuels from a renewable source as part of the UK energy system."

This has been motivated by current research into this area, particularly in Denmark. It is evident that the transport sector lags behind other areas in terms of sustainability and so a solution must be found to improve this. Previous research will be evaluated and applied, if possible, to the UK energy system to give a recommendation for future transport systems.

1.3. Overall Approach and Objectives

The key steps which have been identified to achieve the project aim are listed below in the order in which they will be completed. Sub-objectives as part of each main objective will be identified throughout in order to provide a clear plan of progression.

- Produce a literature review comparing available technology and approaches for synthetic fuels
- Become familiar with the capabilities and limitations of energyPLAN software by undertaking tutorials and learning the user interface
- Use EnergyPLAN Software to model different scenarios with and without synthetic fuel integration
- Compare and analyse results
- Investigate validity and accuracy of results
- Make suggestions as to how they may or may not be implemented and discuss alternatives
- Identify future research and possibilities
- Draw concise and useful conclusions from all of the prior sections

Initially, a literature review was performed to provide an understanding of the current technologies and future concepts in the area of synthetic fuels. Once a basis was built through this literature review, a modelling process could be undertaken which examined the main points of interest highlighted from literature. These results are found in section 4 of this thesis. The modelling software and literature was evaluated and scrutinised in order to identify any limitations and possible discrepancies. Section 5 is a discussion of the main results and is presented to give an idea of the important points to take from the analysis. Objectives and aims are discussed and an attempt is made to answer any questions. Further research was identified in the discussion, highlighting areas which were scoped out of the thesis but are worth pursuing given a longer time period. The modelling results give an interesting insight into the future possibilities of synthetic fuels and allow conclusions to be made on how the future UK system should be designed with regards to transport fuel. The appendices section provides additional data used in the modelling section.

1.4. Project Scoping

As this project has a relatively tight time constraint, the limitations and scope of the work were identified early in the process. The principal focus was to determine the possibility of synthetic fuels being integrated into the UK system. Feasibility was judged through economic comparisons, environmental effects, and how synthetic fuels would affect the rest of the energy system. Economics are addressed through inputting costs into the analysis model, however, a detailed economic analysis was scoped out of this thesis due to the limited time available.

The UK is powered through a mixture of different energy sources. Not all of these were considered in this thesis, noticeably nuclear energy. It was decided to focus more on a renewable energy generation strategy than fossil fuels or nuclear which can be both be considered damaging to the environment in some way.

Biofuels are a similar concept to synthetic fuel, usually produced using organic matter. The production of synthetic fuels using biomass gasification will be discussed in this report, although, biofuels from food crops will not be focussed on. This is a separate, but similar technology, which may be elaborated on with more time.

Electric vehicles are referenced throughout this report although they do not constitute a part of the analysis as an alternative to synthetic fuels. The analysis focuses on the feasibility of synthetic fuels when compared to fossil fuels and electric cars are discussed as a replacement for both of these technologies.

The costs and other inputs for transport and electricity systems are considered in the analysis although a detailed heating or gas network is not considered within the scope of this project.

Further assumptions for modelling are detailed in section 3.3.1. and include the scope for the analysis.

2. Literature Review

From performing a literature review, it is clear that there are many potential methods of producing synthetic fuels of various types through renewable and environmentally friendly means. Detailed reviews of the performance, uses, and impacts of these fuels were found in various pieces of literature. Not only the positives were investigated, however, the challenges facing the emergence of synthetic fuels were also identified throughout this review.

The main aim of the review is to provide an overview of the available technology which could be used to establish a basis for the modelling section of the thesis. A comparison between different fuels is undertaken and a current state of affairs in the UK transport sector is described. The review aims to give a strong idea of gaps in research which could be investigated as well as key aspects which must be considered when modelling.

2.1. Smart Energy Systems – University of Aalborg

Many of the concepts arising in this section have been taken from the work of a group of researchers from the University of Aalborg, Denmark.

This thesis has looked to critique and learn from various pieces of research carried out in the University of Aalborg. They have devised the concept of a "Smart Energy System" which can interlink the main energy sectors of heat, electricity, and transport in an intelligent and efficient way. Synthetic fuels are an important part of this system, linking electricity with transport and also providing a new energy storage option.

The concept of a smart energy system is one which involves every part of the overall energy system working in synchrony together to allow for greater efficiency and the ability to incorporate large amounts of renewable energy. This means that heat, carbon dioxide, electricity, and hydrogen are shared throughout the system in order to minimise losses and emissions. For example the carbon captured from CHP plants can be used as a feedstock to synthesise electrofuels. An electrofuel is a synthetic fuel produced using electricity as opposed to biomass or other sources. [2] These are seen as the most sustainable form of synthetic fuel. The heat produced from creating these fuels can be used for district heating. A smart energy system requires a lot of planning although it is necessary to use the resources we have in an advantageous way by utilising interconnections and recycling between sectors.

While there are many costs associated with the conversion of an energy system from fossil fuel reliance to renewable energy, the University of Aalborg cited job creation as a major positive for this switch. This point cannot be disregarded as it is inevitably true, whether it is true to the extent they envisage may not be the case.

In IDA's 2050 Energy Vision report, job creation is discussed and is assumed that 50,000 jobs/year are created in Denmark through switching to a 100% renewable based energy system. [3]This is a sizeable additional employment rate, however, this does not take into account synthetic fuel, only heating and electricity. It is then hard to quantify the effect that changing the transport sector would have on employment.

The overall concept of a smart energy system will be alluded to but not focused on in this study. It provides context for the wider picture in which synthetic fuel integration may be possible.

The studies undertaken by the University of Aalborg tend to focus on a future energy system of 2050 or 2030. Therefore much of the work is estimative and cannot be taken as absolute truth. The research performed is based on the Danish energy system and integrating several relatively unproven technologies. The robustness of these findings when applied to other countries is not guaranteed. Modelling using some of their assumptions and tailoring the model to the UK system means that a conclusion on the possibility of such a system in the UK can be made.

The diagram below (figure 2) provides a visual representation of a "Smart Energy System" [4]

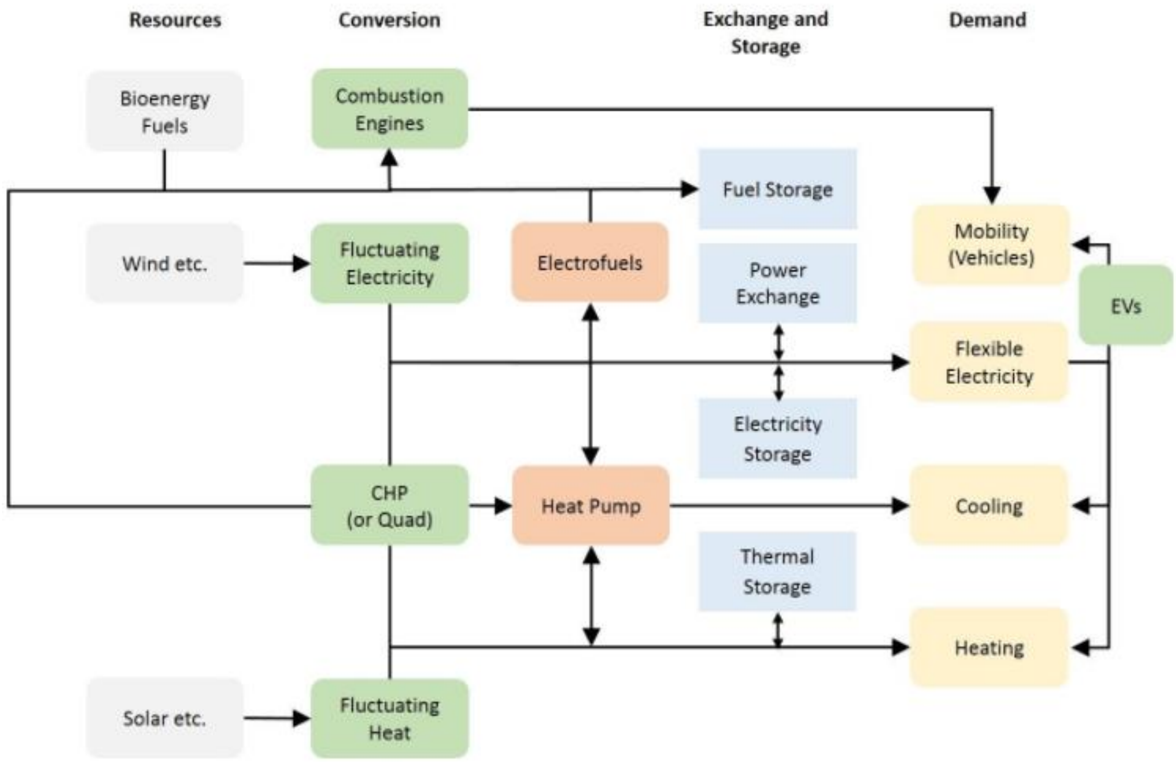


Figure 2 - University of Aalborg's Smart Energy System

The interconnection between different parts of an energy system is shown in figure 2. Denmark, as well as other Scandinavian countries have strong infrastructure already in place for combined heat and power plants as well as for heat pumps. If a UK "Smart Energy System" was designed, different technologies may prevail as those the system relies on.

2.2. UK Transport Statistics

It is important to identify the fuel requirements for the UK transport industry before any modelling may take place. The UK government website provided valuable information with regards to emissions, fuel types, and the make-up of the current vehicle fleet.

The UK transport sector consumption as of 2016 was roughly 55,000,000 tonnes of oil equivalent. This equates to 640tWh. [5] Road transport accounted for 40,500,000 tonnes of oil equivalent in 2015, while aviation used 12,573,000 tonnes of oil equivalent. There are 37.5 million registered road vehicles currently, with 31.1 million being cars. [6]

If 50% of transport demand is supplied by synthetic fuels, this would mean 233twh in cars, 73twh in aviation fuel.

New cars have increased in fuel efficiency; cars produced in 2015 had an average efficiency of 52.1mpg for petrol and 61.7mpg for diesel. [6]

Carbon dioxide reductions in the transport sector are not as high as reductions to other harmful emissions. A decrease from 127.9 million tonnes of CO_2 to 116.6 million tonnes between 2004 and 2016 has been observed.[7] Clearly improvements are being made as there are significantly more vehicles in operating today.

Attempts are being made to reduce greenhouse gas emissions across all sectors. Currently though, transport in the UK is lagging behind. As shown in figure 3, only a 2% decrease in GHG emissions has been seen between 1990 and 2015. [8] When compared to "Energy supply", for example, with 48% reductions, transport does not compete.

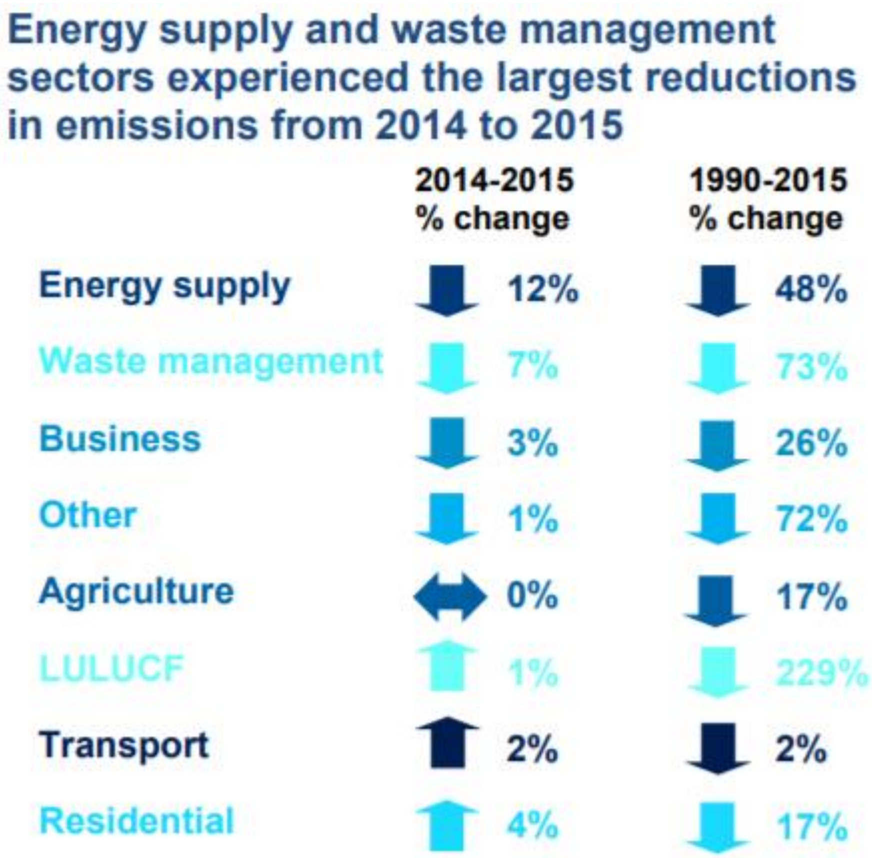


Figure 3 - Emission reductions by sector

Carbon monoxide and benzene are the harmful emissions which have been most successfully reduced in the last 10 – 15 years.

From table ENV0501 of UK government statistics, renewable fuels accounted for roughly 3% of the total consumption by volume in the UK in 2015. [9] Between 15 April 2016 and 14 April 2017, 423 million litres of renewable fuel was supplied in the UK.

In the UK, used cooking oil and tallow make up a large proportion of the renewable fuel totals. These both allow for 83% savings on greenhouse gas emissions. The UK statistics for 2014/2015 may not be an accurate representation currently. [10]

165 million litres of renewable fuel has been shown to pass sustainability standards. The breakdown of this fuel is as follows: 50% biodiesel, 49% bioethanol, and 1% biomethanol.[10]

During 2016, the number of new cars registered in the UK which were categorized as "ultra-low emission vehicles" (ULEVs) accounted for around 1% of the total. In 2015, they accounted for 0.8%, in 2014, 0.2%. This represents a fairly substantial growth, however, the market penetration of electric and hybrid vehicles is still relatively unsubstantial. [10]

Overall, greenhouse gas emissions in the UK increased until 2007, then began to decrease before plateauing by 2015. This can still be seen as reduction since the transport industry is growing, although, there is much room for improvement. 121.9 million tonnes of CO_2 equivalent greenhouse gas emissions were released in 1990, and 120 million tonnes in 2015. [11] This shows a very slight decrease but more considerable reductions should be strived for.

In recent years, diesel and petrol prices have remained similar, with diesel generally slightly more expensive. As of April 2016, the price for both diesel and petrol was roughly 106p/l, of which 71p/l was tax.[12] This is the area in which renewable fuels must compete in order to become more widely used.

When comparing the emissions from diesel and petrol cars in urban areas, diesel engines produce substantially more nitrous oxide emissions per kilometre than petrol engines, although carbon monoxide emissions are decreased. Motorcycles are more polluting in all aspects. [13]

Looking into the future, it is likely that in the next two or three decades there will be a majority of cars still using standard internal combustion engines. There is a market gap for a sustainable option and synthetic fuels will play an interesting role. The investment required to meet a large proportion of demand may not be practical as electrification is the main goal which should be strived for.

There is an incentive in the form of a grant available for plug-in vehicles which has allowed the technology to develop. Depending on the price reductions seen in electrofuel and biofuel production, the government may have to subsidise these alternate blends.

2.3. Geography of Fuel

With the world's major oil reserves generally unevenly distributed with large deposits in areas such as the gulf region, it is in many countries interests to invest in locally sourced alternative solutions. While these renewable systems may be ostensibly more expensive options, a look at the benefits including job creation and less of a reliance on import can make them a sound investment.

It is not something which is immediately considered when examining the economic potential of different technologies, but the importance of job creation and minimising import should not be ignored. This is alluded to in IDA's Energy Vision 2050 (Lund et al).[3] Freight costs and associated emissions would be lowered with increased local generation, although some countries lack adequate funding or resources to implement renewable energy on a large scale.

2.4. Synthetic Fuels

Synthetic fuels are liquid or gaseous hydrocarbons made through chemical synthesis with carbon and hydrogen based feedstocks and are designed to replicate the characteristics of fossil fuels. The major advantage of synthetic fuels is that they can be produced to a far more environmentally efficient standard than fossil fuels, using a multitude of different feedstocks. If produced using a biomass feedstock or excess renewable electricity, they can be considered a renewable energy source capable of replacing current fuels. When a synthetic fuel is produced using captured carbon dioxide as its carbon source, it can be said to be carbon neutral as the carbon emissions are equal to the consumed carbon in the initial phase. Figure 4, below, shows a proposed process pathway to synthetic fuel production from captured carbon: [2]

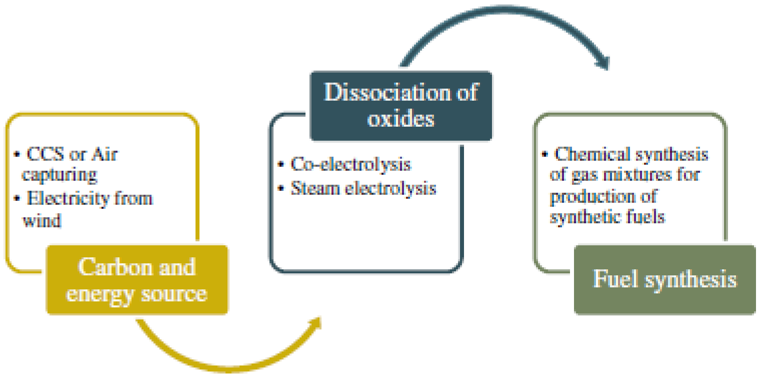


Fig. 1. Production cycle of synthetic fuels.

Figure 4 - Electrofuel Production Pathway

The concept of synthetically produced fuels is not a new one. The Fischer-Tropsch process was discovered in 1925, nearly 100 years ago.[14] This process allows the synthesis of carbon and hydrogen based inputs to create synthetic fuel. Fischer-Tropsch synthesis will be elaborated on in section 2.5. Since the process was discovered, it has not progressed as quickly as may have been expected and the relative cheapness of fossil fuels has always put them as the first choice. Now that global warming is a known issue, and that fossil fuel reserves are dwindling, the technology is being pushed to the forefront of research and development once again.

In the UK the energy demand for transport is roughly twice what is required for electricity. There is a huge scope for improvement in the transport sector as the vast majority of this energy is still provided from fossil fuels.

Synthesis gas or syngas is a gaseous mixture comprised of mainly hydrogen and carbon monoxide. Syngas is the bridge between raw carbon feedstocks and liquid synthetic fuels. It is created through gasification and partial oxidation techniques.

The gaseous mixture contains carbon monoxide, carbon dioxide, and hydrogen. It has the potential to be used directly as a fuel or can be synthesised further into more effective fuels.

Syngas is a useful commodity in the chemical industry with the ability to be converted into a range of products and materials depending on the ratios of hydrogen or carbon monoxide in the mixture. Some of these can be shown in the diagram below: [15]

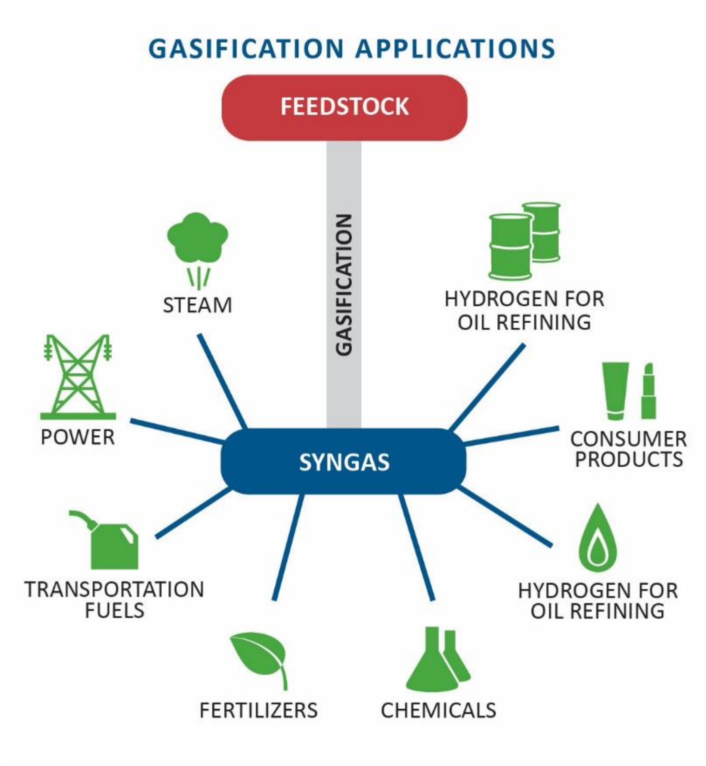


Figure 5 - Uses of Syngas

Gasification using coal as a feedstock is not a renewable form of fuel generation, however, it does substantially reduce emissions compared to standard uses of coal.

When compared to both solid and liquid fuels, gaseous feedstocks are more easily adjusted to remove harmful emissions and have the potential to be used in combined cycle generation which has a much higher efficiency than a normal combustion cycle.

Synthesis gas generally has an energy density roughly half as much as natural gas.[16] This means that syngas used as a combustion fuel on its own is not very high quality. Its strengths lie in the potential of creating other liquid or gaseous chemicals. A large range of fuels with a variety of uses can be produced using syngas meaning it is a valuable commodity. The wide range of precursors to synthesis gas means there is an abundant potential source available.

2.5. Fischer-Tropsch Fuel Synthesis Process

The chemical reactions of carbon monoxide and hydrogen to form high energy hydrocarbons is called the Fischer-Tropsch process. This is the basis of creating synthetic liquid fuels from a gaseous feedstock.

This synthetic fuel contains less of the environmentally harming constituents that are released when standard diesel or petrol burns. Sulphur is removed during the process to prevent the poisoning of catalysts and to prevent sulphurous harmful emissions from combustion of the final product.

The main reaction associated with Fischer-Tropsch synthesis is as follows:

$$CO + 2H_2 \ \rightarrow\rightarrow\rightarrow \ -CH_2- \ +H_2O$$

Where $-CH_2-$ is a hydrocarbon chain.

Alkanes or paraffin are desirable products from the process and can be given with the reaction:

$$nCO + (2n+1)H_2 \ \rightarrow\rightarrow\rightarrow \ C_nH_{2n+2} + nH_2O$$

In this case n is the number of moles of each element or compound in the reaction.

Olefins or alkenes are also a useful product characterised by the reaction below:

$$nCO + 2nH_2 \ \rightarrow\rightarrow\rightarrow \ C_nH_{2n} + nH_2O$$

Alcohol is the third desirable product from Fischer-Tropsch synthesis, the reaction is given below:

$$nCO + 2nH_2 \ \rightarrow\rightarrow\rightarrow \ C_nH_{2n+1}OH + (n-1)H_2O$$

The water-gas shift reaction can be used to regulate the hydrogen to carbon monoxide ratio in order to yield slightly different products and to increase efficiencies.

On a large scale, the Fischer-Tropsch process is mainly used for either the reformation of methane or for gasification of a coal feedstock. The process has many potential products and is possible to scale-up if required. Figure 6 below shows the main steps from feedstock to synthetic fuel using a biomass feed. [17]

The process remains largely the same although to provide an even cleaner process, the syngas is produced from renewable electricity and captured carbon.

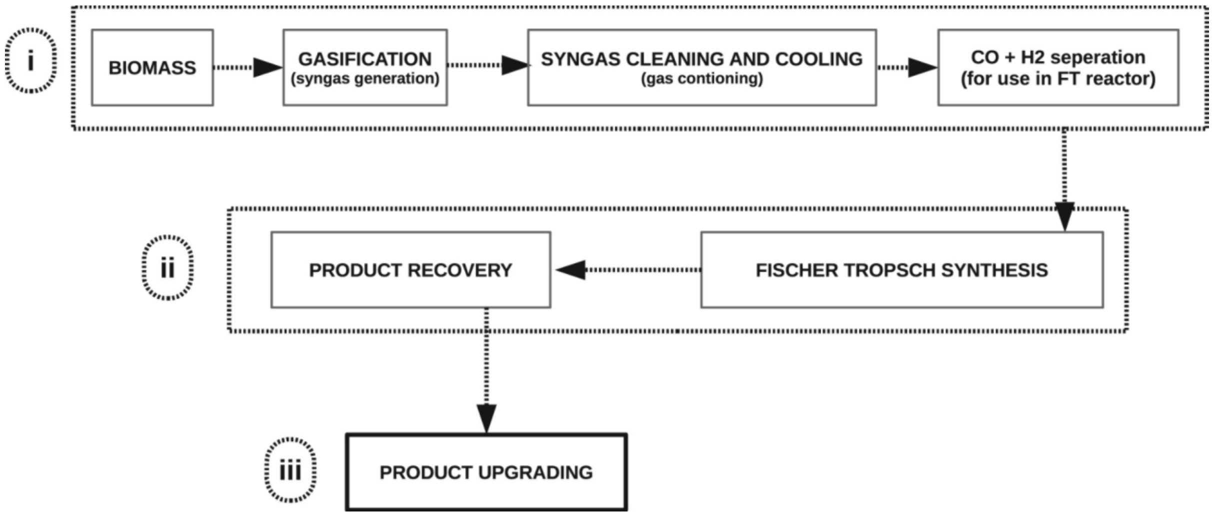


Figure 6 - Biomass to Synthetic Fuels Process

2.6. Potential Fuel Types

There is a long list of fuels which may be derived from synthesis gas, those with the greatest potential will be discussed here. For road vehicle applications, the most promising synthetic fuels include: methanol, di-methyl ether, synthetic gasoline, and synthetic diesel. Slightly different processes are required for each fuel type once syngas is obtained. More detailed analysis of these fuels is given in the sections for each different fuel.

In the case of aviation, there is currently less choice of proven fuel, however ongoing research is being made into potential alternatives. Currently the prevailing technology is synthetic paraffinic kerosene which can be produced in a similar way to the aforementioned road vehicle fuels or through a biofuel process using oil based plants or used cooking oil.[22] For this project, the synthetic production pathway from Fischer-Tropsch synthesis will be focused on.

2.6.1. Methanol transport fuel

The production of methanol involves the reaction of carbon monoxide and hydrogen to produce methanol, as can be seen in the following reaction:

$$CO + 2H_2 \rightarrow\rightarrow\rightarrow CH_3OH$$

Some additional reactions occur alongside this:

$$3H_2 + CO_2 \rightarrow\rightarrow\rightarrow CH_3OH + H_2O$$

$$H_2 + CO_2 \rightarrow\rightarrow\rightarrow CO + H_2O$$

Methanol is an important part of the chemical industry and has the capability of being a very effective fuel. It can be produced through various methods such as coal gasification, steam reforming, biomass gasification, or even from captured carbon.

China has begun to incorporate a large amount of methanol into the transport sector by producing several methanol and gasoline blends. [18] Fuel methanol in China is predominantly produced from fossil fuel sources such as coal and natural gas. Life-time environmental effects from producing methanol in this way can often be as considerable as standard fossil derived fuels. This energy strategy has courted controversy because of this reason.

The price of methanol is strongly connected to that of crude oil and has followed a similar path in recent years. As crude oil reserves diminish, this relationship could change but for this project, the relationship will be assumed to remain.

Having the ability to be stored and used as fuel for heating or transport gives it a high potential now and in the future.

Synthetic gasoline can be produced using the methanol to gasoline process. MTG – Methanol to Gasoline process can be used to create alternate gasoline with low sulphur content without compromising its other qualities.

Methanol is an extremely versatile fuel. It has the ability to be used directly in internal combustion engines while it is also possible and simple to convert into higher performance fuels. Methanol’s high octane number is very important for use in an internal combustion engines, leading to high performance and preventing engine knocking. Its use in the chemical industry as a feedstock for many different chemical processes renders it an important part of many industries.

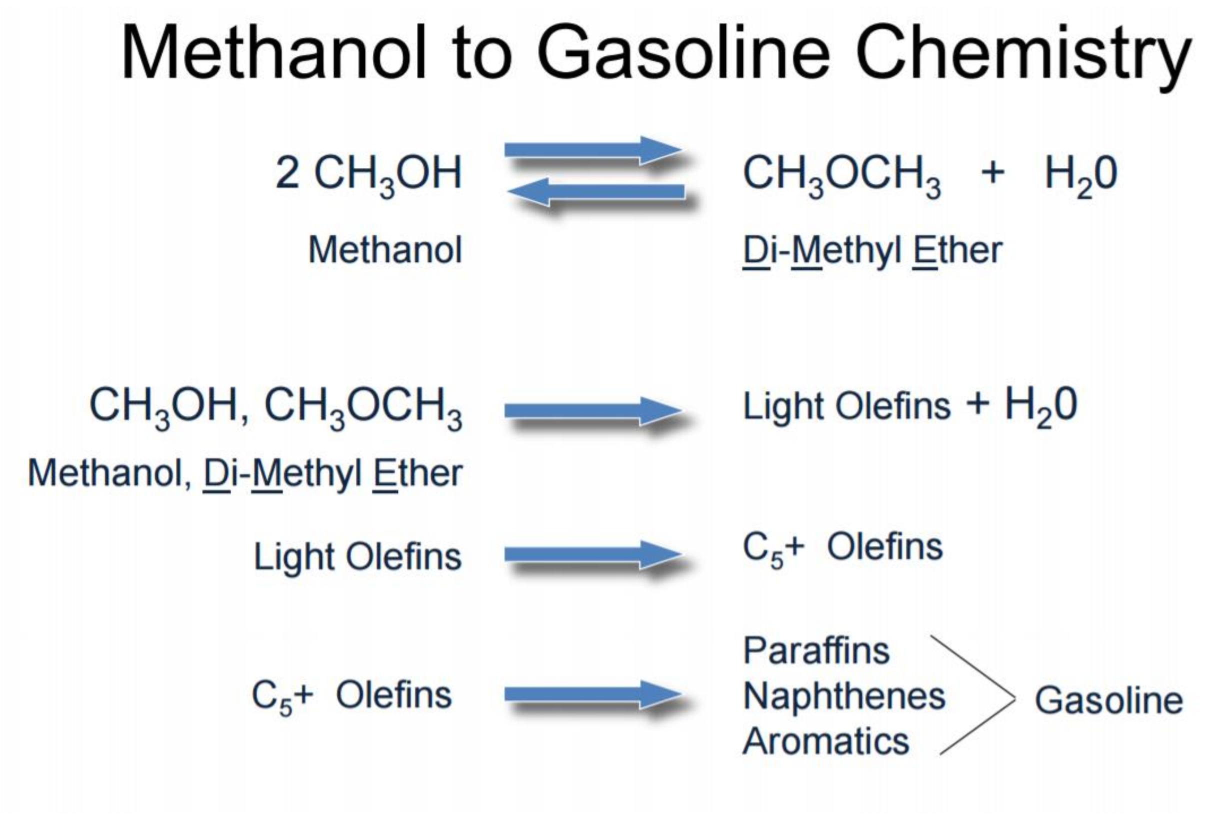
A further advantage of using methanol is its biodegradability. If a spillage occurs, methanol is quick to biodegrade, reducing the likelihood of harmful effects to the environment.

Weighing up this information, methanol looks to have a future in cleaner alternative fuels and large investment is already being made into developing it.

2.6.2. Synthetic Gasoline

Having produced methanol, it is then possible to further synthesise to produce gasoline using the Mobil process. Research leading to this discovery took place in the 1970's and led to a working process being created in 1979.[19]

Below is shown the outline of the methanol to gasoline process chemistry: [19]



The first stage in the process is the conversion of methanol to di-methyl ether through dehydration. Following this, the DME, and methanol reacts to produce light olefins. Polymerization and hydrogenation stages allow for these olefins to be converted into gasoline, a mixture of paraffins, napthalenes, and aromatics.

Synthetic gasoline can be produced with far lower amounts of harmful sulphur or nitrogen oxides and is almost chemically identical to standard petrol. If the carbon and hydrogen can be sourced by renewable means, it is a cleaner alternative to fossil gasoline. Despite this, further steps are required to produce synthetic gasoline meaning a more complicated process.

2.6.3. Synthetic Diesel

The Fischer-Tropsch process has the ability to produce fuels usable in a diesel internal combustion engine (compression ignition engine). As mentioned previously, di-methyl ether is a promising diesel alternative which can be produced from syngas.

Di-methyl ether (DME) is a hydrocarbon fuel, characterised by the chemical formula: CH_3OCH_3, which can be created using Fischer-Tropsch synthesis. It is often used for domestic heating but also has the capability of replacing diesel in diesel internal combustion engines. [20] Having a high cetane number allows self-combustion in compression ignition engines normally used with diesel fuel.

DME can be produced from methanol dehydration or from synthesis gas using particular catalysts. Reaction conditions and catalysts present determine the exact hydrocarbon chain produced. The equation below shows the dehydration process from methanol to DME:

$$2CH_3OH \rightarrow\rightarrow\rightarrow CH_3OCH_3 + H_2O$$

As with other synthetic fuels, sulphur can be removed in order to prevent Sulphurous oxide emissions which are detrimental to human health. Additionally, carbon monoxide and nitrous oxide emissions can be greatly reduced.

One drawback which should be noted is that DME only has half the energy density of diesel.[21] This could be seen as a barrier to widespread usage as a diesel replacement.

Another difficulty is the need to store DME in a pressurised container in order to be in liquid from; it is gaseous at standard atmospheric conditions.

2.6.4. Synthetic Jet Fuel

An area which is likely to expand substantially in the near future is aviation.[22] This will lead to far greater fuel demand in an industry already posing significant negative effects to the environment. The need for a greener alternative to existing jet fuel is of paramount importance if overall carbon dioxide emissions are going to be reduced. A cleaner form of fuel called synthetic paraffinic kerosene has been suggested as an appropriate replacement for standard jet fuel.

Kerosene is the currently established fuel used in the aviation industry.

As with many of the other synthetic fuels identified in this project, there is the opportunity for cleaner jet fuel being produced from an initial supply of excess renewable electricity.

Said to account for roughly 2% of human CO_2 emissions, the aviation industry is one which can have a large impact on climate change. [23]

Overall, according to (Gutiérrez-Antonio et al) above, the transport sector consumes 27.9% of the energy produced worldwide (2014) and consumption is set to roughly double by 2050.[23] This highlights the need for reducing emissions substantially within this sector.

Synthetic jet fuels tend to have longer carbon chains than gasoline and shorter chains than diesel. A range of length and ratios can be used in each case although key physical properties should remain similar. There are a plethora of techniques used to form renewable jet fuel, as can be seen in the figure below: [23]

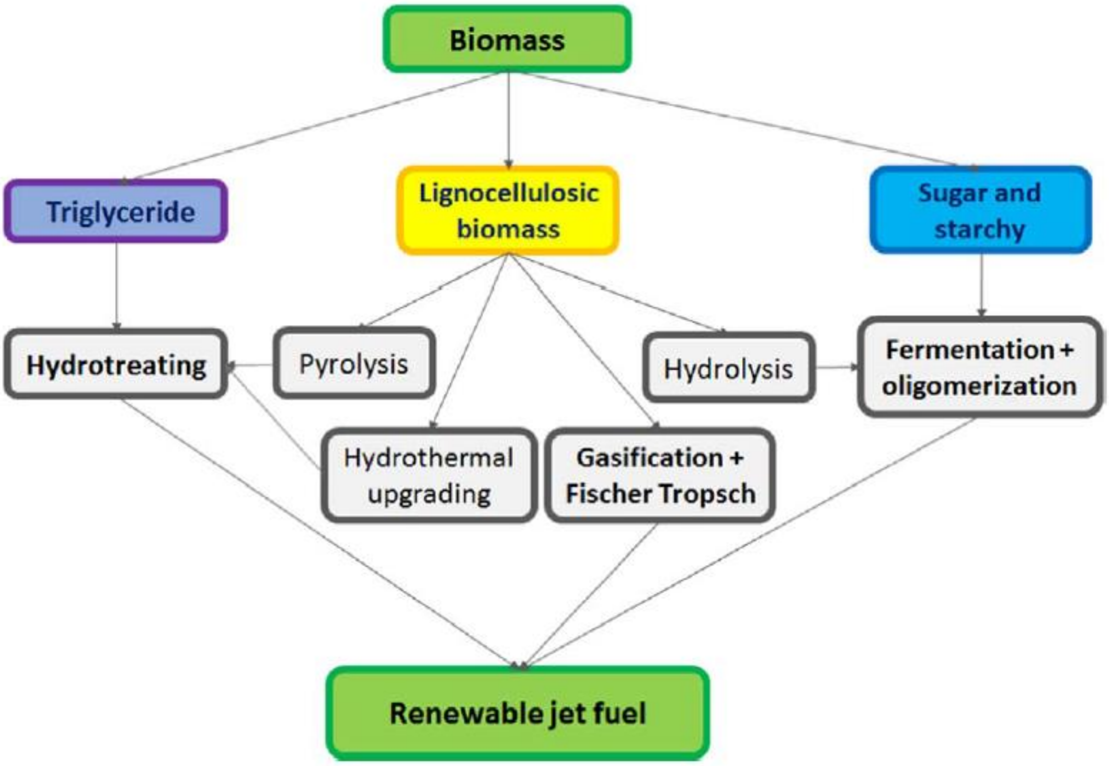


Figure 7 -Synthetic Jet Fuel Production Pathway from Biomass

In 2007 biojet fuel was produced and tested in some domestic flights in the USA. The fuel was in the form of a 50% blend with traditional fuel. The company responsible, UOP, estimated that lifetime emissions of green-house gases amounted to 65-85% lower than standard jet fuel.[23] Aviation is an ever-growing segment of the transport sector and if these emission reductions are possible, it would contribute a large step towards global environmental targets.

However, concerns over project cost and safety arose because of the high amount of hydrogen required for the process. This is the main negative aspect which arises from most types of synthetic fuel, the high feedstock and energy demand.

The yields achieved through various methods of producing kerosene based jet-fuels are generally fairly low. From Gutiérrez-Antonio et al, the highest jet fuel yield was using a corncob feedstock. This was still just 50%, however.

A similar chemical process to that used in the synthesis of methanol and other Fischer-Tropsch fuels is used in the synthesis of biojet fuel. A cracking/isomerizing stage is performed in order to yield the aviation fuel. It may be possible to design plants producing both road and aviation transport fuels with only small changes in the production for each.

There are many ways to produce renewable jet fuels, whether through different processes or by yielding different products. An ideal would be to produce a fuel with almost identical physical characteristics to conventional jet fuel, whilst producing insignificant emissions through all stages, as well as sourcing this fuel by renewable means.

Syngas is the basis for most synthetic fuel so if it is produced from a renewable source then the final fuel can be classed as renewable.

2.7. Hydrogen from Water Electrolysis

An essential input to syngas production is hydrogen gas. Hydrogen can be produced through the electrolysis of water. This involves using an electrical current to spilt water into hydrogen and oxygen molecules. An emerging technology called a solid oxide electrolyser can efficiently produce hydrogen with water and electricity. If this electricity were to come from excess renewable generation, it would further enhance the potential environmental benefits of electrofuels.

It is estimated by the IDA that SOEC's in the year 2050 will cost 280,000 Euros/MW capacity, with a 15 year lifetime and operations and maintenance costs of around 3% of initial investment. [3] This cost prediction may be overly optimistic and assumptions of this being a cheap and effective solution in the future may be premature.

IDA's cost predictions for 2020 are much higher, at 600,000 Euros/MW, a 20 year lifetime and 2.5% O&M.

Solid Oxide Electrolyser Cells (SOECs) are still yet to be proven on a large scale so it is a hopeful assumption that these will be widespread and effective in the future. The initial signs are promising so they may well be the prevailing technology in the years ahead. A major benefit of the SOEC is that the high operating temperature of the electrolysis will require less electricity to produce the equivalent hydrogen than other types of electrolyser. [24]

A basic diagram showing water electrolysis is given below: [25]

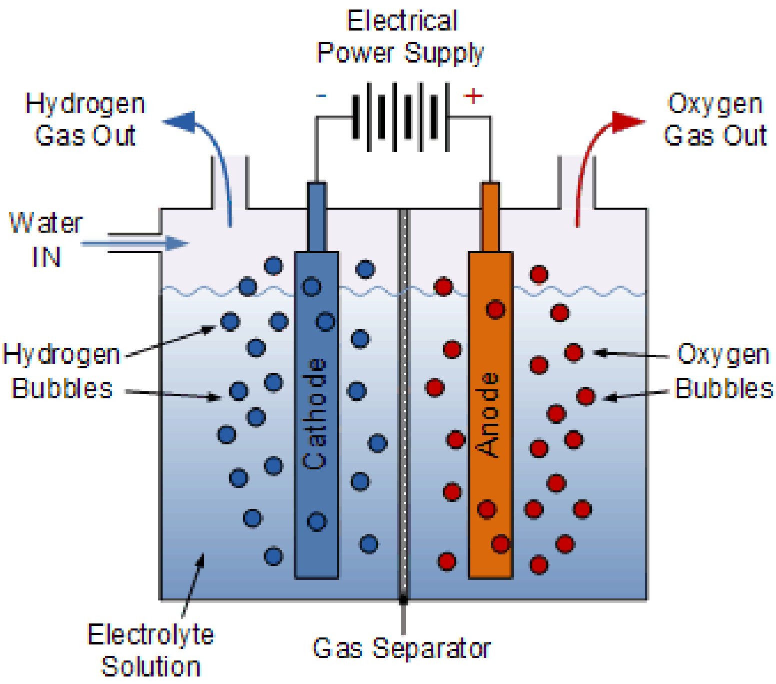


Figure 8 - Water Electrolysis for Hydrogen Production

2.8. Potential for Anaerobic Digestion Hydrogen Feedstock.

Anaerobic digestion output only contains a small amount (<1%) of Hydrogen.[26] However, this biogas could be used as an intermediary in producing liquefied green fuels. In the UK, syngas feedstock may need to come from multiple sources such as AD and biomass facilities in order to meet demand.

In the UK, according to NNFCC (National Non-food Crop Centre), there is 363.23MW of electric anaerobic digestion capacity. [27] The production of biomethane amounts to roughly 45,000Nm3/hr of biogas. The amount of hydrogen required for large scale synthetic fuel production is beyond the capabilities of anaerobic digestion currently.

An AD system can function using a wide variety of feedstocks including distillery waste, sewage, wastewater, and cheese whey. There is not a large production of hydrogen through anaerobic digestion currently, although with the wide-range of possible feedstocks and reasonable economic potential, this may increase substantially in the future. [26]

Table 8
Cost of hydrogen production using different energy sources.

Raw material	Process	Production cost ($/kgH$_2$)	References
Natural gas	Steam Methane Reforming	0.75	[134]
Natural gas	Steam Methane Reforming (with carbon capture & storage)	2.67	[135]
Nuclear	Electrolysis	2.4	
Nuclear	High Temperature Electrolysis	3.5	[136]
Nuclear	Copper–chlorine	1.7	[137]
Nuclear	Sulfur–iodine cycle	1.9	
Coal	Gasification (with carbon capture & storage)	1.8	
Solar	Electrolysis	7.7	[138]
Solar	Photovoltaic electrolysis	9.1	[139]
Solar	Photoelectrochemical	3.5	[140]
Wind	Electrolysis	7.2	[137]
Wind	Electrolysis	7.3	[141]
Biomass	Gasification	1.65	[142]
Biomass	Gasification	1.4–2	[143]
Biomass	Pyrolysis	1.3–2.2	
Biomass	Gasification	4.60–7.86	[144]
Geothermal	Steam electrolysis	1–2.6	[145]

Figure 9 - Cost of Hydrogen Production with Various Technologies

A can be seen in the table above, from Zhang et al, the costs of producing hydrogen through various processes can be quite different.[26] Electrolysis using solar and wind energy is an expensive method although the electricity used may be wasted otherwise. A more practical approach could be through the gasification or pyrolysis of biomass which is thought to be noticeably cheaper.

Primarily, anaerobic digestion aims to produce a biogas mixture consisting of mainly methane and carbon dioxide with small quantities of hydrogen. Alternatively, anaerobic digestion plants can be set up to favour the generation of "biohydrogen".

In this format, much larger quantities of hydrogen could be obtained. This is a possibility to reduce the reliance on expensive, electricity consuming electrolysers to generate hydrogen.

2.9. Impacts of Synthetic Fuel Production Using CO_2

While there are many positives to be taken from the possibility of using synthetic fuels as a means of replacing fossil fuels in transport and as a storage option, negatives have also been identified.

The idea of taking carbon dioxide which would be released to the environment and then re-releasing it when the fuels are combusted may seem counter-intuitive but the recycling effect it has on CO_2 is beneficial considering the CO_2 would have been released otherwise. It may be argued that power stations which release any CO_2 should be replaced by purely clean and renewable forms of generation. This would ideally be true, however, the sheer amount of intermittent renewable energy generation required to avoid the need for a steady load source of energy is currently unfeasible. Back-up reliable power sources are essential to energy security currently.

The extra electricity or biomass required to supply the synthetic fuel process is likely to contribute to environmental impacts unless all electricity is renewable. Currently renewable energy does not provide enough in most countries to produce reasonable amounts for fuel synthesis.

At the moment, carbon capture technology and the unrefined techniques of synthetic fuel production are both relatively inefficient. [2] It remains to be seen to what extent the process can be optimised. The large amount of energy required is a barrier, as is the fact that carbon capture techniques not being effective in removing all of the carbon dioxide from a power plant waste output.

2.10. Energy Storage Opportunities

An important attribute of synthetic fuels, identified by the University of Aalborg's research team, is the ability to be used as an energy storage medium. When compared to electrical and thermal storage solutions, fuel storage is far more effective both practically and economically. A comparison is made in Lund et al between fuel storage and pumped hydro storage.[4] They estimate that the cost of storing energy in the form of electrofuel in tankers would be roughly

2 Euro Cents per kWh. When compared to the cost of 175Euros/kWh for pumped hydro storage, this is seemingly a far stronger method. On closer inspection, the quoted cost of pumped hydro appears to be inaccurate. A number of other sources estimate the cost of pumped hydro to be around a factor of one thousand lower than this. [28]

Shown below in figure 10 is a table of the levelised cost of energy for a selection of storage types and scales from a study on the cost of storage.[29] From Smart Energy Europe's study, they estimate the cost of storing energy in the form of methanol to be 68 Euros per MWh. This is decidedly more cost-effective than any of the technologies shown in the diagram. Discrepancies in the values quoted by the authors of this source across various publications on the subject of energy storage mean that this value cannot be immediately accepted. Smart Energy Europe's value for the levelised cost for pumped hydro storage is roughly 13,000 Euros per MWh which seems to be grossly inaccurate from studying other literature.

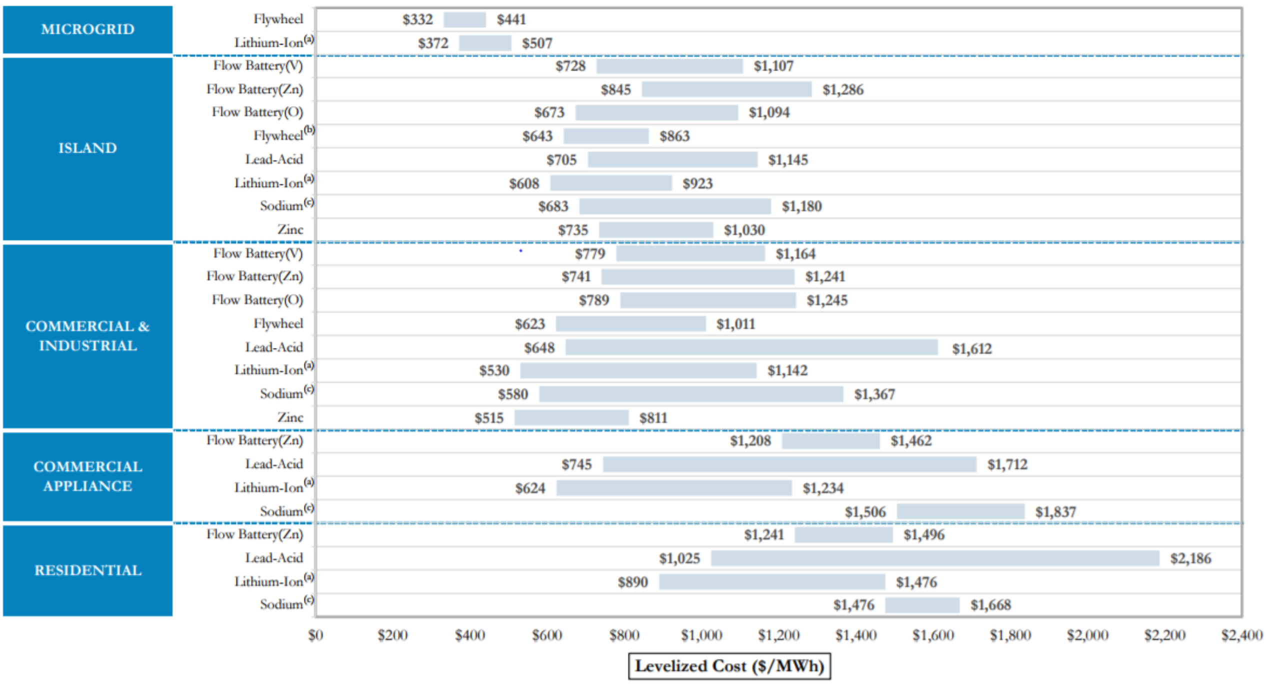


Figure 10 - Levelised Cost of Energy for Storage Technologies

Irrespective of the price of alternatives, synthetic fuel storage is a practical option. Electrical energy storage is an area in which much research is being carried out. However, the progress towards achieving truly efficient and economically viable storage solutions is slow. Fossil fuels represent an extremely practical method of storage although their major drawbacks of scarcity and environmental impact mean they are not a long term sustainable option. Synthetically created fuels allow a clean alternative with competitive storage capacity and capabilities.

This storage concept is an important part of EnergyPLAN's future energy system. It allows for a flexibility while relying mainly on renewable energy. It is a useful way of shifting energy between sectors efficiently when there is the requirement for this energy. Storage is key to supply and demand balancing with renewable energy. No storage method has established itself at the forefront of the technology so there is a niche available for an efficient and practical electrical storage technique.

2.11. Carbon Capture and Recycling/Sequestration

An important part of the process of sustainable synthetic fuel production is the capture of carbon feedstock. It is suggested that carbon can be taken from a biomass source with gasification; alternatively the concept of CCR (Carbon Capture and Recycling) is a promising and demonstrable method of recycling carbon dioxide from the output of a power plant. The double benefit achieved is the prevention of carbon dioxide entering the atmosphere while also obtaining a useful fuel for chemical synthesis.

Carbon capture and sequestration is a concept which has attracted a lot of interest in recent years. This involves the storage of carbon dioxide once it has been captured. Injecting and storing this carbon dioxide deep underground prevents the CO_2 from exhibiting the greenhouse effect which accelerates global warming.

The process of carbon capture involves using metal hydroxides to react with carbon dioxide in industrial flue gases resulting in the formation of carbonates. The carbon dioxide can then be extracted from these carbonates. The technology will require reasonably large investment.

A possibility for the future is the extraction of carbon dioxide directly from the air. Various conceptual technologies have emerged although none have been proven to be effective on any reasonable scale. Concepts designed to extract CO_2 from the atmosphere using "carbon trees" have emerged although this seems a distant reality on a large scale.

When carbon capture technology is installed within a plant, the energy supply to the process needs to increase. Electricity and steam needed for the carbon capture process must come from further fuel combustion which will in turn increase carbon emissions further. In Gustavsson et al, it is calculated that for a coal power plant the energy consumed per MWh of electricity output is usually 2.29MWh, and with carbon capture integration it is 2.89MWh. [30]

From the Smart Energy Europe Report, the estimated costs for investment and lifetime operations and maintenance were given for carbon capture. [3] Per Mt of captured carbon dioxide, an initial investment of 30 million Euros was given. This is an extremely large cost and will need to be reduced in order to become feasible.

When considering that it takes 250,000 tonnes of CO_2 to produce 1twh of synthetic fuel, an investment of 7.5 million euros would be required per TWh for carbon capture technology alone. These values are given in the figure below.[3] If a conservative 10% of transport fuel demand was met through synthetic means, this would require 150 million Euros investment using the EnergyPLAN model for just the carbon capture technology.

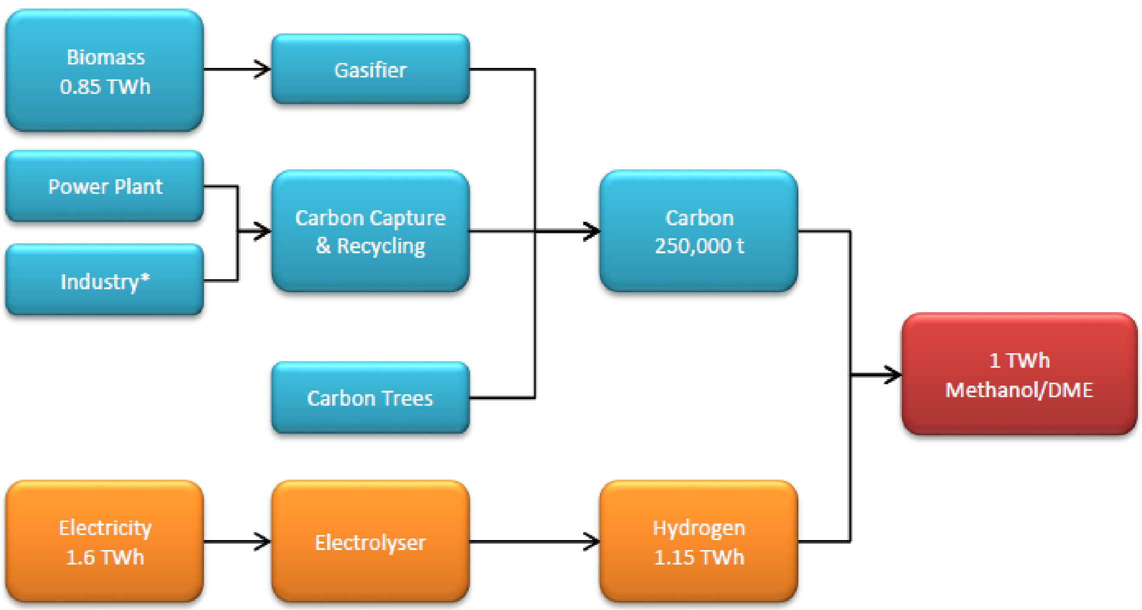


Figure 8: Carbon and hydrogen required to produce electrofuel in the form of methanol or dimethyl ether (DME). A variety of different carbon options are displayed here to illustrate the options available. *Cement production is one very good example of an industrial process with surplus carbon.

Figure 11 - Process and Energy Requirements for Synthetic Fuel

The figure from IDA's Smart Energy Europe report show's a potential pathway to producing di-methyl ether and methanol. Noticeably the efficiency in terms of electrical to stored energy is not very high, however, a large amount of renewable energy will need to be produced in a 100% renewable scenario so there will be significant surplus. The stored energy can be used in the transport sector so it has two potential uses: producing electricity or fuelling transport.

According to the Smart Energy Europe figure, it requires 1.15TWh of hydrogen and 250,000 tonnes of carbon dioxide feedstock to produce 1TWh of methanol or DME fuel. In order to produce this hydrogen and carbon dioxide, 0.85TWh of biomass and 1.6TWh of electricity are required, as well as the captured carbon from industrial processes. It must be noted that these are merely estimates and it is quite possible the energy requirements would be higher.

2.12. UK vs Denmark Energy Systems

Denmark is currently a leading nation in sustainable energy. Its renewable generation is largely dominated by wind, which produced 41.8% of electricity consumed in Denmark in 2015. [31] As well as this, the energy security of Denmark is very reliable and strong interconnection between other nations is important there.

Compared to the UK, there are definite differences, although the potential for the UK to recreate a similar system does exist. Some concepts from Denmark can be borrowed, while others would be difficult to implement due the size and population differences as well as differing domestic resources. Both countries have a high potential wind resource as well as biomass potential; the much larger consumption in the UK is the main factor which separates the countries. For this reason, the UK will likely be built on a mixture of lots of different energy types as the demand cannot be satisfied through only one or two sources.

Denmark, because of its concerted efforts towards wind power generation, has a higher renewable penetration than the UK. This gives more of a potential for the synthesis of electrofuels through renewable means. The UK is improving towards higher levels of renewable energy and this can be seen in figure 12. Denmark is still far ahead of the UK in renewable electricity generation, shown in figure 13. Figure 13 highlights the slow progress from the UK transport sector when it comes to renewable energy. This is also the case in most countries.

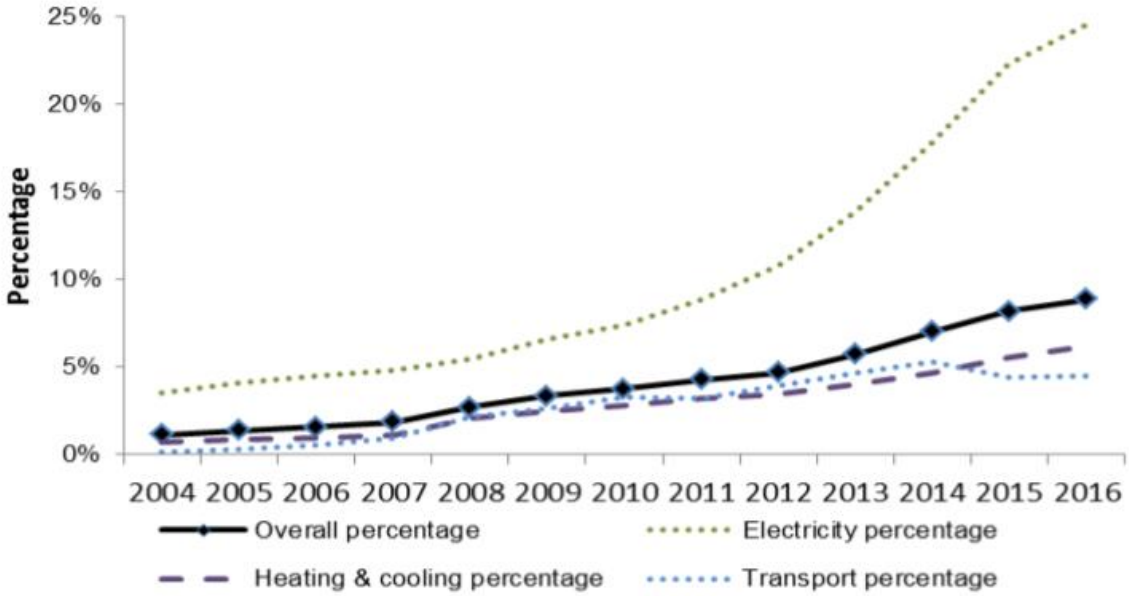


Figure 12 - Renewable energy as share of different sectors

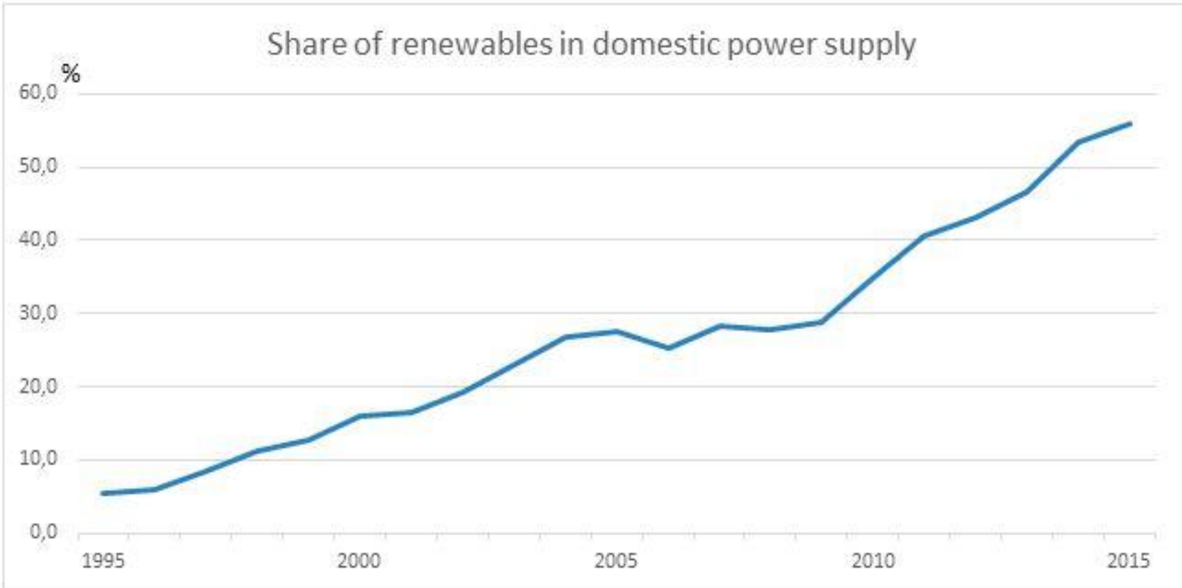


Figure 13 - Percentage share of renewable energy in domestic power supply

The UK has recently backed a large scale nuclear power station at Hinkley point, England. This will hopefully mean that fossil fuel generation can decrease whilst renewable generation continues to increase. In saying this, many of the current nuclear power stations are coming to the end of their lifetime so the future of nuclear is unpredictable in the UK. It is difficult to see whether the government will continue to back renewable energy in a time of political uncertainty.

Denmark on the other hand is likely to continue expanding its renewable energy output, leading to greater possibility for synthetic fuels to become an important part of the energy system.

2.13. Alternatives – Electric and Biofuel Powered Vehicles

Biofuels are an increasingly produced alternative to fossil fuels. They can be made through the fermentation of agricultural waste or food crops to produce alcohol based fuels such as bioethanol. Environmental performance of these fuels is good, although the land area and food crops required if biofuels are to become a major player in the transport sector is extremely high.[32]

Ethanol produced from cellulosic biomass requires large land use which could be used for food crops. There is not enough resource available to use ethanol as a main source of fuel, however, it is effective as a supplement in blends to decrease the environmental impact of some fuels.

Ethanol exhibits a lower energy density than pure gasoline. Cars designed for gasoline have a better efficiency with gasoline, however, engine modification could lead to higher ethanol fuel efficiencies.

Biofuel is a more geographically dependent technology. If there is a smaller population density and a large enough area of arable land capable of producing energy crops then it is possible to generate large quantities of biofuel without compromising food supply. Brazil has proven that successful widespread biofuel production is possible – bioethanol is a prominent fuel in Brazil.

The weather-dependent nature of growing crops to produce fuel will always give uncertainty to both supplier and consumer as to the quality or quantity of fuel available. There is an element of risk which demands a back-up plan if yields fall.

Scandinavian countries have been prominent in using ethanol as a low percentage fuel blend in their standard fuel stations.

Additionally, job creation in more rural areas is beneficial in most countries as many need to move to urban areas for work.

IDA (Danish society of Engineers) believe that the electrification of transport supplemented by electrofuels is a more beneficial strategy than the use of biofuels. [3]

Connolly et al estimate that biofuels and electrofuels will be cheaper than fossil fuels by 2050.[2] A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system is carried out in Mathiesen et al.[33] There are a variety of possible fuel types although a prevailing feedstock type or process is yet to be identified. At this time though, they are still a distance from competing price-wise, especially due to the current low oil prices.

Electric vehicles are an attractive option as they do not produce emissions as the motor runs. This will drastically improve air quality in cities and will reduce health and environmental risks. Currently electric cars do not have the range required to be practical for long distance drives or rural areas due to battery life and a lack of infrastructure. Despite this, steady improvements are being made and it will not be too far into the future that electric vehicles will be ubiquitous. At the moment, electric cars only account for a small portion of the passenger car market. The figure below gives an indication of the status of electric cars in the EU.[34]

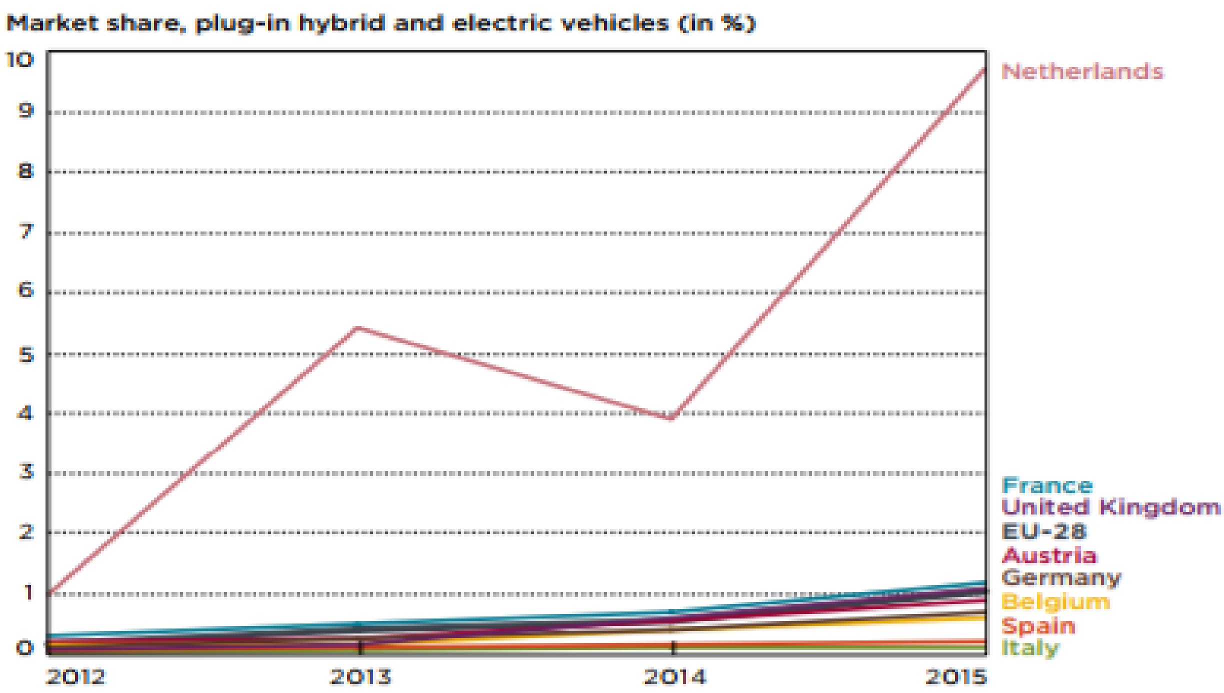


Figure 14 - Current electric/plug-in hybrid share of European passenger car market

The diagram shows how far most countries are from having widespread electric vehicles. There is plenty of room for alternative renewable technologies to supplement electric vehicles and alleviate the dependency on them.

As mature as technology becomes, many will not be able to afford a new electric vehicle so there will be a place for more environmentally friendly fuels in the meantime. It must also be noted that while fossil fuel electricity generation is still the prevailing technique, electric vehicles are only as clean as the electricity being used to power them. It may be more beneficial to use synthetic fuels in vehicles than to use coal powered electric vehicles for example. In the future electric vehicles will become increasingly efficient and environmentally friendly.

National energy policies will play a big part in the advancement of electric vehicles. Grants and subsidies are available in most countries to promote "green" vehicles although this is particularly generous in Scandinavian countries (especially Norway) and the Netherlands which are leading the way in electric vehicles in Europe. The graph below shows the sales of percentage of new cars sold which are fully electric or plug-in hybrid in a range of countries.[34]

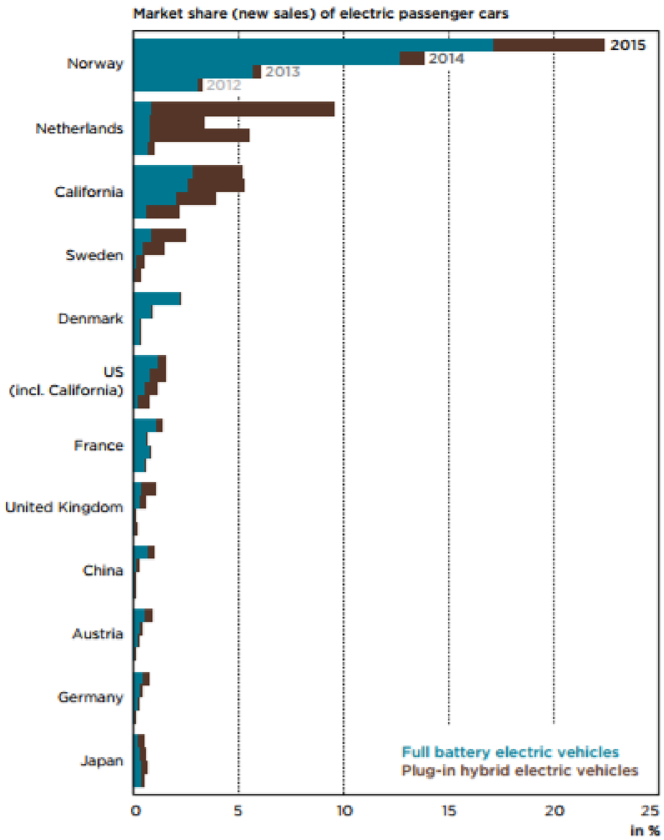


Figure 15 – New Sale Electric Car Share in Different Countries

Norway is showing that there is the available technology although the especially high GDP per capita and taxation there does allow for this investment in electric vehicles.

2.14. Literature Review Summary

From the literature, information on the state of the art technology and possibilities for synthetic fuels has been collected. This gives a good idea of the key parameters which should be evaluated to continue the investigation into the feasibility of synthetic fuels in the UK.

According to Steffen Schemme et al, the key determinants on the cost of electrofuel production are the electricity price and electrolyser costs.[35] The economics associated with fuel synthesis will be investigated.

The ability to source the carbon component of fuel from a renewable source is an important part of synthetic fuels. The effect this has on carbon emissions will be analysed.

Another important consideration is how the integration of synthetic fuels affects the rest of the energy system. A knock-on effect can occur with their introduction which can significantly increase the renewable penetration in an overall system but can conversely have detrimental effects in some cases.

Overall, electrofuels are a clever way to connect aspects of the modern and future energy system such as transport, storage, and electricity. They have benefits environmentally and provide possible storage solutions. Economically, the several stages to the process and electricity requirement mean that feasibility is still debateable. Adding to this, energy efficiency is not especially high.

The technology is available but whether this can fit into a complex national energy system is the next question to be answered.

3. Main Analysis Introduction

This section will give an introduction to the analysis stage of the project, highlighting the aims for this part and describing the methodology. Important assumptions made for the analysis are listed and discussed. Information on the software used as well as why it was used is found in section 3.2.1. The software notes and observation section provides additional context with regards to the EnergyPLAN programme and its uses and limitations.

3.1. Aim of Analysis

The main aim of the project, as stated in the introduction was:

“To investigate the feasibility of synthetic transport fuels from a renewable source as part of the UK energy system.”

For the analysis section, the possibility of synthetic fuel will be evaluated by creating a UK model and running several simulations for different synthetic fuel scenarios. Visual representation of the effect of synthetic fuels in the UK will be shown and their feasibility determined.

It will be investigated whether the proposals of a “smart energy system” by the EnergyPLAN researchers could be applied to the UK, with a focus on synthetic fuel. Assumptions and suggestions from their research will be scrutinised to make a judgement on the validity of the programme and the future of synthetic fuels.

It is hoped that by using modelling software, ideas and potential future strategies which could not be found in the literature review can be identified.

3.2. Analysis Approach

The analysis will aim to achieve several objectives, each helping to contribute to answering the aim of the project. The list of objectives completed throughout the modelling stage were as follows:

- Become familiar with the capabilities and limitations of EnergyPLAN software by undertaking tutorials and learning the user interface
- Study the EnergyPLAN manual and appropriate literature in order to understand the reasoning behind assumptions and programme decisions
- Run a series of test scenarios to narrow the modelling scope and decide on appropriate scenarios to move forwards with
- Design final scenarios to see how different strategies of synthetic fuel integration compare and how they fit in with the overall UK energy system
- Run the simulations for the main scenarios and identify key parameters and results to focus on in the discussion section
- Critique and evaluate the programme and the assumptions used throughout analysis

Completing these objectives will give a platform on which to form conclusions and complete a discussion section reviewing the project aim.

3.2.1. EnergyPLAN Introduction

For the modelling and experimental portion of the thesis, it was decided to use EnergyPLAN software as it is a tool created by the researchers from the University of Aalborg, Denmark, whose work this thesis investigates and evaluates. The software allows for the simulation of a full energy system at a large range of scales with accurate results in 1 hour increments. EnergyPLAN has several ready-built scenarios based on the Danish energy system which can be used as reference.

EnergyPLAN gives information on carbon dioxide emissions from the whole system, as well as showing demand vs supply graphs, system costs, renewable generation and renewable share of total energy supply.

EnergyPLAN is tailored to a specific ideology of how the energy systems of the future should or could look with several example scenarios available to run. The programme encapsulates what their researchers describe as a "smart energy system" – an integrated and intelligent system connecting all of the sectors efficiently and in a sustainable way. For this analysis, a blank scenario was created to which data from the UK was inputted as well as cost data from an EnergyPLAN database. [36]

Transport fuel was the main focus although many parameters across the programme were adjusted to create an accurate representation of current and possible UK energy landscapes. Models were then created for several scenarios to evaluate the possible effects of synthetic fuel integration in the UK. Comparisons were made to alternative pathways and possibilities with the aim of determining whether synthetic fuel production is a worthwhile substitute to fossil or biofuels.

3.3. Analysis Methodology

The main objective was to compare different options for implementing synthetic fuels and to weigh up the advantages and disadvantages of each.

A basic UK energy system model was then built to examine the feasibility of implementing synthetic fuels for use in transport. The model included current UK energy generation and consumption by sector. Electricity generation sources were also specified. Several changes were made resulting in new scenarios with different penetrations of synthetic fuel within the transport sector.

Once general trends were seen in terms of which scenarios produced the best results, smaller parameters and details were changed. As the simulations were run, improvements and adjustments were made to the models culminating in the main results discussed in Chapter 4.

Graphical results were produced from the main scenarios chosen and these were analysed in order to draw conclusions. The advantages and disadvantages of each system were weighed up meaning that suggestions on strategy could be made.

The four scenarios that were chosen to present in this thesis are outlined below:

Scenario 1

Firstly, it was chosen to focus on the production of both synthetic petrol and diesel alternatives for road vehicles, as well as for synthetic aviation fuel. The demands for the scenario were taken from government statistics.[37] This scenario models a UK energy system with different percentages of synthetic fuel within the transport sector. Carbon capture from industrial processes is used as the carbon source while water electrolysis is the basis for the hydrogen input. A hydrogenation process was used to create the syngas. It was required to change electrolyser sizes and electricity supply as more synthetic fuel was produced. Scenario 1 is described in full in section 4.1.

Scenario 2

In the second scenario, a similar model was set-up to produce different amounts of synthetic fuel in each simulation for both road vehicles and air travel. However in this case, the carbon required was sourced from biomass gasification gas and syngas was produced in a synthetic gas plant as opposed to a hydrogenation plant. Electrolysers were also required for hydrogen production. Results and a description of scenario 2 are found in section 4.2.

Scenario 3

For the third scenario, a mixture of both the above methods was evaluated. 50% of the synthetic fuel was produced using carbon capture and electrolysis, while the remaining 50% was provided from a biomass feedstock. This was to examine whether there were advantages to spreading the required feedstocks across different areas. Section 4.3 elaborates on scenario 3.

Scenario 4

Synthetic jet fuel was investigated in the final scenario. Jet fuel had been part of the prior scenarios but on this occasion in is examined on its own. Aviation was covered by increasing amounts of synthetic jet fuel while remaining areas of the transport sector were provided with fossil fuel. In this scenario, the synthetic jet fuel is produced using gasification gas with the same process as discussed in scenario 2. The final scenario is detailed in section 4.4.

For this scenario, the synthesis gas was supplied from a hydrogen and gasification gas feedstock. Carbon capture and Storage was not considered. Simulations were run for various different levels of synthetic fuel penetration meaning biogas production and electrolyser sizes were adjusted accordingly.

A further scenario investigating only synthetic jet fuel was set up to see how feasible this may be as an alternative to a fully synthetic transport system.

3.3.1. Assumptions

The main assumptions used throughout the analysis are identified below. Assumptions can change the main results quite significantly so care was taken to ensure assumptions were not overly unrealistic.

- UK energy system did not include nuclear energy, instead a power plant capacity of biomass and natural gas was chosen (80% natural gas, 20% biomass)
- The fuel efficiency of synthetic fuels is equal to that of fossil fuels for the end-user
- Renewable electricity was generated from wind, solar pv, and hydroelectric
- Costs taken primarily from the EnergyPLAN cost database for the year 2020
- Costs are given in yr2009 Euros
- Some costs were not input into EnergyPLAN if they were not relevant to the scope and would not be affected by synthetic fuel generation, this means overall system costs will be underestimated slightly.

- The efficiencies built into the model were assumed to be correct although the accuracy of these will be analysed in section 5.

The main forms of renewable energy in the UK were included with their current capacities. Developing renewable generation technologies such as wave and tidal were not considered.

Synthetic fuels have differing fuel efficiencies but in general similar to those of fossil fuels so this assumption was deemed appropriate.

The EnergyPLAN website provides an extensive cost database which can be used to input costs for fuels and technology in the EnergyPLAN programme. A 2016 version of the database was used in this study.

The costs were given in 2009 Euros and were estimated for current prices as well as for future scenarios. The degree of accuracy of these costs is inherently unknown as with any predictions of future markets although for the purposes of this report they will be used.

As financial aspects are not the main area of interest in this study, the cost database is of adequate quality.

Costs are input into fields for a list of technologies and give a resulting output for the annual and total lifetime expenditure. The fuel, investment, and additional costs assumed for the modelling phase are shown below:

Fuel Costs

Table 1 - EnergyPLAN Fuel Costs

Fuel Type	Fuel Price (EUR*/GJ)
Carbon Dioxide	28.6 Euros/tonne CO_2
Diesel	15
Petrol/Jet Fuel	15.2
Natural Gas	9
Biomass	1.8

*2009 Euros

Investment Costs

Table 2 - EnergyPLAN Investement Costs

Technology	Investment (Million Euros/MW Installed)	Lifetime (Years)	O&M (% of initial investment)
Large Power Plant	1	30	2
Wind	1.5	25	2
Photo Voltaic	0.9	40	1
Hydro Power	3.3	50	2
Hydro Storage	7.5	50	1.5
Hydro Pump	0.6	50	1.5
Electrolyser	0.6	20	2.46
Biogas Upgrade	0.3	15	15.79
Gasification Upgrade	0.4	15	15.79

Additional Costs

Table 3- EnergyPLAN Additional Costs

Technology	Investment (Million Euros/MW Installed)	Lifetime (years)	Operations and Maintenance (% of Initial Investment)
Biogas Plant	240*	20	6.96
Gasification Plant	0.4	25	5.3
Synthetic Gas Plant	0.4	25	5.3
Chemical Synthesis	0.6	20	3.48

*Million Euros/TWh/Year

The cost for a synthetic gas plant is not given in the EnergyPLAN cost database and so was assumed to be equal to that of a gasification plant.

The inputted values for various forms of generation and demand have been estimated for a 2020 UK Power system. The energy mix can be changed slightly without much effect on synthetic fuel in the system. It is in place to give a general idea of how much effect the implementation of synthetic fuels would have on parameters such as carbon emissions, renewable energy penetration, and overall costs.

Statistics on the energy share in the UK can be seen in the table below. [37]

Generation (TWh)	2014	2015	2016	Percentage share in 2016
Onshore Wind	18.6	22.9	21.0	25.2%
Offshore Wind	13.4	17.4	16.4	19.7%
Shoreline wave/Tidal	0.0	0.0	0.0	0.0%
Solar photovoltaics	4.1	7.5	10.4	12.5%
Hydro Small scale	0.8	1.0	1.0	1.2%
Hydro Large scale	5.1	5.3	4.4	5.3%
Landfill gas	5.0	4.9	4.7	5.7%
Sewage sludge digestion	0.8	0.9	1.0	1.1%
Municipal solid waste combustion	1.9	2.6	2.7	3.3%
Co-firing with fossil fuels	0.1	0.2	0.1	0.1%
Animal Biomass	0.6	0.6	0.7	0.8%
Anaerobic Digestion	1.0	1.5	2.1	2.5%
Plant Biomass	13.1	18.6	18.8	22.6%
Total generation	**64.5**	**83.4**	**83.2**	**100.0%**

Figure 16 - UK Energy Generation Share

The generation for these renewable technologies were input into the software while a power plant capacity comprised on natural gas and biomass accounted for the additional demand. This included electrical, heat, and transport fuel demand. The 80% to 20% ratio of natural gas to biomass is roughly accurate according to Ofgem government statistics. The current electricity share is illustrated in the graph below from government statistics. [38]

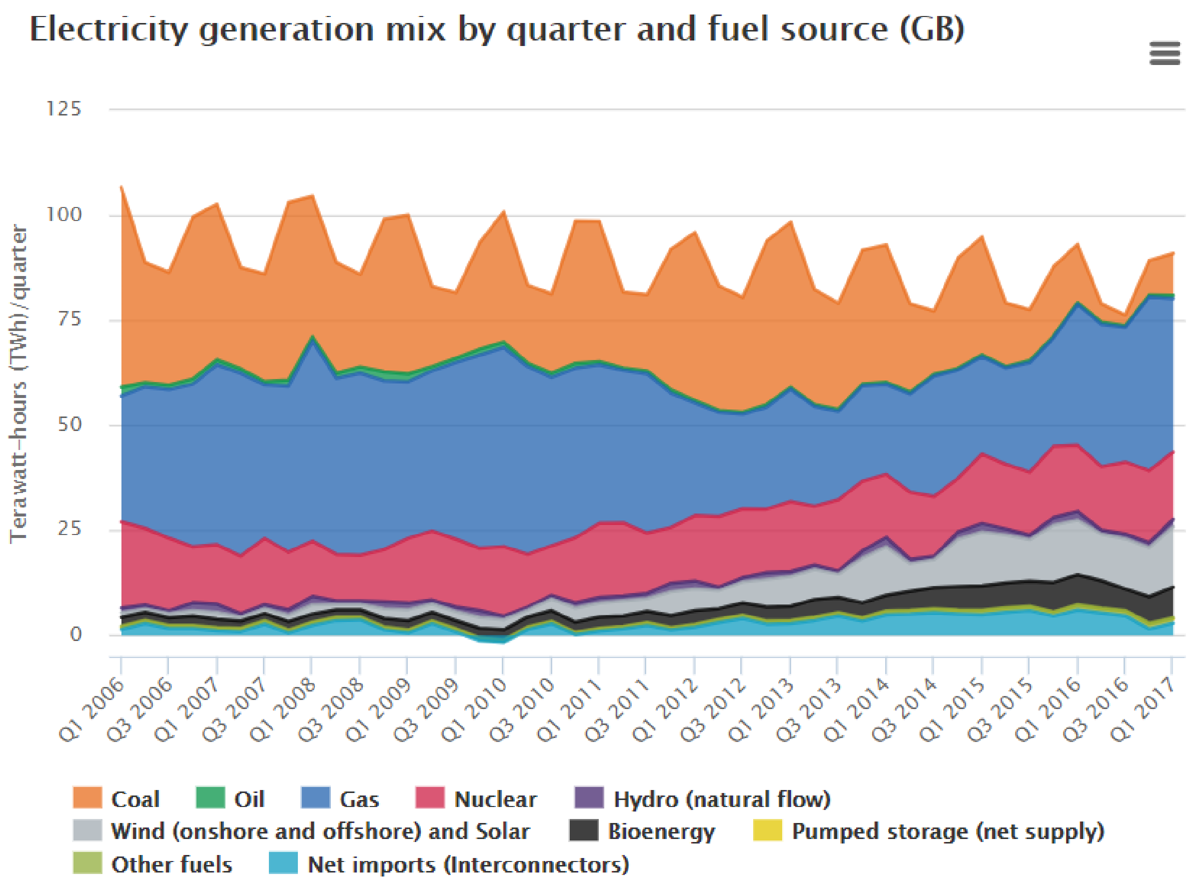


Figure 17 - UK electricity generation mix by source

As can be seen in the graph, coal reserves are dwindling while natural gas is still providing large amounts of electricity. Nuclear has remained steady over the last ten years and wind, solar, and bioenergy are increasing quite quickly. Coal was not considered in the modelling as its importance has sharply declined.

3.3.2. EnergyPLAN software notes and observations

Figure 18 below represents the full system which is considered in EnergyPLAN software. [39]The interconnections between different branches of the energy sector is a key factor in creating balance and flexibility across a national energy system.

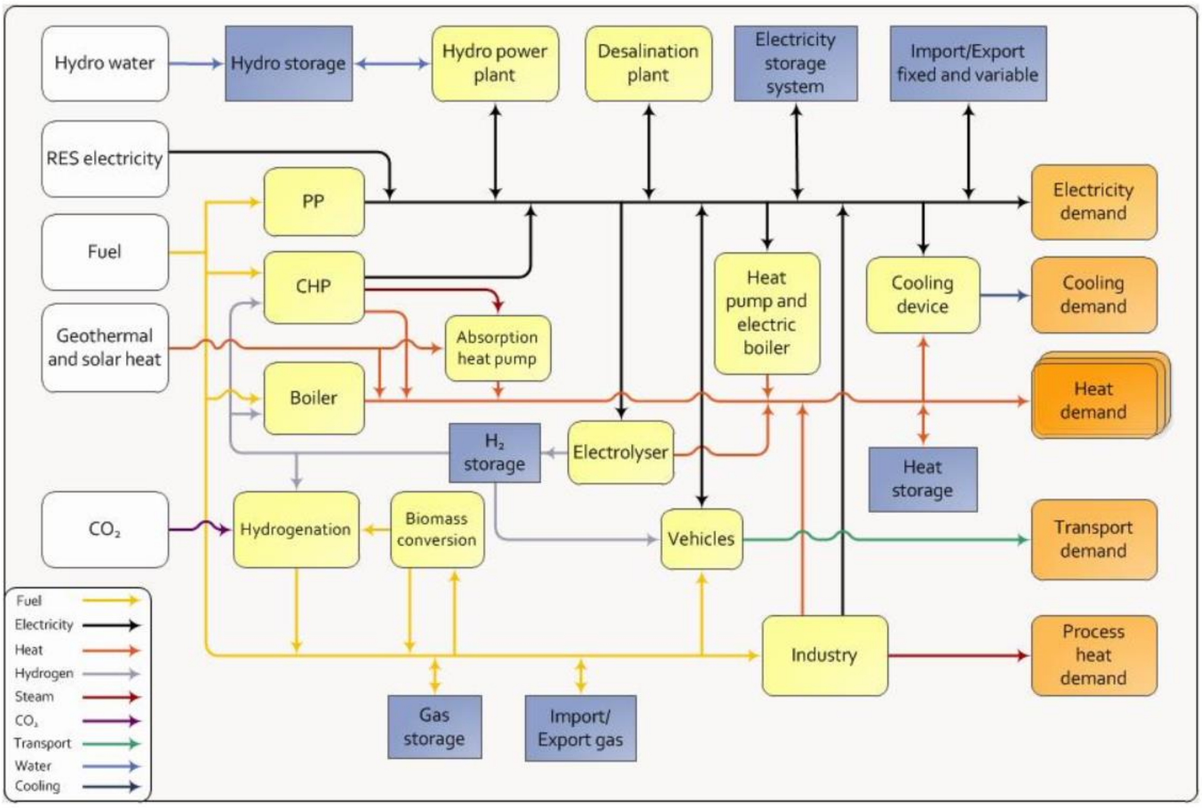


Figure 18 - EnergyPLAN Programme Systematic Diagram

In the synthetic fuel section, it can be shown that to produce 5twh of synthetic diesel and 5twh of synthetic petrol, 20.6tWh of electricity are required. This gives an efficiency of roughly 50%. Other methods with a far greater efficiency are possible. When considering emissions, unless the electricity is taken from a 100% renewable source then there will be significant electrical requirement resulting in high emissions. Accurately modelling an entire energy system is out with the scope of this thesis so the models created do not fully describe the UK's energy system, just those parameters that are important or relevant to synthetic fuel integration.

As mentioned earlier, some of the assumptions and values quoted by EnergyPLAN researchers or built in to the software were not seemingly accurate. Costs of 175Euros/kWh and 100 Euros/kWh for pumped hydro storage were contradictory and inaccurate and led to the questioning of the validity of some results. Optimistic assumptions with regards to the cost and availability of unproven technology such as Solid Oxide Electrolyser Cells (SOECs) were given although, in general, assumptions were consistent with other literature.

The geography of Denmark is not conducive to large hydropower output so it is understandable that they have not considered this in their system. Large differences in the energy landscapes of Denmark and the UK mean that their overall energy system plan cannot be applied to the UK, however, the importance of synthetic fuels and the modelling software can be used.

It is important to work with accurate data on the current state of the UK's energy system in order to give context to each scenario. Statistics were collected from the UK government website for electricity consumption and the transport sector. These could then be input into the programme.

The UK electricity consumption was roughly 300TWh in 2016; the generation was around 335TWh.[37]

For the EnergyPLAN analysis, major costs have been inputted into the model although a detailed financial analysis using this software will not be carried out. It is not within the objectives for this project. Economics will be considered in other areas but a full analysis will not be conducted in the modelling.

From government statistics on transport emissions, steady reductions have been made every year leading up to 2014.[40] The emissions from aviation can be hard to quantify due to the different altitudes and zones they occur.

Below are two diagrams (figures 19 and 20) illustrating the two possible pathways to producing synthetic fuels. The first diagram shows the gasification gas from biomass pathway, and the second shows the hydrogen electrolysis and carbon capture pathway. [41]

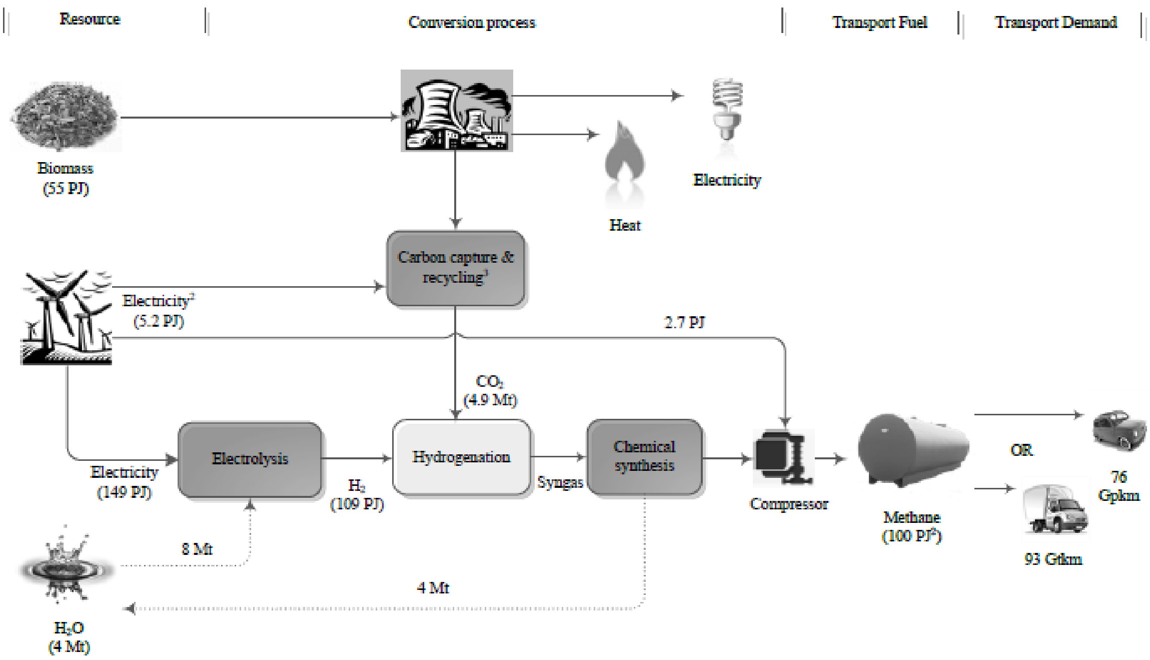


Figure 6: An example of a CO_2-electrofuel production process: carbon that is sequestered using CCR at a power plant and afterwards, it is hydrogenated to produce methane [42, 76].

Figure 19 – CCR and Renewable Energy to Synthetic Fuel Process with Energy Values

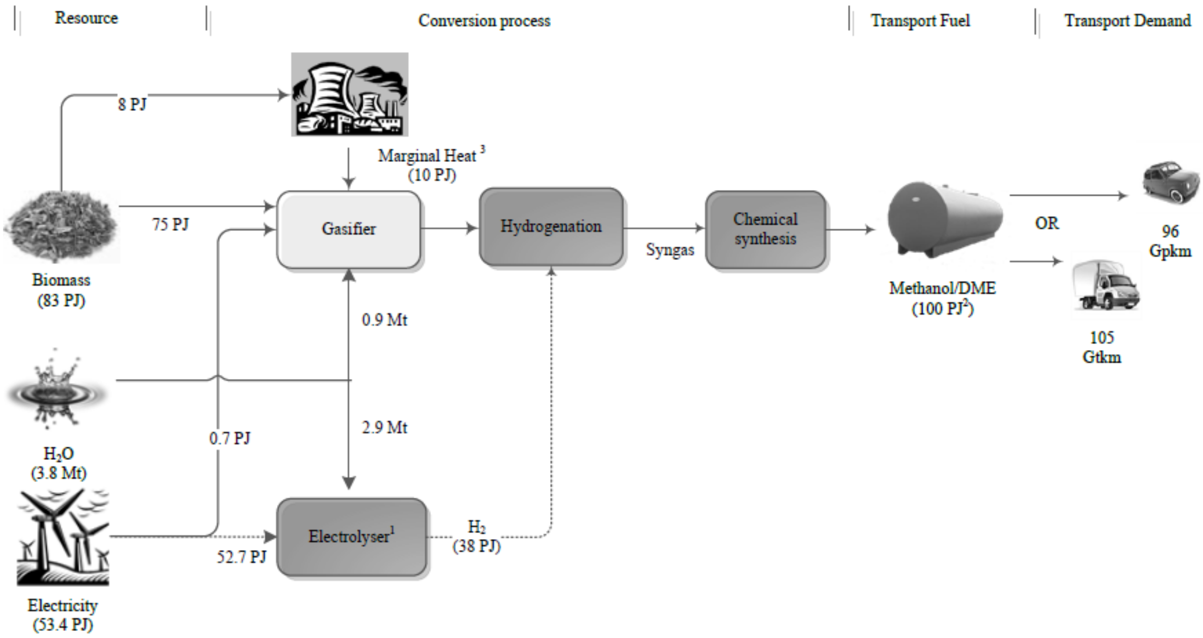


Figure 5: An example of a bio-electrofuel production process: biomass is gasified and the resulting gas is hydrogenated to produce methanol or dimethyl ether (DME) [42, 76].

Figure 20 - Biomass Gasification to Synthetic Fuel Process with Energy Values

Above diagram from Smart Energy Europe 2015.

There were some shortcomings to the software with regards to missing fuel types. Synthetic versions of diesel, petrol, and jet fuel were all considered but the exact form each of these fuels was in was not specified. A comparison between various options such as DME, methanol, and synthetic gasoline would give a more detailed insight into the effectiveness of different fuel types. These are relatively new topics of research so may be difficult to model successfully at this time.

Another improvement which could be made to the programme would be to quantify other emissions such as nitrous or sulphurous oxides. This would give a wider perspective of the effects of different technologies or strategies.

For fuel consumption, 600tWh was taken to be consumption across road and aviation sectors. This was comprised of 460tWh from road, and 140tWh from air travel. So for example in the 50% synthetic scenario, 50% of road travel (230tWh) and 50% of aviation (70tWh) was provided by synthetic fuel.

4. Analysis Results

This section shows the graphical results and analysis from modelling different scenarios on EnergyPLAN. Each of the four scenarios will have the results presented, followed by a discussion of these results.

The results given by EnergyPLAN deemed to be the most important were carbon dioxide emissions, system costs, and the percentage share of the primary energy supply from renewables. Hence, these are graphically illustrated and discussed.

Simulations were run for different percentages of transport fuel. In the first 3 scenarios discussed, the following applied:

Table 4 - EnergyPLAN Simulation Types

Simulation number	**Synthetic fuel percentage**
Simulation 1	0% synthetic fuel
Simulation 2	20% synthetic fuel
Simulation 3	40% synthetic fuel
Simulation 4	50% synthetic fuel
Simulation 5	60% synthetic fuel
Simulation 6	80% synthetic fuel
Simulation 7	100% synthetic fuel

For scenario 4, fewer simulations were run, going from 0% to 100% synthetic jet fuel in 25% increments.

4.1. Scenario 1 – CCR and Electrolysis

Building from the concept of electrofuels, a scenario was designed in which synthetic fuels were produced from captured carbon and hydrogen produced through electrolysis. Simulations were run using 0%, 20%, 40%, 50%, 60%, 80%, and 100% synthetic transport fuel. The carbon capture capacity chosen equated to the amount of carbon dioxide feedstock required for fuel synthesis.

An electrolyser is required for this scenario with increasing capacity as more hydrogen is required to produce more synthetic fuel. In this case biomass is not required in fuel synthesis.

4.1.1. Results

High costs are the most visible result when synthetic fuels and carbon capture are implemented within a system. This is in part due to the very high electricity demand required for carbon capture and electrolysis. CO_2 hydrogenation is a substantial expenditure (around six billion Euros per annum for the 100% synthetic simulation) which increases as synthetic fuel is added to the system. An increase is seen in the share of renewable energy as part of the primary energy supply as higher amounts of synthetic fuel are produced.

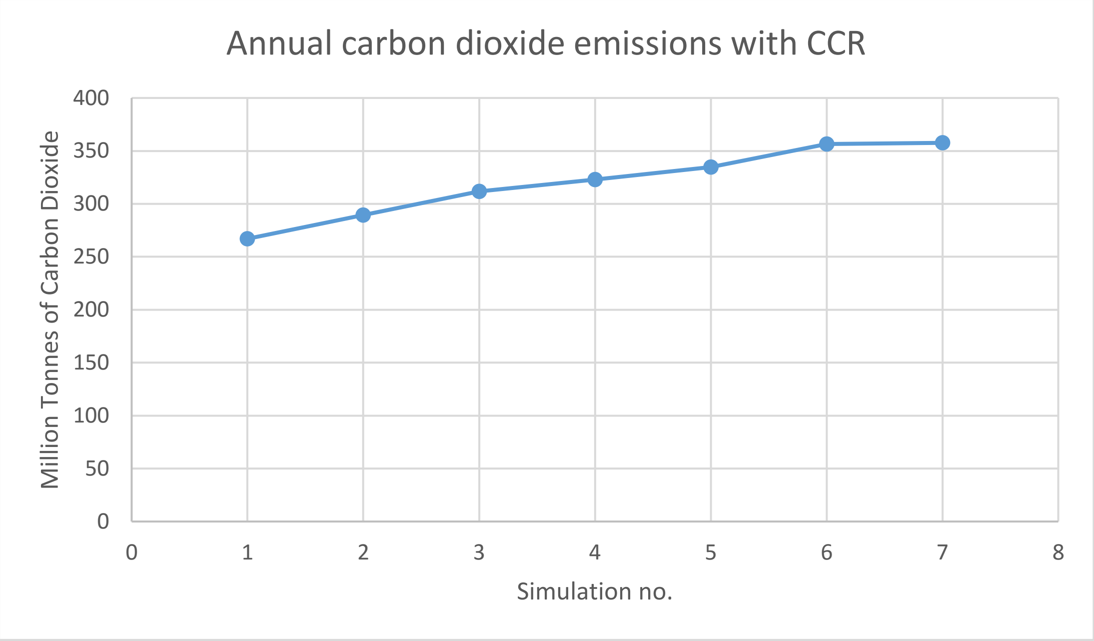


Figure 21- Scenario 1: CO_2 Emissions

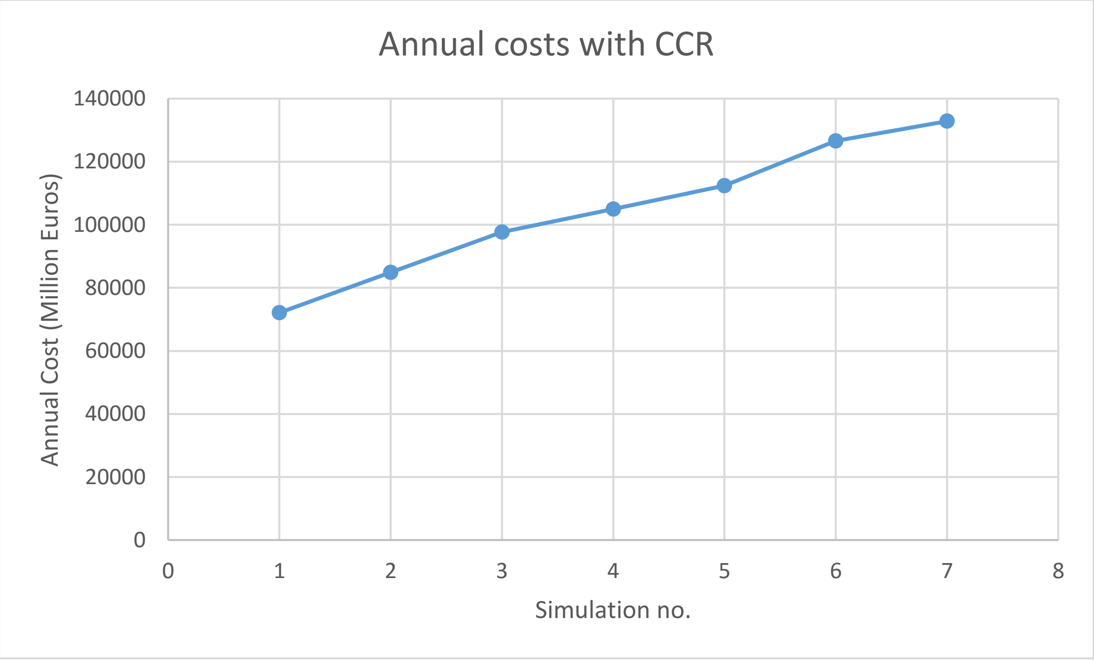


Figure 22 - Scenario 1: Annual Costs

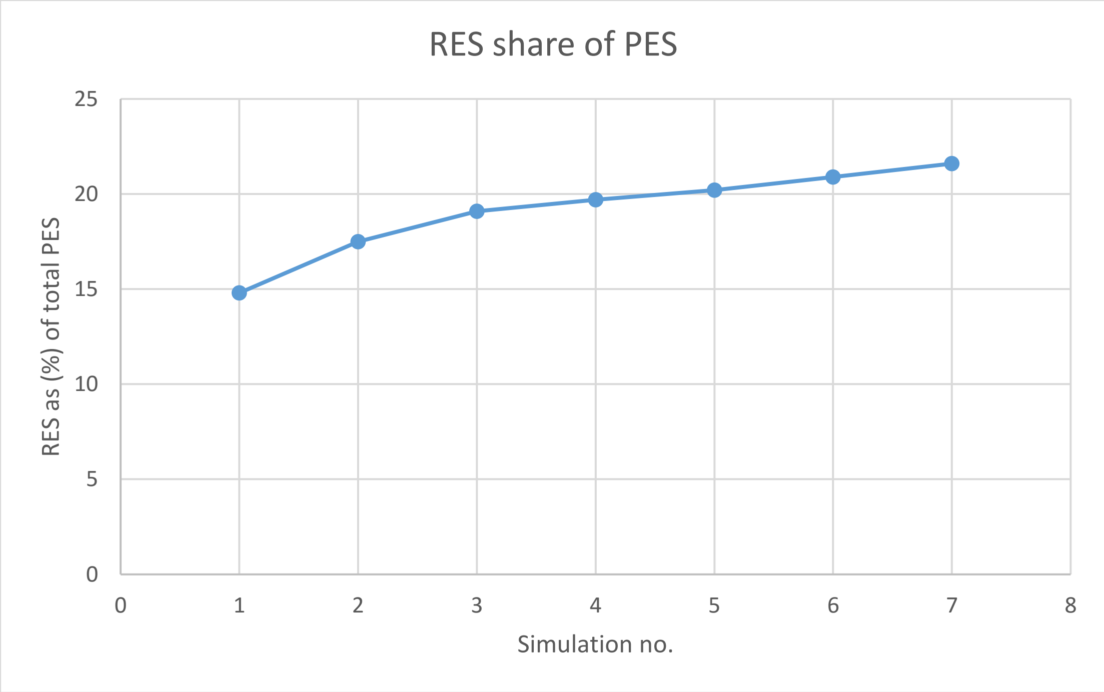


Figure 23 - Scenario 1: RES Share of PES

4.1.2. Discussion

Figure 21, above, shows that the production of synthetic fuels with CCR technology will increase CO_2 emissions. In reality this would not be the case, certainly not as drastically. The model has used considerable amounts of fossil based electricity to supply the electrical demand required to capture carbon and run hydrogen producing electrolysers. If renewable energy was in excess then this additional electricity would not increase CO_2 emissions.

In the EnergyPLAN models, the electricity supply to electrolysis when large amounts of hydrogen were required was predominantly from power plant sources. This led to greater carbon emissions than expected, even with carbon capture.

The effect seen on RES share of the PES is noteworthy although not as important a contribution as in some of the other scenarios. When electricity is used rather than biomass as a source of hydrogen, natural gas producing this electricity is more prominent and still accounts for a large share of overall energy requirements. Renewable energy cannot supply enough for the large electricity demand so power plant capacity must be increased. This leads to higher emissions while wind, solar, and hydro power remain with the same output.

From the results, it seems too large a financial outlay to produce synthetic fuel on a large scale using carbon capture and electrolysis. In a country such as Denmark with a very strong wind resource and a relatively small population. The ability to store excess energy generated and utilise it within the transport sector seems a lucrative opportunity. In the UK however, the amount of renewable electricity which would need to be produced in order to facilitate the electrolysis and production of hydrogen on a large scale seems infeasible.

Further electricity was required for chemical synthesis and hydrogenation. Overall the electricity required for a 100% synthetic system was over 1000TWh. This is over three times the normal electricity demand of 300TWh and almost three times as much as the current supply of 335TWh. Realistically 100% synthetic fuel is unfeasible, however even a smaller penetration such as 30% would require UK generation to double in order to supply the required electricity for syngas production. Electricity requirements were predominantly for electrolysis and a comparatively small amount was needed for carbon recycling. Only 60% of the electricity input is converted into syngas while further losses are seen when fuel is produced from the syngas. This again highlights that only countries with energy systems heavily reliant on renewable energy would produce enough excess electricity for synthetic fuel electrolysis to be feasible.

4.2. Scenario 2 – Gasification Gas and Hydrogen

The second scenario is similar to the first in that different synthetic fuel market penetrations are examined, however, in this case the fuel is produced using gasification gas and hydrogen. Electrolysers are still required for hydrogen generation but not as high an electricity supply is needed. For these simulations no carbon capture technology was installed in the system.

4.2.1. Results

As increasing amounts of synthetic fuel were included in the model, the overall system costs increased by a small factor. This can be shown in figure 25. Carbon dioxide emissions were reduced noticeably as the percentage of synthetic fuel rose. When synthetic fuels were used in transport, the renewable percentage share of the primary energy supply rose markedly An increase from an initial 14.8% with no synthetic fuel to 45.2% with 100% synthetic fuel was seen.

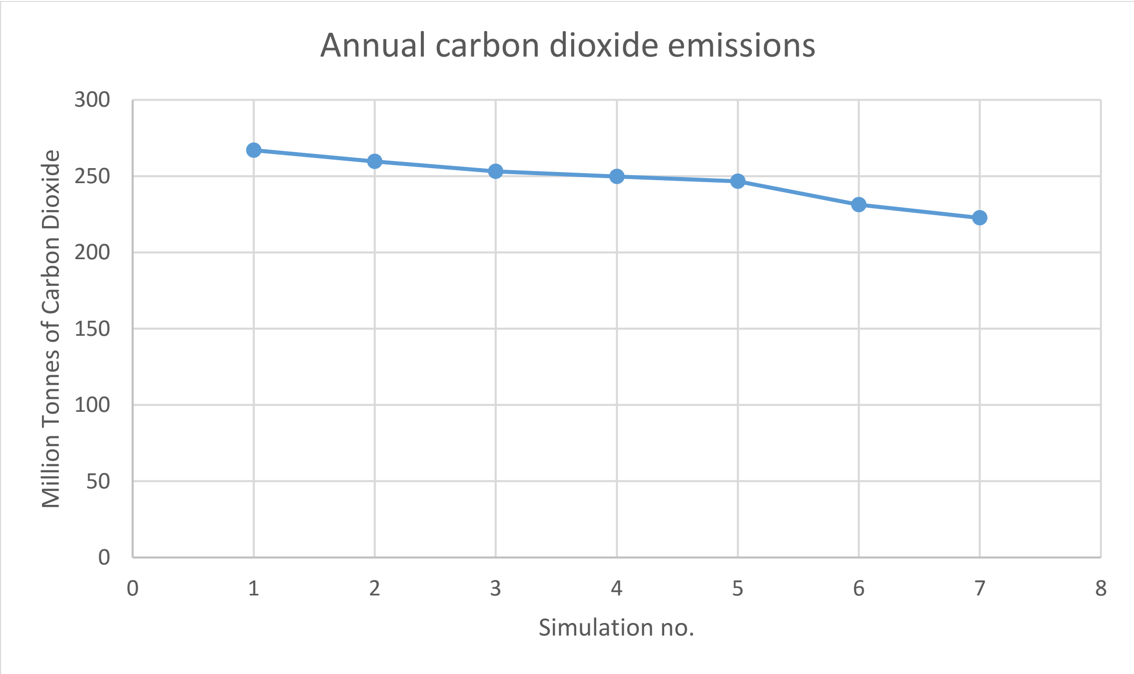


Figure 24 - Scenario 2: CO_2 Emissions

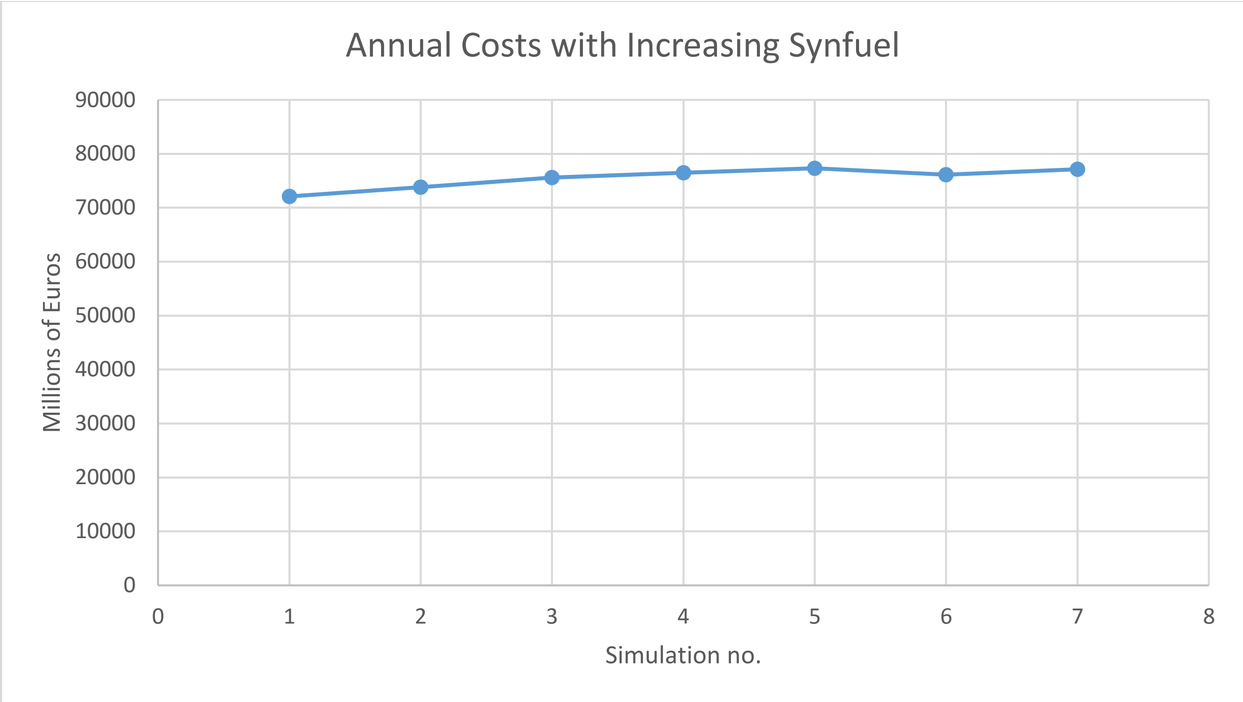


Figure 25 - Scenario 2: Annual Costs with Low Resolution

Annual costs can be shown at a higher resolution to highlight the variability more clearly.

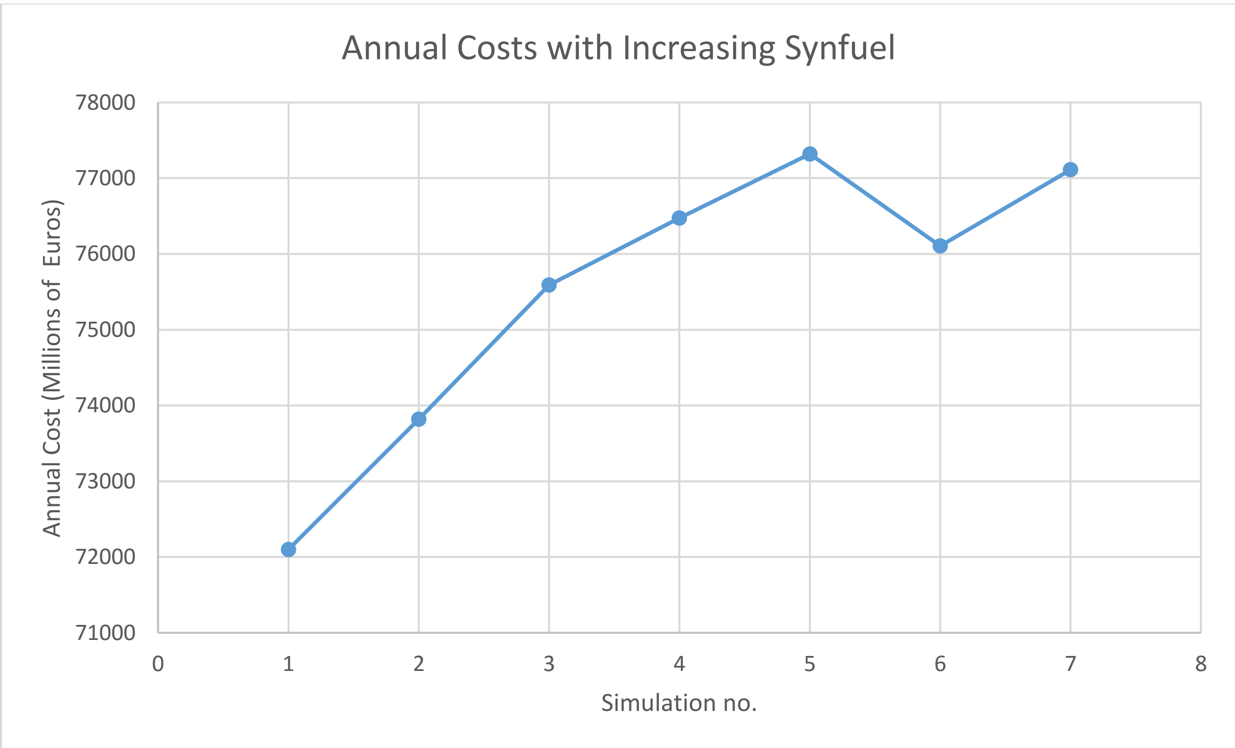


Figure 26 - Scenario 2: Annual Costs with High Resolution

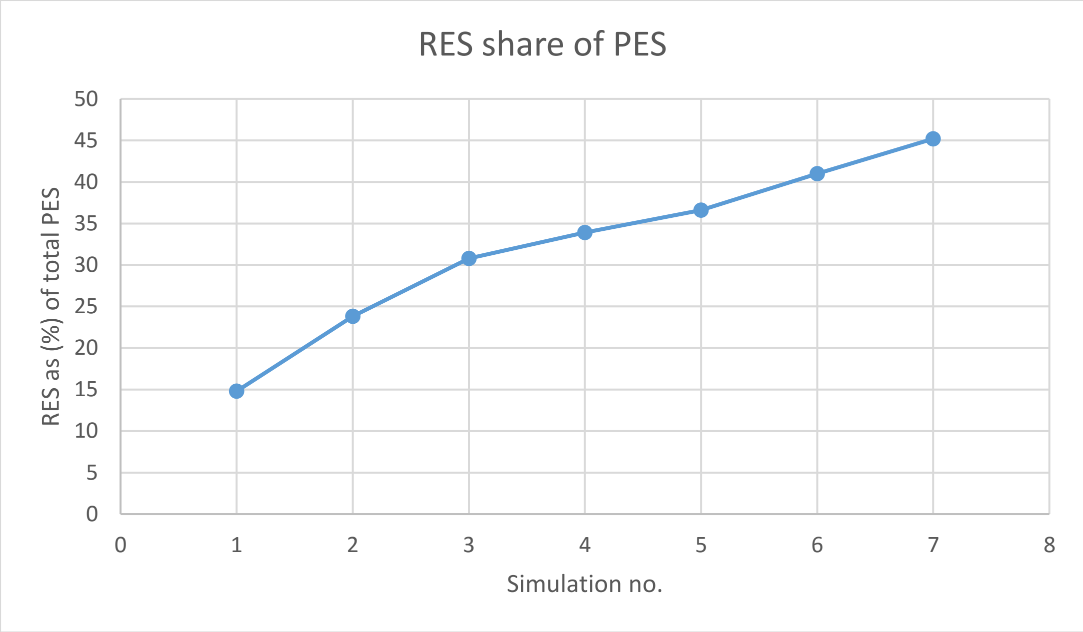


Figure 27 - Scenario 2: RES Share of PES

When examining the effect of synthetic fuel produced using gasification gas and hydrogen electrolysis, it is interesting to see how this effects the generation and consumption of electricity. The graphs below are taken from a 100% fossil fuel scenario, and a 100% synthetic fuel scenario over a time period of a week in January.

Graphs were created in EnergyPLAN to highlight the increasing energy demands associated with synthetic fuel.

Figure 28 shows the electricity consumption in a purely fossil transport fuel scenario. When compared to figure 29, which shows the consumption when synthetic fuels are introduced to the system, it is seen that the general consumption is very similar but with a large amount of electricity also being used to power electrolysers. This clearly shows the impact that producing this quantity of synthetic fuels has on the over electricity consumption.

When it comes to electricity generation, figure 30 is from a fossil transport fuel system and shows quite a high percentage of energy produced coming from renewables. Figure 31 is the synthetic fuel scenario and has the same renewable generation but the additional electricity requirements are met by power plant capacity meaning renewables account for a smaller portion of electricity generation. These graphs show the overall electricity supply, the primary energy supply takes into account transport energy requirements also. In the synthetic fuel scenarios, this synthetic fuel is classified as renewable energy.

When summer months were analysed, similar graphs were produced – with slightly lower consumption and generation values as expected.

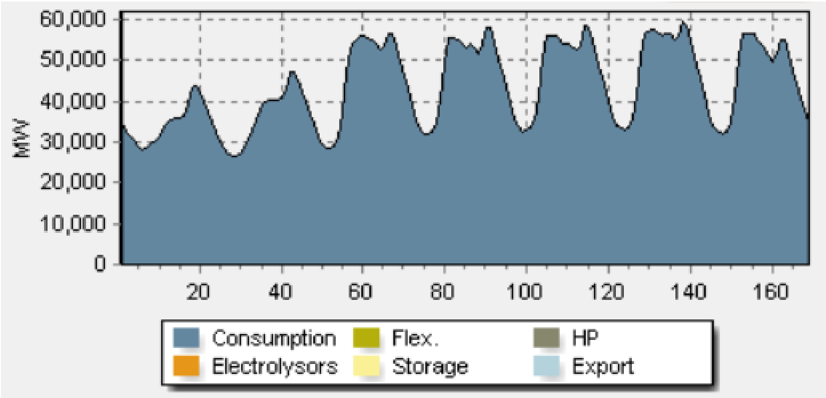


Figure 28 - Scenario 2: Total Electricity Consumption with Fossil Fuel Only

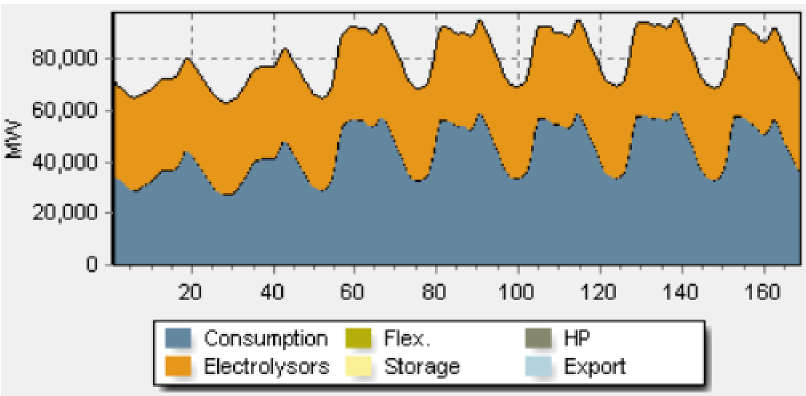


Figure 29 - Scenario 2: Electricity Consumption with 100% Synthetic Fuel

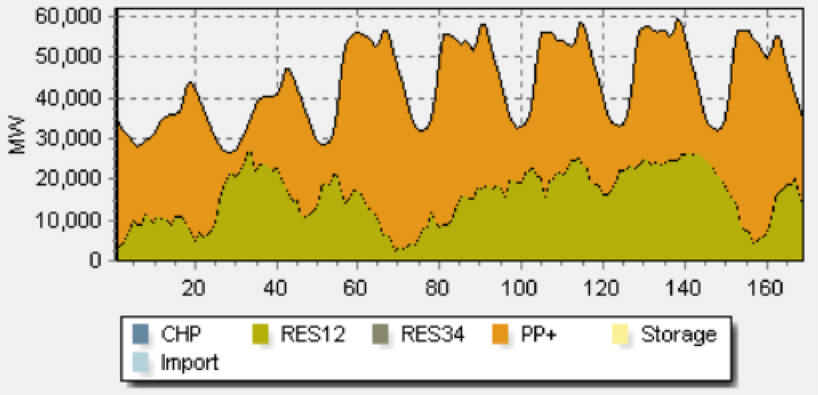


Figure 30 - Scenario 2: Electricity Generation with Fossil Fuel Only

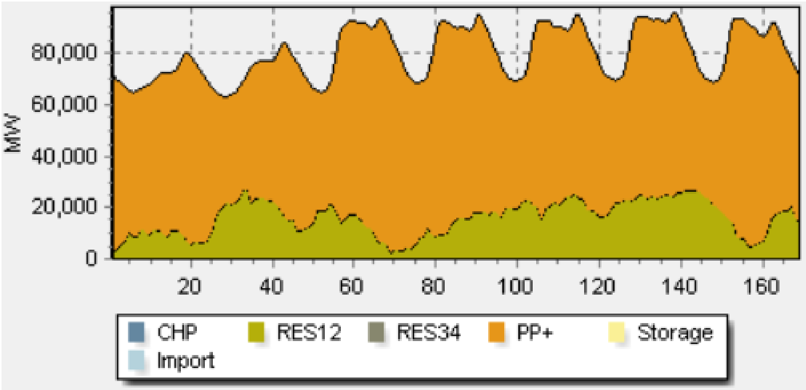


Figure 31 - Scenario 2: Electricity Generation with 100% Synthetic Fuel

4.2.2. Discussion

Unsurprisingly, synthetic fuel integration led to increased system costs. In reality there would likely be a more substantial increase due to unforeseen costs and from optimistic assumptions. The cost of developing new technology to a commercial level will often be higher than expected. However, synthetic fuel storage will allow for higher energy flexibility within the overall energy system. The opportunity for new job creation also arises from producing synthetic fuel and reducing the requirement for energy import.

This scenario seems far more beneficial than the previous carbon capture based scenario. Electricity demand does not need to increase so drastically and the gasification technology is more mature than carbon capture currently. The increase in the renewable share of the PES gives a good indication of progress towards a 100% renewable energy system. The synthetic fuel production decreases the reliance on fossil fuels which in turn reduces the fossil fuel share of the primary energy supply. A large amount of primary energy is now in the form of synthetic fuel and biomass without the need for additional power plant capacity. This means that cleaner fuel can be created through renewable means.

When considering a 20% synthetic fuel scenario, 125TWh of biomass is required to provide the carbon source for this fuel. In 2016 the UK produced roughly 20TWh of biomass energy.[42] At this level only around 3% of transport fuel could be covered by synthetic fuels. Again, it is seen that producing synthesis gas in a renewable manner requires excessively large amounts of energy. If both of the methods - gasification gas or carbon capture - were used in tandem, this could at least ease the reliance on either electricity or biomass. This is examined in Scenario 3.

4.3. Scenario 3 – 50% from Gasification Gas, 50% from CCR

Scenario 3 involves using both methods of syngas production simultaneously – through biomass gasification and through electrolysis. This is carried out in the hope that synthetic fuels are more feasible when sourced from two separate feedstocks.

4.3.1. Results

From Figure 32, it is clear that carbon emissions do not increase as much as in Scenario 1. There is still a noticeable increase which was not fully offset through using gasification gas. Similar results can be seen in terms of finance with an increase from 72 billion Euros to 100 Billion Euros annually. There is not as high an increase in costs, although still more than is practical. A steady increase in the RES share of the PES is seen in this scenario, increasing from 15% to 30% as synthetic fuel share rises from 0% to 100%.

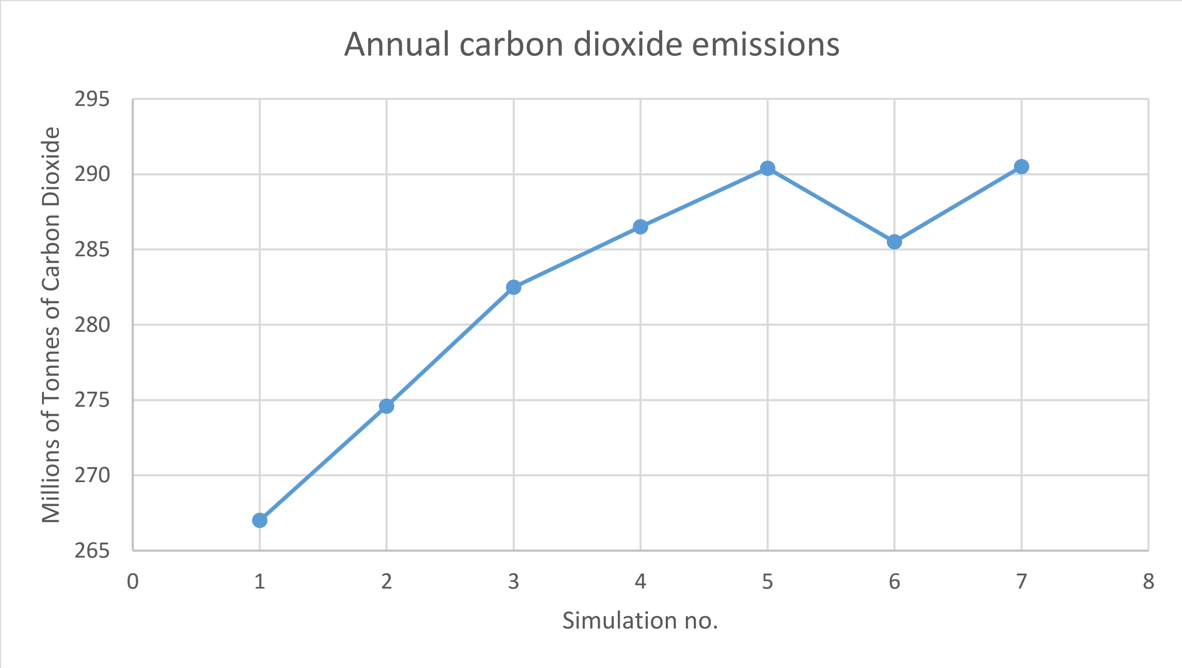


Figure 32 - Scenario 3: CO_2 Emissions

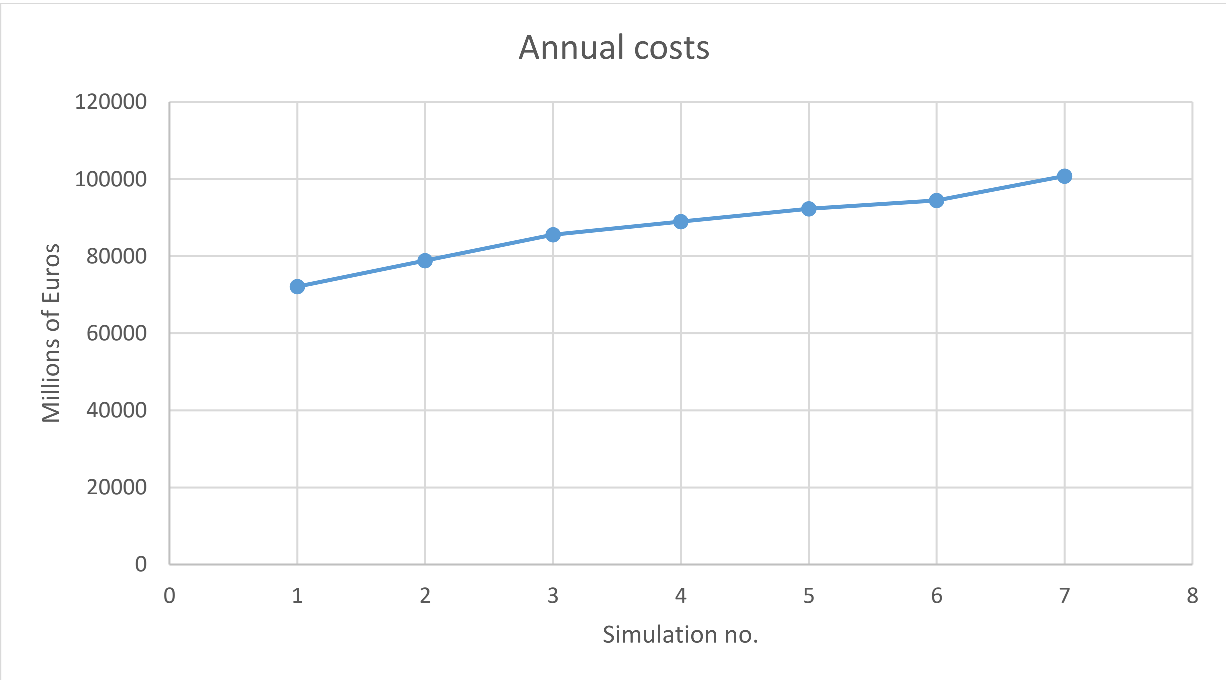


Figure 33 - Scenario 3: Annual Costs

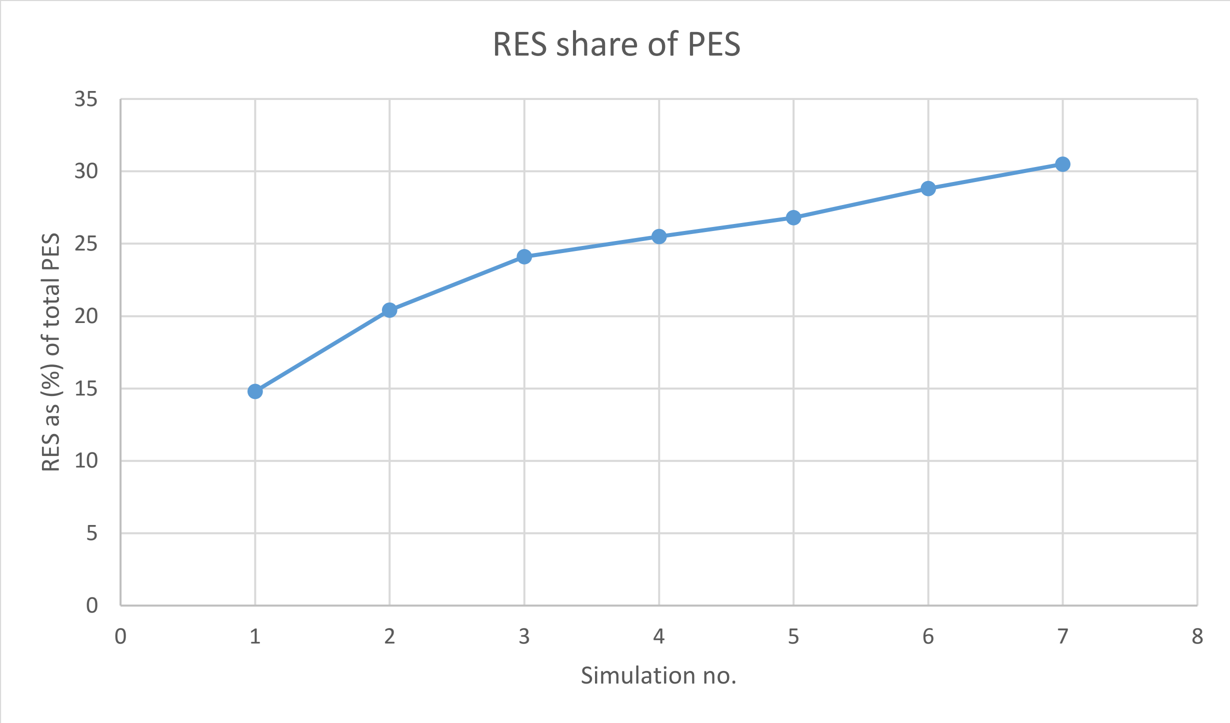


Figure 34 - Scenario 3: RES Share of PES

4.3.2. Discussion

Immediately this does not look an effective pathway to sustainable transport. The increase of both system costs and carbon emissions are not the desired results. As explained in the previous scenario discussions, the high electricity demand for electrolysis, as well as high biomass requirement are both unfeasible. The requirements for the aforementioned technologies are less demanding, however this brings additional system costs without decreasing carbon emissions. As with scenario 2, there is a promising increase in the primary energy supply from renewable energy although this benefit is not substantial enough to offset the shortfalls of the scenario.

Within a current UK energy system, this scenario is not feasible. If the energy landscape were to drastically change then a similar pathway to this scenario may be feasible although this seems unlikely. As with the previous scenario, if there was a greater renewable energy generation, CO_2 emissions would go down as the electricity required for electrolysis and fuel synthesis would be coming from a renewable source.

4.4. Scenario 4 – Synthetic Jet Fuel

The final scenario is focussed on aviation. 0%, 20%, 40%, 60%, 80%, and 100% synthetic aviation fuel simulations were run. The aviation fuel in this case is produced using syngas from gasification gas and hydrogen, similar to scenario 2. Of the total of 600TWh of transport demand, aviation accounts for roughly 140TWh. This mean that the overall energy system is not as noticeably affected as when road transport fossil fuel is replaced by synthetics.

4.4.1. Results

As renewable jet fuel was used in place of traditional fossil derived jet fuel, a notable decrease in carbon dioxide emissions was seen alongside relatively constant total costs. CO_2 emissions were at 267Mt/year with 100% fossil air transport and when 100% synthetic jet fuel was used 254Mt/year was emitted. The reasonably low fuel requirements mean that this scenario is not a 100% synthetic fuel scenario like the other three. Fuel demand is 600TWh while in the 100% synthetic jet fuel simulation only 140TWh of this fuel is synthetic. This means that as synthetic fuel increases, the oil required for fossil fuel transport decreases, however the natural gas power plant requirement for fuel synthesis also increases meaning a relatively constant RES share of the PES.

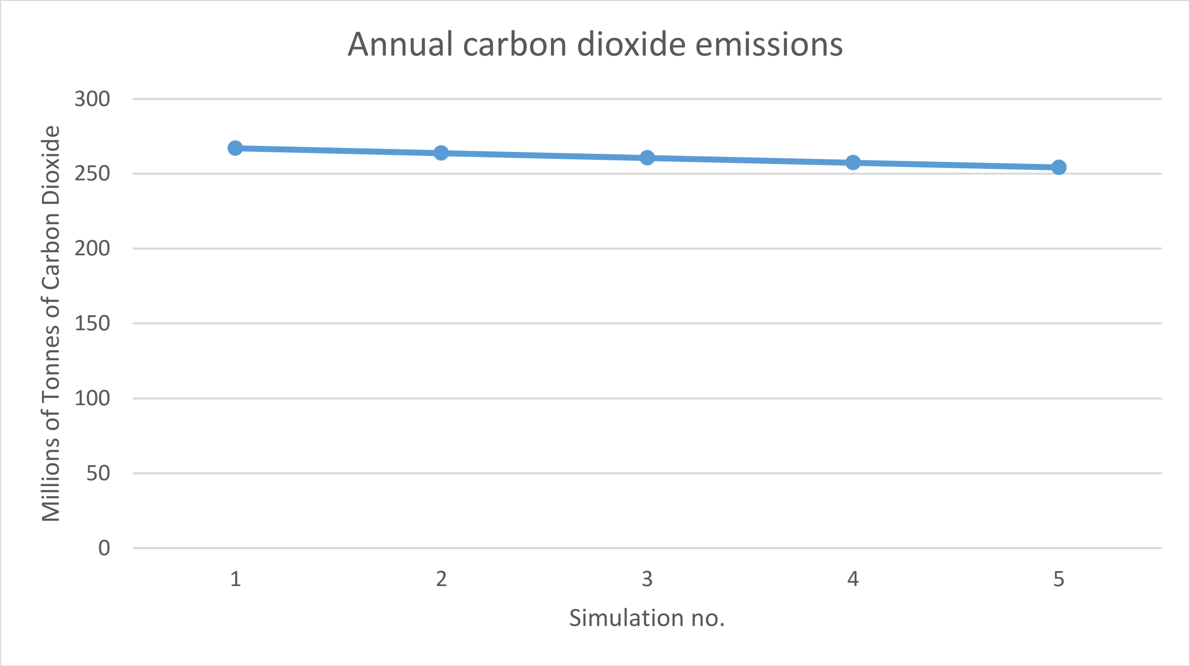


Figure 35 - Scenario 4: CO_2 Emissions

This graph accentuates the increase and decrease in total costs. In reality, the annual costs stay relatively stable around the 72million Euros mark.

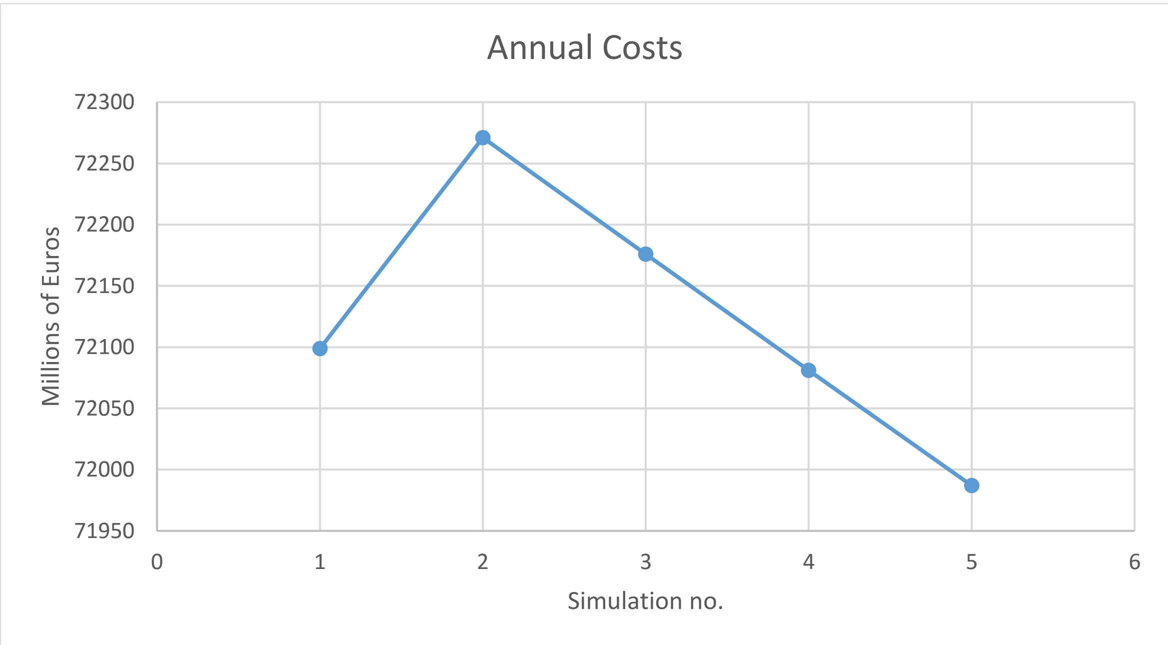


Figure 36 - Scenario 4 Annual Costs with High Resolution

When illustrated on a larger scale, it is shown that annual costs remain almost uniform through the various simulations.

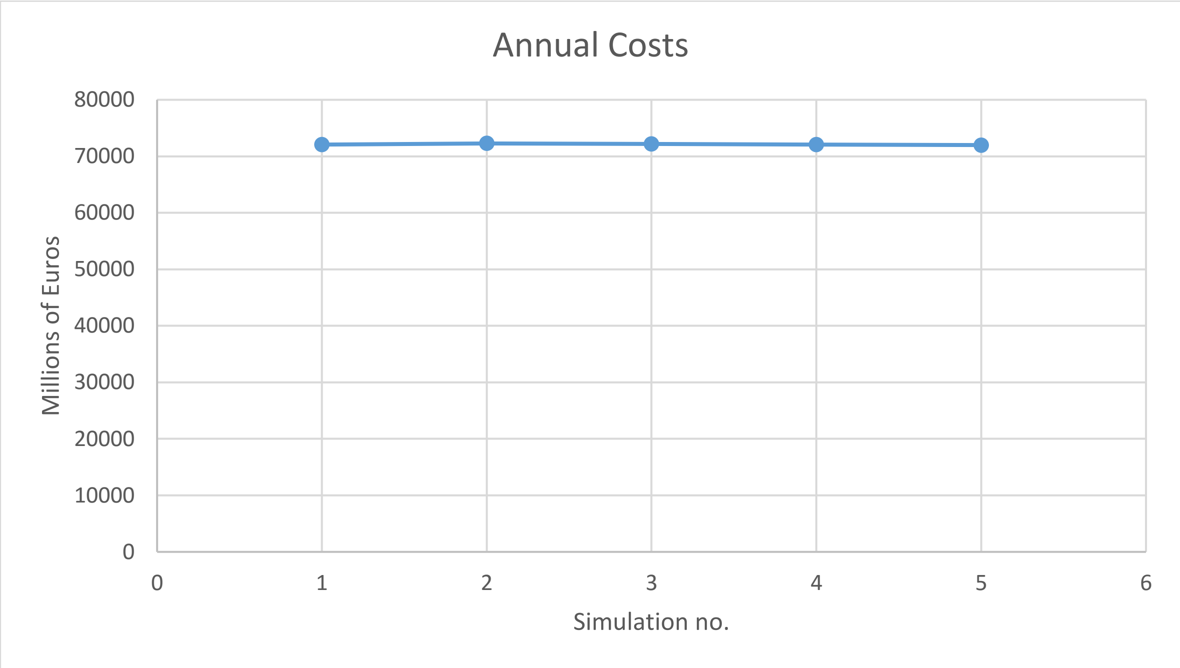


Figure 37 - Scenario 4: Annual Costs with Low Resolution

The RES share of PES increases initially when synthetic jet fuel is added then proceeds to decrease slightly as the amount of synthetic jet fuel is increased.

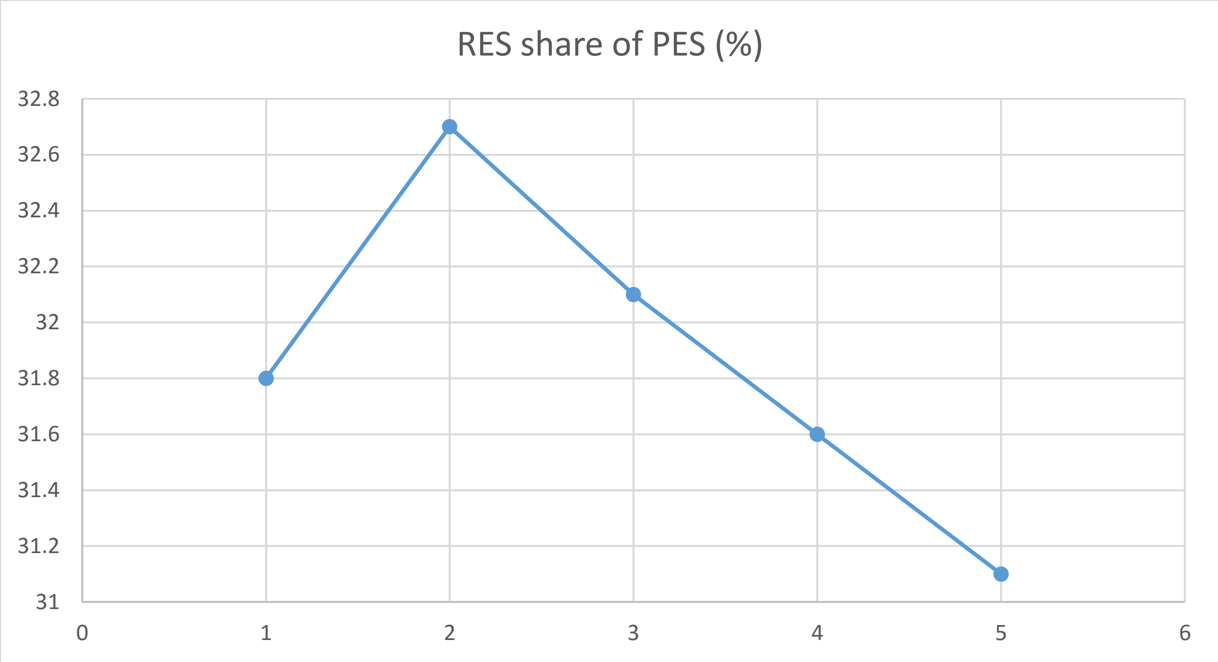


Figure 38 - Scenario 4: RES Share of PES

4.4.2. Discussion

The efficiency of producing synthetic jet fuel from syngas is higher than for petrol or diesel alternatives, at least according to EnergyPLAN assumptions. This results in a lower cost of biomass gasification and electricity requirement. It is an area in which a solution must be found as electric planes are not a technology likely to exist in the near future. Therefore, it is the only one of the Scenarios where 100% synthetic fuel is a realistic possibility. It would require a worldwide effort to replace existing jet fuel with synthetic fuel in order to make a substantial difference.

If 50% of the fuel demand for aviation in the UK was met through synthetic jet fuel. This would require 60TWh of energy from biomass. This is a far more realistic possibility than the amount needed for road vehicles. The technology is available and has been proven to work in plane testing. The renewable energy supply share of total primary energy supply remains relatively constant with increasing synthetic jet fuel. This is the case because natural gas required to provide electricity for electrolysis is roughly equivalent to the oil required for fossil transport fuel. This means that the renewable energy supply is responsible for almost the same share of the PES irrespective of the amount of synthetic jet fuel in the system.

The reduction in carbon emissions is not huge, however it is an improvement considering relatively low cost requirements and shows the potential for improving jet fuel sustainability on a larger scale.

From investigating different options for synthetic fuel production, jet fuel yielded the most positive results. While the results may be optimistic due to assumptions and the use of only one modelling software, there is reason to further investigate the possibility of pursuing synthetic jet fuel.

5. Overall Discussion

This section will collate the main findings from the literature review and analysis phases and comment on the outcomes. A section on future research presents ideas which may be beneficial to pursue which were beyond the scope of this thesis.

Initially the main aim of this thesis was as follows: “To investigate the feasibility of synthetic transport fuels from a renewable source as part of the UK energy system.” This aim was addressed through an extensive literature review and modelling using EnergyPLAN software. The review provided an important basis on which to build and gave opinions as to the potential for synthetic fuels. Much of the research examined belonged to the team responsible for EnergyPLAN and they give a positive take on synthetic fuels. On the other hand, some research was more sceptical of the possibilities. Chiefly, the large amount of energy required to produce synthetic fuels was seen as impractical.

The software used was developed by researchers promoting their concept of a “Smart Energy System”. Potential bias or inaccuracy of the results obtained have been scrutinised in this section. The benefits of the software have also been considered and discussed.

Overall the EnergyPLAN programme provided adequate means to achieving objectives set out at the beginning of this project. It provided a platform on which to judge the potential of synthetic fuels in terms of sustainability. The major factors determining sustainability are environmental considerations, economics, and social sustainability. EnergyPLAN gives useful results for the economics and environmental impacts although the information is limited and some key data must be elicited from other sources. For example, the only form of emission considered in the software is carbon dioxide. This is a useful indicator in environmental impact but does not give the full picture of environmental impact. It is only possible to estimate other emissions using different publications.

The Social impacts of this shift in fuel dynamics are not clear from the software. However, in “IDA’s Energy Vision” (Lund et al), the expected job creation from the introduction of synthetic fuels is given. 50,000 new jobs/year until 2050 was estimated to be the effect.[3] In a country the size of Denmark with a population of only just over five million, this figure seems inflated. It is proposed that the employment benefits would offset much of the additional investment costs. If 50,000 jobs/year were created this may be the case but it cannot be justified as a solution.

Modelling the effects of the synthetic fuel within a wider energy system exposed the main barriers to the success of the technology. There were promising results as well as drawbacks. The required energy for synthetic fuel production was the main issue, as identified in the literature review, although a potential solution would be the import of synthetic fuels from countries with the capability of producing excess fuel. Interconnection between different countries in order to maintain a supply/demand balance is an important part of the electricity network. Import and export of synthetic fuels could allow the storage required for grid balancing without the need for fossil fuels.

The scenario based on renewable energy and captured carbon is ostensibly an ideal solution allowing for renewable energy storage as well as removing greenhouse gas emissions from the atmosphere. In reality, the results show that this process remains largely unfeasible unless very specific resources and low energy demand exists. This is why syngas production from gasification gas may be a more viable option in the UK, at least.

As well as limitations, positives of the technology can be taken from the modelling. It was shown that the overall primary energy supply could be increased sizeably through adding synthetic fuel. Transport demand makes up a large portion of the overall demand and if renewable energy can power the transport sector this will make a large difference to the overall system.

The quality and accuracy of results and data given using the EnergyPLAN software must be analysed. Since the programme is created by advocates of synthetic fuels, it must be considered carefully whether their assumptions are overly optimistic. Comparisons of several assumptions with those of other publications were made, although there is limited proven research in the area of synthetic fuel feasibility. An EnergyPLAN manual provides most of the assumptions and relevant data on which the programme was created.[39] This gives clarification on some points although some assumptions are lacking full justification.

The electrolysers used in the model are assumed to be Solid Oxide Electrolyser Cells (SOECs). These are yet to be proven commercially and have a stated efficiency of 80% in EnergyPLAN. In general, effective hydrogen production from water electrolysis is still a developing technology with no assurances that large scale process will be feasible. In other literature, stated efficiencies for SOECs are generally between 50% and 75%.[43] Established alkaline electrolysers tend to be even lower. For these reasons, a stated efficiency of 80% is too high for an unproven technology and this assumption has a direct effect on important values such as hydrogen production, electricity consumption, and system costs.

For the synthetic jet fuel scenario, the results obtained during modelling were positive and seemed to show that synthetic jet fuel to replace existing fuel is a feasible scenario to pursue in the UK. These findings must be scrutinised to examine whether this is likely to be the case in reality.

The efficiency of the syngas to synthetic jet fuel process has been assumed by EnergyPLAN to be 100%. Any industrial process will have a lower efficiency that 100% so immediately this is an optimistic assumption. If the equivalent TWh output of jet fuel is yielded from an equivalent TWh of syngas, there will still be energy required for heating and maintaining process conditions. All of this will take place through a new process, the effectiveness of which is still unknown on a large scale. If the quoted efficiency is higher than the actual value then this will affect the amount of hydrogen and electricity by an even greater degree. According to Selvatico et al, the efficiency of syngas conversion to Fischer-Tropsch fuel is around 40%.[44] This may not be 100% accurate either but is far more realistic than an assumed efficiency of 100% Efficiencies are key determinants in process performance so inaccurate efficiencies have major permutations to results achieved.

When using large amounts of biomass as feedstock for synthetic fuel production, EnergyPLAN has assumed biomass to be a carbon neutral technology. In many cases the biomass will be grown, and will consume as much carbon dioxide as it releases when turned into fuel, however this will not always be possible. Carbon dioxide emissions can be high if biomass is not produced and treated in a sustainable way. This assumption may not be valid for the biomass industry in most countries depending on how the biomass is sourced. Another assumption made which may have given unrealistically favourable results is the cost of a synthetic gas plant. This was assumed to be equal to that of a gasification plant. While it is difficult to predict the cost of a new process, it was assumed to be considerably lower than the equivalent hydrogenation plant used in the CCR scenario.

In scenario 2, the syngas was produced using biomass and hydrogen from electrolysis. Various assumptions are quoted for parameters such as hydrogen share of input, steam ratio to biomass required, and different efficiencies. From comparing these values to literature, the efficiencies seem again to be higher than is likely. In a 100% synthetic fuel scenario, 251.8TWh of

Hydrogen and 560TWh of biomass can be used to generate 657.5TWh of syngas. This equates to an output/input ratio of 0.81. Efficiency is inversely proportionate to the S/B ratio (Steam/Biomass), and a very low ratio of 0.17 is assumed in the model. According to Dascomb et al, the efficiency at this S/B ratio would be around 70% or less depending on operating temperature.[45] At this S/B ratio, the literature claims that the syngas produced would be of low energy content. This does not appear to be considered in the model. The inaccuracy of the efficiency assumption is clear when examining further literature. [46]

While shortfalls in the modelling software can impact results, there will also be inaccuracies and information gaps due to time constraints and scoping decisions made over the course of writing this thesis. Relevant costs were input into the EnergyPLAN model although a cost-analysis outside of this frame-work may have allowed for more accurate results. This was deemed out with the scope of this project due to time constraints and because economics were not the principal focus of the project.

The simulations carried out were not focussed at a very high resolution in terms of synthetic fuel penetration. Further simulations could have been run at more exact percentage shares of fuel. It was decided not to perform these as the results gave a good general idea of the effect of synthetic fuels and the accuracy of results is not reliable enough to make very precise calculations worthwhile.

It was decided to model the current state of the UK energy system. The researchers at the University of Aalborg created scenarios for how the Danish system may look in the year 2030 or 2050. It is difficult to predict how the UK energy system will shape up in the future so it was deemed appropriate to examine how close to synthetic fuel feasibility the UK is currently.

Having reviewed literature and modelled potential scenarios, an attempt to address the aim of the project can be made. The feasibility of synthetic fuel within a UK energy system has been shown to be implausible on a 100% synthetic level. This was the expected outcome due to energy requirements, cost of infrastructure and operation, as well as the emergence of alternative technologies such as electric or biofuel vehicles. It has been found that a currently unfeasible amount of electricity or biomass would be required to replace fossil transport fuels. There are positives to be taken from the findings. With a mixture of production techniques, and supplemented by alternatives such as electric or hydrogen vehicles, synthetic fuels could provide a cleaner solution to transport fuel. The storage capability mentioned is of great importance and could help to solve another major challenge in any energy system.

The UK transport sector will undoubtedly change drastically in the coming decades. Synthetic fuels are likely to become part of this in some capacity although this research has shown they should not be the technology focussed on primarily. Aviation is the area which has the most potential and it is possible that synthetic paraffinic kerosene or a similar hydrocarbon fuel will replace standard jet fuel in the near future.

Focussing efforts on one particular technology can lead to problems. Scenario 3 which explores the possibility of producing synthetic fuel from two different sources wasn't economically feasible in this model, however, sharing the transport demand across various fuel types may be beneficial. Hydrogen vehicles and synthetic fuel vehicles both rely on electrolysers with high electricity loads. This puts a strain on national electricity systems. On the other hand, using only electric vehicles to satisfy transport requirements may cause problems due to the scarcity and expense of rare earth metals and the environmental impact said to be associated with the mining of theses metals. There are several technologies which could provide for a future transport system however the majority of countries seem to be favouring a move towards electric vehicles. France and the UK have pledged to ban the production of petrol or diesel cars by 2040, while Norway has set the same target for 2025.

The effectiveness of synthetic fuels does depend on the make-up of the energy sector as a whole. There is real potential in Denmark due to their existing renewable infrastructure and willingness of government and civilians to contribute to a cleaner environment. In areas of high, intermittent renewable output, the electricity produced at peak generation times may be wasted so using it as a feedstock for a useful production process is beneficial. Some countries will be slower than others in adapting to electric vehicles and synthetic fuels due to economic situations or availability of resources. Designing an energy system must be performed on a country by country basis factoring in politics, geography, available resources, and budget.

5.1. Further Work

Due to the time constraints associated with this project, some potentially important lines of research were scoped out of the report. This analysis leaves room for further research which could be made in the area of synthetic fuels.

Firstly, as previously mentioned, not all of the technology discussed in this report is being commercially deployed currently. A life-cycle analysis into the production of synthetic fuel using this technology could be carried out. A major doubt of synthetic fuels is that they require a lot of energy to produce. Estimations have been made but a definitive efficiency has not yet been observed.

A deeper and more detailed model of the UK energy system could be designed on EnergyPLAN or on another software to form a comparison. This would give a more accurate set of results.

Nuclear energy has been overlooked in this study as a comparison on the various different primary energy generation systems and is not relevant to the research when considering time constraints. Nuclear has very low carbon emissions which could see it as a potential electricity supplier for synthetic fuels so further research into this possibility would be valuable.

Biofuels produced from plant matter are an alternative to synthetic fuels. While synthetic fuels require large amounts of electricity or biomass to produce them, biofuels require large areas of land devoted to their production. A similar study could be performed assessing the feasibility of biofuels compared to synthetic fuels.

Using synthetic fuel in an energy storage capacity has been discussed in this report. An investigation into the practicality and potential of its storage capabilities would be beneficial. The cost and efficiency of using excess renewable energy to create synthetic fuel, which in turn could be used to generate electricity, when compared to alternative storage technology would make for interesting further research.

An extensive study purely into renewable aviation fuel may be of significance. There is ongoing research into new jet fuel alternatives and high performance, but sustainable, synthetic jet fuel. This is an area in which an alternative fuel must be found rather than relying on electricity or hydrogen solutions. Combining the storage capability with jet fuel production could be a valuable pathway to follow.

Having input a current UK energy system into EnergyPLAN, it may be beneficial to attempt to model future possible UK systems. If it was seen how the system would need to look in order to be compatible with large-scale synthetic fuels, this may be beneficial further research.

While the possibility of synthetic fuels in freight vehicles such as large trucks and ships was alluded to previously, this report did not investigate this possibility in depth. Similarly to air transport, heavy-duty vehicles have particular fuel requirements which electric batteries are unlikely to meet. This would be an interesting area of continued research.

The theme of large energy requirements has arisen several times in this report. Hydrogen generation through electrolysis requires a huge outlay of electrolysis. An answer to this problem may be the sourcing of hydrogen from anaerobic digestion plants. Usually only a small amount of hydrogen is produced but reaction kinetics can be adjusted to achieve higher hydrogen yields. If this was to occur in tandem with biomass gasification, the electrical load could be greatly reduced. This is an area in which further research could be valuable.

6. Conclusions

This thesis cannot provide a definitive yes or no answer to the question of whether synthetic fuels are a feasible technology within the UK energy system. Nevertheless, conclusions can be made on the part they may play in the future.

Modelling on EnergyPLAN software emphasised the high demand on electricity and biomass production required for a large percentage of the UK's transport demand to be met by renewable synthetic fuels. Vast energy requirement for fuel production is the principle barrier to feasibility and this energy efficiency will need to be improved to compete with alternatives in the future. This low efficiency means it is not capable of becoming a dominant fuel type in the UK without drastic change to the entire energy system. The University of Aalborg's proposed Danish energy system of the future may be able to integrate large amounts of synthetic fuel due to their comparatively lower fuel demands and high intermittent renewable energy.

As other technologies also have their shortfalls, synthetic fuels could account for a portion of demand, supplementing other fuels and helping to decrease emissions in the UK. As discussed, the capability to store excess renewable electricity in the form of synthetic fuels may prove to be just as important as their contribution to transport.

The most promising of results from modelling came in the synthetic jet fuel scenario. The production of synthetic paraffinic kerosene from either renewable electricity or biomass – or a mixture of both – was reckoned to be feasible using EnergyPLAN software.

There is much to be excited about in the case of synthetic fuel technology. While it is not presently as practical as other technologies, it is an area worth pursuing and continuing to develop as there is much room for improvement in the worldwide transport sector.

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7. Appendices

7.1. Appendix 1 - Estimated Costs

This figure shows costs assumed by EnergyPLAN for various technologies. [3]

Production type	Unit	Investment (M €/unit)	Lifetime (Years)	Fixed O&M (% of investment)
Electrofuels				
SOEC electrolyser	MWe	0.3	15	3.0%
Hydrogen storage	GW h	20	30	0.5%
Chemical synthesis MeOH	MW-Fuel	0.6	20	3.5%
Carbon capture costs for CO_2-electroFuel	Mt	30	25	0.0%
Energy storage				
Thermal storage	GW h	3.0	20	0.7%
Pumped hydro-electric energy storage	MWe	1.2	50	1.5%
Pumped hydro-electric energy storage	GW h	7.5	50	1.5%
Oil storage	TW h	23	50	0.6%
Methanol storage	TW h	52	50	0.6%
Gas storage	TW h	48	50	1.0%
Bioenergy conversion				
Gasification plant	MW Syngas	0.3	25	7.0%
Gasification gas upgrade	MW Gas Out	0.3	15	18.8%
Biodiesel plant	MW-Bio	1.9	20	3.0%
Bioethanol plant	MW-Bio	0.4	20	7.7%
Biojetfuel plant	MW-Bio	0.4	20	7.7%

Figure 39 - Appendix 1: EnergyPLAN Estimated Costs

Exact values of the results discussed in the results section for each of the four scenarios.

Simulations with synthetic fuel from CCR and electricity

Table 5- Appendix 1: Full Results for Scenario 1

Transport fuel breakdown	Scenario	Carbon dioxide emissions (Mt)	RES share of PES (%)	Annual costs (million Euros)
100% fossil no CCR	1	267	14.8	72099
80% fossil 20% synthetic + CCR	2	289.4	17.5	84896
60% fossil 40% synthetic + CCR	3	311.8	19.1	97652
50% fossil 50% sythetic + CCR	4	323	19.7	105041
40% fossil 60% synthetic + CCR	5	334.6	20.2	112431
20% fossil 80% synthetic + CCR	6	356.6	20.9	126609
100% synthetic + CCR	7	357.6	21.6	132842

Synthetic Fuel from Gasification Gas and Hydrogen

Table 6 - Apendix 1: Full Results for Scenario 2

Transport Fuel Breakdown	Scenario	Carbon dioxide emissions (Mt)	RES share of PES (%)	Annual costs (million Euros)
100% fossil	1	267	14.8	72099
80% fossil 20% synthetic	2	259.6	23.8	73818
60% fossil 40% synthetic	3	253.1	30.8	75591
50% fossil 50% synthetic	4	249.8	33.9	76472
40% fossil 60% synthetic	5	246.5	36.6	77320
20% fossil 80% synthetic	6	231.2	41	76106
100% synthetic	7	222.6	45.2	77110

Synthetic Fuel from 50% gasification gas 50% from CCR

Table 7 - Appendix 1: Full Results for Scenario 3

Transport fuel breakdown	Scenario	Carbon dioxide emissions (Mt)	RES share of PES (%)	Annual costs (million Euros)
100% fossil	1	267	14.8	72099
80% fossil 20% syn	2	274.6	20.4	78828
60% fossil 40% syn	3	282.5	24.1	85592
50% fossil 50% syn	4	286.5	25.5	88968
40% fossil 60% syn	5	290.4	26.8	92311
20% fossil 80% syn	6	285.5	28.8	94498
100% synthetic	7	290.5	30.5	100794

Synthetic Jet Fuel Scenarios

Table 8 - Appendix 1: Full Results for Scenario 4

Jet fuel type	Scenario	Carbon dioxide emissions (Mt)	RES share of PES (%)	Annual costs (million Euros)
100% fossil	1	267	31.8	72099
75% fossil 25% synthetic	2	263.8	32.7	72271
50% fossil 50% synthetic	3	260.6	32.1	72176
25% fossil 75% synthetic	4	257.4	31.6	72081
100% synthetic	5	254.2	31.1	71987

Renewable Energy Generation

Table 9 - Renewable Energy Generation Data[42]

Renewable Energy	Installed Capacity (MW)	Annual Energy Output (TWh)
Wind Power	16,000	33.2
Photovoltaic	12,000	24.9
Hydro	1,600	6.0

Carbon Capture and Hydrogenation Requirements

Table 10 - Carbon Capture and Hydrogenation Data

Fuel Breakdown	Electrolyser electricity demand (TWh/year)	CCR electricity demand (TWh/year)	CCR electricity/ CO_2 (TWh/Mt)	CCR CO_2/syngas (Mt/TWh)	Hydrogenation syngas output (TWh/year)
100% fossil fuel	0	0	0.289	0.252	0
80% fossil 20% syn	225.3	10.4	0.289	0.252	143
60% fossil 40% syn	450.6	20.8	0.289	0.252	286
50% fossil 50% syn	563.2	26.0	0.289	0.252	357.5
40% fossil 60% syn	675.8	31.2	0.289	0.252	429
20% fossil 80% syn	901.1	41.7	0.289	0.252	572
100% synthetic	1035.8	47.9	0.289	0.252	657.5